Critical Assessment of Helmet Retention System Test Methods

A. Gilchrist and N.J. Mills,
School of Metallurgy and Materials,
University of Birmingham,
Birmingham B15 2TT, UK.

Abstract

The validity of helmet retention system test methods have been evaluated by considering the impact mechanics of accidents, and the mechanical design of the tests. The test methods are simple falling weight lab tests where the drop height of the mass is adjusted to reproduce the type of failures found in accidents. The causes of force peaks and oscillations in the test traces have been identified, and a means found of obtaining reliable chin strap force measurements. Recommendations are made for improving the test, so that chin straps and buckles are adequately strong but not over-designed. It is vital to measure the dynamic force and to relate it to the likely force in an accident. The retention system effectiveness test has reduced the incidence of helmet roll-off by an inertial mechanism, but oblique impacts can still cause roll-off.

1. Introduction of the tests into the motorcycle helmet standards

In a survey of 93 fatal motorcycle accidents (1), it was found that helmet loss occurred for a number of reasons. In 15 of the helmets there was evidence of mechanical overload of the chinstrap or its fastenings, and 12 helmets came off without sustaining a major direct impact. Fig 1 shows how a polyester webbing chin strap has pulled off the single steel rivet that was used to fasten it to the helmet shell, allowing the helmet to come off. The British Standards for motorcycle helmets prior to 1980 (2) had a 'static' test for chin strap strength, in which the strap was slowly loaded to a force of 1350 Newtons; this force was not enough to cause failures of the kind observed in accidents. Glaister (3,4) devised a 'dynamic' test in which the chin strap was shock loaded(fig 2a). The preload on the chin strap consists of the weight of the vertical shaft and anvil. The chin strap stirrup rollers, 12.5 mm in diameter and 76 mm apart, represent the edges of the jawbone. The helmet is supported at its lower edge on rigid plates, inclined at a suitable angle so that the helmet is in the normal wearing position. A drop mass falls through the distance specified in Table 1 before it impacts a flat anvil. He reproduced webbing and rivet failures by systematically increasing the drop height of a 10 kg mass by 0.25 m steps, until at 0.75 m these failures were reproduced. The limit of 25 mm maximum extension, preserved from the earlier BS 2495 static test (2), was to prevent helmets coming off if the strap stretched too much. The test was incorporated into BS 2495 and BS 5361 by means of Amendment 4 published in February 1980, hence into the new standard BS 6658:1985. This empirical solution of the helmet failure problem assumed that the level of forces in the laboratory tests was the same as in the real-world accidents. Since 1980 manufacturers have sewn the chin strap ends around a steel hanger plate, which is riveted to the shell, and used more substantial buckles. As a result failures of the chin strap have ceased to be a feature of reports of fatal motorcycle accidents.

The chin strap strength test in the EC standard (5), introduced in the series 2 amendments in 1982, was based on research at UTAC in France(6). This differs from the UK test in that the helmet is supported by a bolt and plate (fig 2b) that pass through a hole drilled in the crown. This system is capable of testing helmets which do not have chin straps as there is a solid complete headform. In the development tests(6) the drop height was only 0.25 m and this produced peak dynamic forces of 1.3 to 1.45 kN; the magnitude of the forces produced by the EC test drop height of 0.75 m is not known.

The introduction of a retention system effectiveness test into the BS 6658:1985 was intended to prevent helmet roll-off in accidents (7). In the authors' experience certain designs of helmet were liable to roll-off due to poor positioning of the chin strap, and inappropriate use of soft foam around the base of the helmet. They were involved in far more roll-off accidents than their exposure rate would predict. The simple test method used a falling mass to jerk the helmet forwards on a modified headform(fig 3a), rather than using a complex decelerating dummy to reproduce the accident events. The tangential forces exerted on the helmet shell were measured (7) to be about 500 N. This force was intended to produce a moment that is the equivalent of the rotational deceleration of the helmet multiplied by its rotational inertia (0.025 kg m^2 for a 1.7 kg motorcycle helmet). The changes in design occasioned by BS 6658 have reduced the incidence of roll-off accidents, but there are still roll-off cases where the chin strap is not fastened.

The series 3 amendments to Regulation 22(5) in May 1987 introduced a roll-off test based on French and Dutch research in 1984(8). In this test (fig 3b) the helmet is also jerked forward by a tangential force. As a headform with a solid chin is used, it is not possible for the helmet to come off - the test failure criterion is if the helmet rotates forward by more than 30°. No forces were reported for these tests. In principle a helmet which could never rotate more than 35° could fail the Regulation 22 test, whereas in the UK test the full roll-off must occur, and the design features that allow this can be identified. The kinetic energy of the falling masses in the two tests are similar; 40 Joules for the UK test (4 kg falling 1 m) and 50 Joules for the Regulation test (10 kg falling 0.5 metre, with a 3 kg preload).

2. Adoption of the tests in bicycle helmet standards

The tests were adopted for use in bicycle (and horse riding) helmet standards, with arbitrary reductions of the drop heights used. There was no accident survey data to validate the level of forces involved in the tests, and no measurements of the forces in the modified tests. Bicycle helmets are much lighter than motorcycle helmets, different materials of construction are used, and the speeds and accident events are quite different from those of motorcycle accidents. This will not matter if there are no bad design consequences - these could be that the retention systems are over bulky and heavy, or that certain types of shell construction are difficult to use. Bicycle helmets need to be light and well ventilated, and one popular design is the soft shell helmet where a cloth cover protects the surface of a polystyrene foam helmet. It is impossible to rivet a chin strap to such a material, so the design of the load path must be altered(fig 4). The polystyrene foam is ductile and quite strong in compression, but brittle in tension as fracture occurs at the boundaries of the moulded beads. Hence any large forces must be spread over a large area of foam and applied in compression. This was found to be a problem when the Regulation 22 test for retention system strength was applied to these helmets as failures at the suspension plate occurred.

The conditions of the retention system strength test are compared for motorcycle and bicycle helmet standards in Table 1. For the bicycle helmet standards the impact energies are arbitrarily reduced to 33 to 40% of the motorcycle helmet values. One important feature of the test is whether there is any pad of foam to cushion the impact between the falling metal cylinder and the metal catcher plate - the different requirements are also given in table 1.

Table 1. Conditions for dynamic chin strap strength tests

Standard	for riding	Preload mass kg	Drop mass kg	Drop height m	Drop energy J	Dynamic extension limit mm	Foam and thickness
Snell (9)	motorcycle	23	38	0.12	45	30	none
BS 6658(2)	motorcycle	7	10	0.75	74	32	PE, 10 mm
	(for second impact	17	10	0.75	74	25)	
ECE Reg 22(5)	motorcycle	15	10	0.75	74	35	none
prEN 398(10)	motorcycle	15	10	0.75	74	35	none
ANSI Z90.4(11)	bicycle	1.5	2	1.0	20	25	any
BS 6863(2)	bicycle	7	10	0.30	29	32	PE, 10 mm
draft prEN	bicycle	15	10	0.25	25	35	none

Although it is not described in the standards, it is practise in the ANSI (11) and BS (2) tests to support the lower edges of the helmet shell laterally to prevent them from moving inwards. This reduces the maximum extension. In the ECE standard there is a metal headform inside the helmet and the sides of the helmet are not supported.

The conditions for the retention system effectiveness test have been modified in a similar way. Table 2 gives the details and shows that the drop weight energies for the bicycle helmet tests are 50 % of those for motorcycle helmet tests.

Table 2. Conditions for roll - off tests

Standard	for riding	Preload mass kg	Drop mass kg	Drop height m	Drop energy J	Test Limit degrees
BS 6658(2)	motorcycle	0	4	1.0	39	roll-off
ECE Reg 22(5)	motorcycle	3	10	0.5	49	30
prEN 398(10)	motorcycle	3	10	0.5	49	30
ANSI Z90.4(11)	bicycle	no test				
BS 6863(2)	bicycle	0	10	0.5	20	30
draft prEN	bicycle	3	10	0.25	25	30

3. Mechanism of retention system failure in accidents, and biomechanics limits

Chin strap loading occurs when one side of the helmet slides on the road surface or a vehicle. One side of the strap is loaded more than the other side, as there is friction of the strap on the chin. The 'oblique impact test' in BS 6658, where a helmet hits an abrasive anvil at a 10° glancing angle at a 10 ms^{-1} velocity, has shown (12) that the tangential forces on the helmet surface are in the range 1 to 3 kN. The velocity of sliding on the road surface determines the sliding forces - it was found that for a GRP helmet sliding on a panel covered with abrasive paper the peak tangential force increased linearly from 0.8 kN at $V=5\ ms^{-1}$ to 2.9 kN at $V=13\ ms^{-1}$. Other tests showed that the magnitude of the force depended on the impact site, being largest on the side of fullface helmets, where the curvature is smallest, so the contact area is largest. Hence the 3.5 kN maximum force in the BS 6658 chin strap strength test is capable of being produced by a sliding impact at a velocity of the order of 10 ms^{-1} of a motorcycle helmet with a road surface.

Hodgson in experiments in which a Hybrid III dummy hit a flat concrete surface at an angle of 45° at 9.7 km/hr(2.7 ms^{-1}), showed that bicycle helmet behaviour depended on the construction(13). If the helmet had a hard shell this momentarily gripped the concrete then it skidded, and the peak tangential force was 1.2 kN. However for a no-shell helmet the polystyrene foam gripped the concrete and the headform and helmet rotated without slipping. The peak force was double at 2.4 kN. The impact site was high on the front of the helmet and the direction of the impact was such as to provide a rearward tangential force on the helmet. These experiments suggest that the sliding behaviour of no-shell helmets will differ from hard-shell helmets and that the tangential forces will be greater for the same tangential velocity. Although the sliding velocities in bicycle helmet accidents are likely to be lower than 10 ms^{-1} the tangential forces can still be as great as with motorcycle helmets.

The practical limit to the strength of a chin strap must be a compromise between the strap breaking and the helmet coming off, and the strap staying intact and the rider's neck fracturing. A voluntary static tensile load of 1.5 kN will not cause a fracture of the neck (14). The load to cause a hangman's fracture must be somewhat larger. The chin strap on one side should be no stronger than 2 kN to avoid the chinstrap causing such a fracture. The BS 6658 test, which produces a peak dynamic force of the order of 3 kN shared between two sides of the chin strap, seems a sensible compromise.

4. Mechanics analysis of the dynamic chin strap strength test

In this section we analyse which of the test rig elements affect the peak force in the retention system, and whether this force can be measured accurately. Glaister et al (3) assumed that the collision between the striker of mass $m_1 = 10$ kg and the preload mass $m_2 = 7$ kg is inelastic, due to the presence of a polyethylene foam pad between the impact surfaces. As the striker falls through 750 mm its initial velocity $V_1 = 3.84$ m s^{-1} whereas the initial velocity of the preload mass is $V_2 = 0$. After the inelastic collision the common velocity V_f of the two masses is

$$V_f = \frac{m_1 V_1 + m_2 V_2}{m_1 + m_2} \qquad (1)$$

since momentum is conserved. Hence $V_f = 2.26$ m s^{-1} and the 73.6 J kinetic energy before the collision is reduced to 43.2 J immediately afterwards. They noticed the inverse correlation between the peak force F_m and the peak dynamic extension x_m, and that the proposed test imposed a force of about 3 kN, but did not take the analysis further.

The first impact is between the drop-mass and the foam on the flat anvil. The impact behaviour of polyethylene foam (15) changes both with the microstructure and with the number of impacts. After multiple impacts the foam becomes softer at low strains, and some permanent deformation occurs. There is no requirement in the standards for a certain area of foam to be used, and the thickness is not always specified. Therefore the force-deflection characteristic of the foam pad can vary widely. If we define, for the two-body collision between the striker mass m_1 and the total preload mass m_2, the 'effective impact energy' E_e = energy input to the foam up until the time when m_1 and m_2 have a common velocity, then irrespective of the coefficient of restitution of the foam

$$E_e = \left(\frac{m_2}{m_1 + m_2}\right)\frac{m_1 V_1^2}{2} \qquad (2)$$

For a 10 kg striker falling 0.75 m onto a 7 kg preload, the effective impact energy on the foam is 30.3 J. If the coefficient of restitution is zero then the masses continue with a kinetic energy of 43.2 J. All real foams have a small coefficient of restitution(15) but the extra kinetic energy after the impact is rapidly dissipated by the oscillations of the drop-mass on the foam.

The simplest approximation for the force-deformation characteristic of the strap and its supports is a linear elastic graph

$$F = k_T x_T \qquad (3)$$

where k_T is the total spring constant. The kinetic energy after the inelastic collision is converted entirely to stored elastic energy in the chin strap at the moment when the striker velocity is zero. If x_m is the maximum allowed deflection, then the maximum force F_m is

$$F_m = \frac{2E_e}{x_m} \qquad (4)$$

Equation (4) predicts, for the second impact in the BS 6658 test, that $F_m = 3.46$ kN. This approximation for the peak force agrees with the experimental values (3) of 2.5 to 3.5 kN.

A detailed analysis of the deformation of the chin strap and the helmet shell during the test has been reported elsewhere(16). The total spring constant k_T of the helmet is analysed in terms of the spring constants k_C for the chin strap and k_S for the shell. The value of the latter varies with angle of inclination of the side parts of the chin strap, whereas the value of the latter varies with the materials used for the shell, and whether there is any constraint applied to the lower edge of the shell during the test. For a typical full face motorcycle helmet with an ABS thermoplastic shell the two factors contribute nearly equally to the total spring constant k_T. The value of $k_T = 300$ kNm^{-1}, calculated from the properties of the strap and the shell, is twice as great as the value deduced from dynamic chin strap test data, showing that chin strap straightening, as the soft foam near the strap is compressed, must make a major contribution to the overall stiffness of the retention system.

5. Force measurement in the dynamic chin strap strength test

The test rig used was similar to that shown in Figure 2a. The vertical movement of the shaft is monitored by a 100 mm travel linear potentiometer, and a 35 kN capacity quartz crystal force cell (Kistler model 9321) is mounted below the stirrup. The first set of results were for testing, under ANSI test conditions, a 'Centurion' model bicycle helmet made by Thetford Moulded Products in the UK. An aluminium shaft was used to keep the preload mass at 1.5 kg, as the steel chin stirrup had a mass of 350 g. Figure 5 shows the force versus time traces for a) 13 mm of 100 kg m^{-3} density high density polyethylene foam, a hard foam that will absorb the 20 J impact energy without 'bottoming out' and b) a 9 mm thickness of 40 kg m^{-3} density low density polyethylene foam, a much softer foam that will bottom-out under the impact. Both traces show a similar initial peak A, but there are smaller oscillations B in the first trace. Computer modelling, using point masses and linear springs, as in (16), identifies the peak A as being caused by the initial collision between the drop mass and the anvil, and the resulting high acceleration of the mass m_3 above the force cell. The oscillations B in fig 5b are at a frequency of 720 Hz. The theoretical angular frequency ω of oscillations of the mass m_3 at the end of the shaft with spring constant k_2, the other end of the shaft being fixed, is given by

$$\omega^2 = \frac{k_2}{m_3} \qquad (5)$$

For the experimental values of k_2 = 5.3 MNm^{-1} and m_3 = 0.35 kg for the bicycle helmet tests, the predicted resonance frequency is 620 Hz. The broad peak C in fig 5b is due to the motion of the total 3.5 kg mass on the retention system spring of total spring constant k_T. Modelling shows that, although the load cell experiences oscillations, there are no oscillations in the force on the chin strap.

Table 3 show how the size of the initial peak A can be changed by using different foams; it could also be increased by using a smaller foam area, or thinner foam. EAR foam is a heavily plasticised foam with very high damping, LDPE is low density polyethylene foam, tradename 'Plastazote' from BXL Limited, HDPE is 'Plastazote' crosslinked high density polyethylene foam.The maximum deflection and force maximum at this deflection hardly change.

Table 3. Test results for a cycle helmet, under ANSI Z90.4 conditions, with different foams between drop mass and catcher plate

No	Foam	Density kg m^{-3}	thickness mm	peak A force N	peak C force N	Max deflection mm	Energy input J
1	EAR	83	25	400	980	14.4	7.0
2	LDPE(new)	40	9	600	1100	15.4	8.9
3	LPDE(old)	40	9	800	1280	15.2	8.7
4	HDPE	100	14	1100	1100	14.8	7.7

The energy input values were calculated from the area under the force-deflection graph while the deflection is increasing. Equation (2) predicts an effective impact energy E_e value of 8.2 J, so if the coefficient of restitution for the foam is zero, 10 J is left in the system immediately after the foam impact. As the measured energy input is 7 to 9 J, there are frictional energy losses of between 1 and 3 J.

For tests under the motorcycle helmet conditions of BS 6658 a steel shaft and a steel chin strap stirrup were used. Initial tests used an area of 7850 mm^2 of the old LDPE foam 3 of table 3, on the catcher plate. The resulting force time trace(fig 6a) has a number of disquieting features:- the initial peak A is higher at 4.5 kN than the 'real' force peak C of 3.5 kN hidden among the force oscillations; the oscillations B have an amplitude of 2 kN ; and at D there is a second impact between the drop mass and the catcher. When the much denser HDPE foam 4 of table 3 is used fig 6b shows that the peak D has disappeared, the peak A has a reduced magnitude of 600 N and the oscillations B are smaller. The maximum chin strap force can be reliably estimated as 3.5 kN. Reducing the stirrup mass from 350 g to 120 g, while keeping the LDPE foam, reduces the size of the features A, B and D by a factor of two. The combined effect of using the light aluminium stirrup and the dense HDPE foam is to remove almost all of the oscillations. Using these 'best' conditions, the helmets listed in Table 4 were tested to see the effect of helmet design features.

Table 4 . BS 6658 tests on fullface motorcycle helmets

Shell material	Buckle type	Max force kN	Max extension mm	Energy input J
ABS	knurled bar	3.55	24.4	41
GRP	knurled bar	3.46	28.3	40
GRP	quick release	3.70	21.5	44

The differences in the maximum force observed are not significant. For the first two helmets the force extension curve is non-linear initially; this may be due to the bedding-in of the polyester webbing in the sliding knurled-bar buckle. The energy input values are in agreement with the 43 J estimate from eqn.(1) .

In the Regulation 22 test rig there is a headform and coupling of mass approx. 8 kg above the load cell and this must be accelerated by the falling mass. The additional force to acheive this will mean that it is impossible to use the load cell to accurately measure the force in the chin strap. The other factor that prevents easy measurement of the force is that there is no cushioning foam between the falling mass and the plate which it strikes. This means that there will be large force oscillations in the system after the initial impact. We conclude that the Regulation 22 rig is less suited for measuring the force in the chin strap than the equipment described here.

6. Mechanics analysis of the retention system effectiveness test

In the initial development of the BS 6658 test it was assumed that the primary mechanism of helmet roll-off was inertial. In the typical accident a motorcyclist crashes into a car which has suddenly pulled out into his path. The motorcycle is checked by the car, but the motorcyclist is thrown upwards over the bonnet of the car. As he somersaults forwards his head moves forward until his chin impacts his chest. The sudden stopping of the forward rotation of the head does not stop the rotation of the helmet, and its angular inertia causes it to roll off forwards. The mass of the helmet and the magnitude of the deceleration on the initial impact are critical. The 1.5 kg motorcycle helmet travelling initially at 50 kph has far more angular inertia than a 0.5 kg bicycle helmet travelling at 30 kph.

There are mechanisms of helmet roll-off other than the inertial one. When the chin bar of a fullface motorcycle helmet makes a grazing impact with the roof of a car or with the road surface, the tangential forces on the helmet are likely to be in the range 1 to 3 kN measured in oblique impact tests, i.e. much larger than the 0.5 kN produced in the BS 6658 test. The direction of the force on the chin bar must be downwards for the helmet to rotate forwards. The roll-off tests in BS 6658 and prEN 398 do not simulate such accidents.

The angular inertia of a bicycle helmet is typically 1/4 of that of a motorcycle helmet with a dense outer shell, and the lower speed of bicyclists means that the inertial mechanism of helmet loss is unlikely to occur. The design of the retention system of bicycle helmets differs from that of motorcycle helmets - in the latter there is usually a single chin strap which allows easy 'ball and socket' rotation of the helmet on the head. Bicycle helmets usually have a nape strap as well as a chin strap and this system(adapted from jockey skull caps) is very effective at limiting rotation of the helmet about a lateral axis. The nape strap prevents the forward rotation of the helmet and the chin strap prevents the rearward rotation. The attachment points of the chin and nape straps should be widely separated, and this is possible with bicycle helmets which hardly come down to the ears at the side of the head. The nape strap is put into tension when the helmet rotates forward, whereas in a motorcycle helmet it is only the fit of the rear of the helmet liner and the nape collar to the rear of the head which provides a 'frictional' resistance to roll-off. Roll off is unlikely for a bicycle helmet unless the nape strap or its fastening fails. For bicycle helmets the retention for lateral blows may be important, as the helmet may not protect the ear region if it is displaced laterally.

7. The interaction of the two tests, and consideration of EN standards

When the dynamic chin strap strength test was introduced the kinetic energy of the drop mass was chosen to produce forces of the order of 3 kN with the then current designs of retention system. Now that most helmet standards contain a separate test to limit helmet 'roll-off', there is no need for a dynamic extension limit in the retention system strength test. The extension limit was to prevent the used of a single elastic strip as a chinstrap, as was used in UK equestrian helmets before 1975. Stretching of the chin strap is only one feature of the roll-off sequence; other important features are the position of the chin strap anchorage, and the materials and fit of the rear of the helmet to the head(7). If the helmet designer produces a helmet with a very stiff shell, and a quick release buckle that does not deform during loading, then it is possible that the peak deflection could be 12 rather than 25 mm. The consequence would be that the strap and buckle must withstand a 6 kN force, which is difficult for the designer to achieve and potentially a risk for the wearer's neck. The way to avoid this problem is to change the test, abandoning the fixed impact energy of 75 J, and specify that the force on the retention system reaches 3 kN. There is a lack of accident statistics for bicycle helmets to show that there is a helmet loss problem

For the bicycle helmet standards the impact energies of the motorcycle helmet retention tests have reduced by 50%, but no experimental force measurements have been published. Our measurements show that the total force in the ANSI test is of the order of 1 kN. As the strength of the rider's neck is the same whether he is riding a motorcycle or bicycle, we suggest that the bicycle helmet chin strap should be subjected to a dynamic force of 2 to 3 kN to avoid unnecessary helmet loss. Further work should be done to better quantify the tangential forces when no-shell helmets hit the road surface obliquely; this information would then allow the forces taken by chin straps in different types of bicycle helmets to be estimated. If the forces are shown to exceed 4 kN then a maximum strength test for the retention system should be considered.

Currently (April 1992) the Comite Europeen de Normalisation (CEN) is devising common safety standards for 'personal protective equipment' for 1st January 1993. The draft standards for bicyclists and horse riders helmets have yet to emerge. These new standards will be in force for many years and they should reflect the current knowledge of accident mechanics. However pressure to preserve the tests from the existing widely used Regulation 22 standard has meant that a scientific assessment of the rival existing tests has not occurred, and the empirically adapted tests in the bicycle helmet standards have not been validated at all. Helmet design has changed in many ways since 1980, so the objectives of the retention system tests need to be restated - to have a system that will not break and not allow helmets to come off, yet not be so strong that neck injuries occur. A consistent set of results for motorcycle helmet tests has emerged- the tangential impact velocities and the materials used for the helmet shells mean that tangential forces of the order of 3 kN are to be expected. It is therefore logical to recast the retention system strength test in terms of the dynamic force to be applied, and to abandon the measurement of the dynamic extension of the system. The roll-off test in BS 6658 is better than the Regulation 22 test because there is very little evidence of aggravated head injuries from a 30° or 40° rearward displacement of the helmet, whereas there are many records of deaths or serious head injuries due to helmet roll-off.

It could be argued that there is no need for a retention system effectiveness test for bicycle helmets - the alternative constructional clause that the helmets should have Y straps, with the 'nape' strap attached to the rear of the shell, would be equally effective. Using the motorcycle helmet tests with 50% of the falling weight energy will not produce a very high tensile load in the nape strap, and the amount of rotation of the helmet will depend on the correct adjustment of the length of the straps.

8. Conclusions

The dynamic chin strap test has prevented chin strap failures in motorcycle helmets, but helmet designers are forced to use compliant retention systems to limit the peak force to < 4 kN. The test equipment needs to be modified, with a suitable foam on the impact anvil and a lower mass chin strap stirrup, to allow accurate measurements of the force on the chin strap. The pass/fail criterion of the test should be rewritten in terms of the peak forces : 'Drop the test weight from a height that will induce a peak force of 3 kN. This can be done by incrementing the drop height by 0.1 metre steps'. For bicycle helmets it is recommended that a dynamic force of 2 kN is applied to the chinstraps of bicycle helmets to ensure that breakage does not occur in accidents.

The retention system effectiveness test has obviated the need for a extension measurement in the retention system strength test. The test has forced motorcycle helmet designers to improve the geometry of their chin straps and the design of the rear of the helmet. The situation with bicycle helmets is less clear- the Y strap system is an effective method of keeping the helmet in a stable position while riding, but there are no accident statistics of a helmet roll-off.

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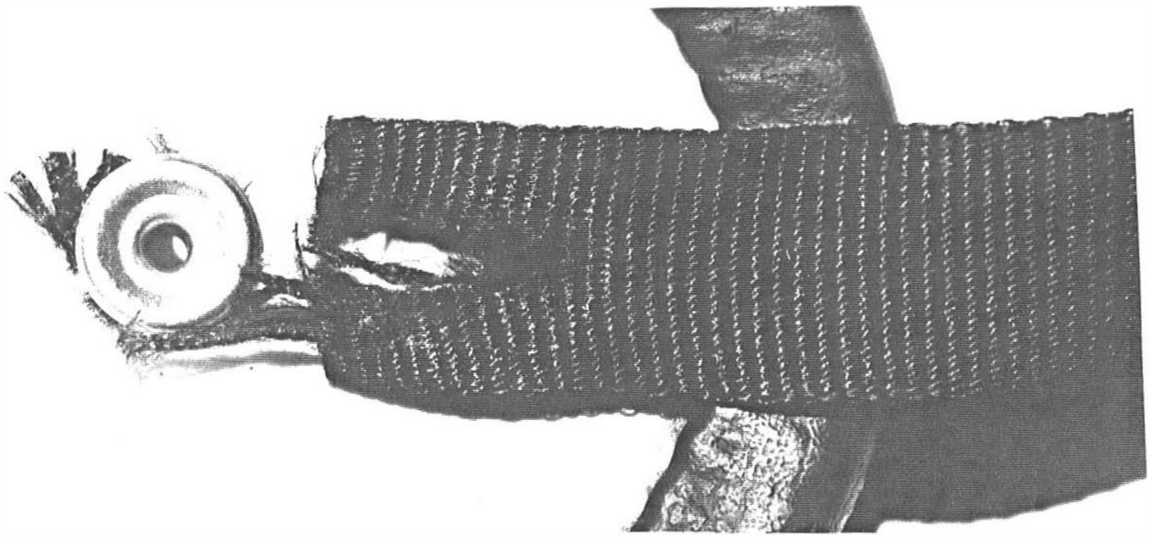


Fig.1.Chin strap failure in a pre-1980 motorcycle helmet, when the webbing pulled off the rivet that attached it to the shell.

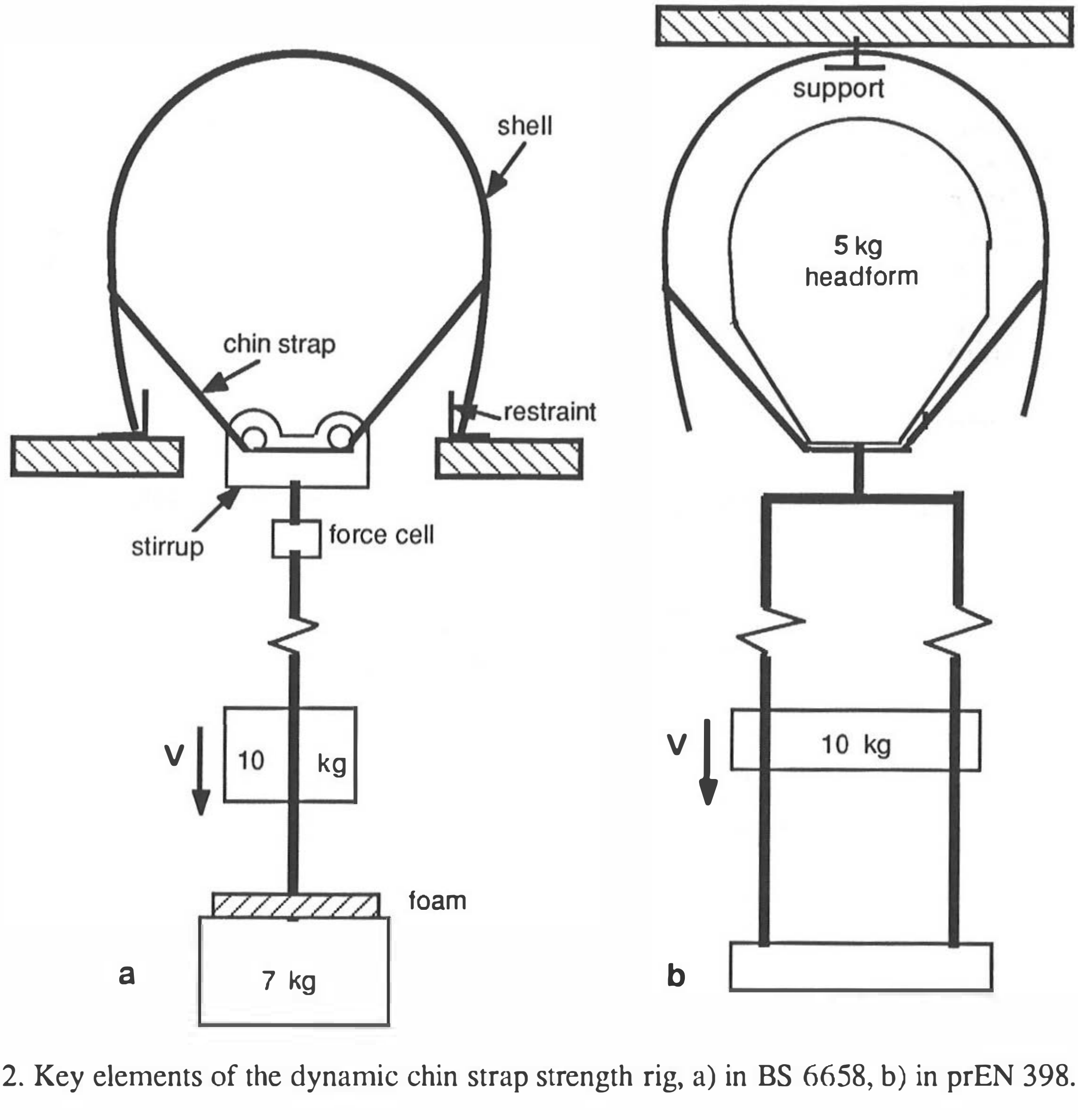


Fig.2. Key elements of the dynamic chin strap strength rig, a) in BS 6658, b) in prEN 398.

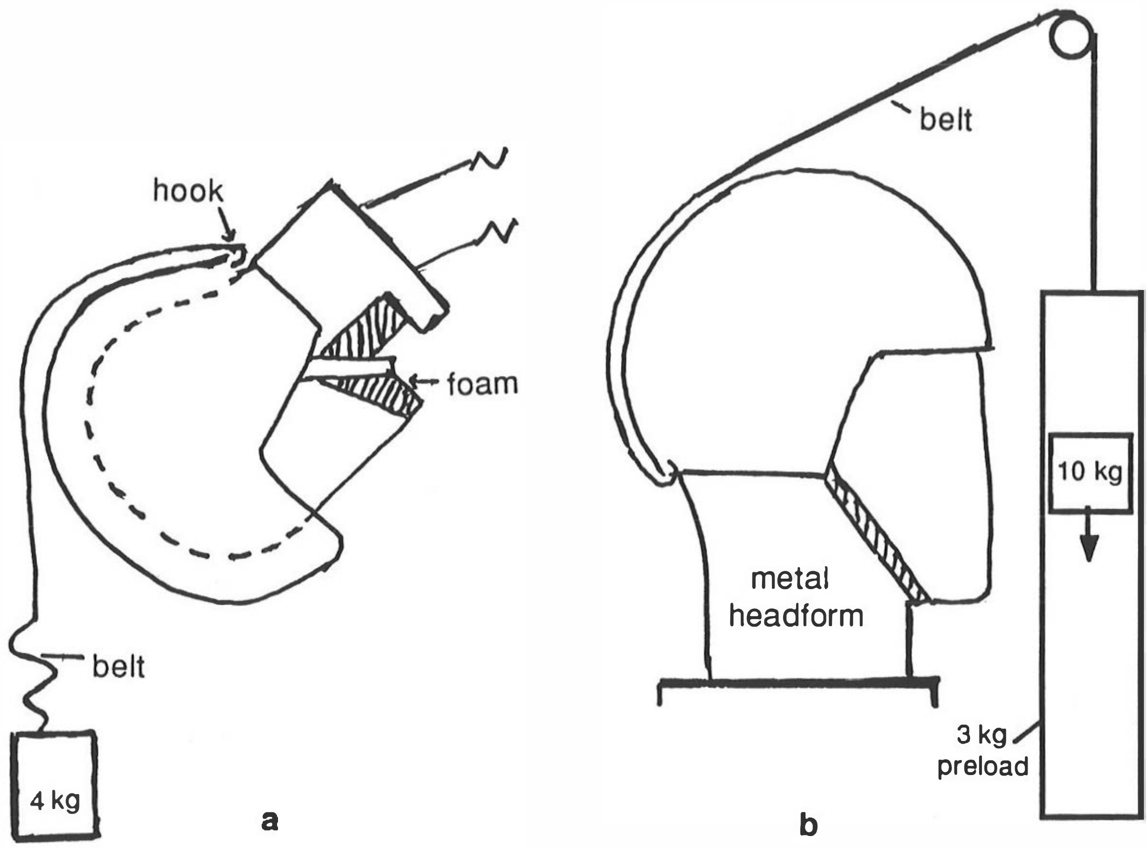


Fig.3. The retention system effectiveness test in a) in BS 6658, b) in prEN 398.

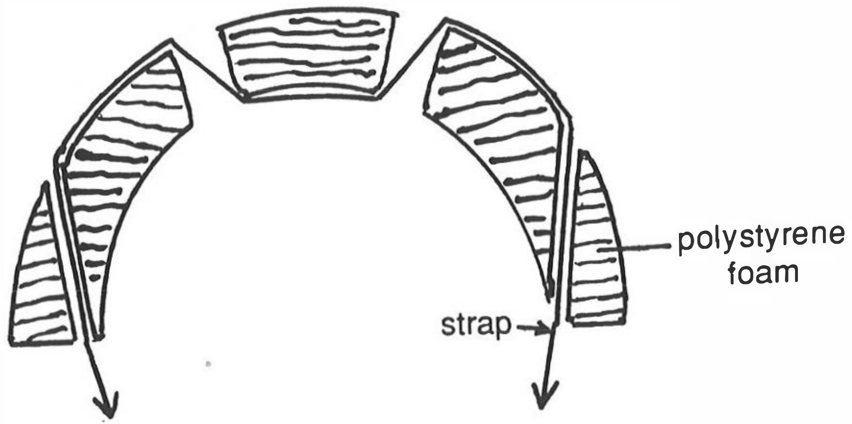
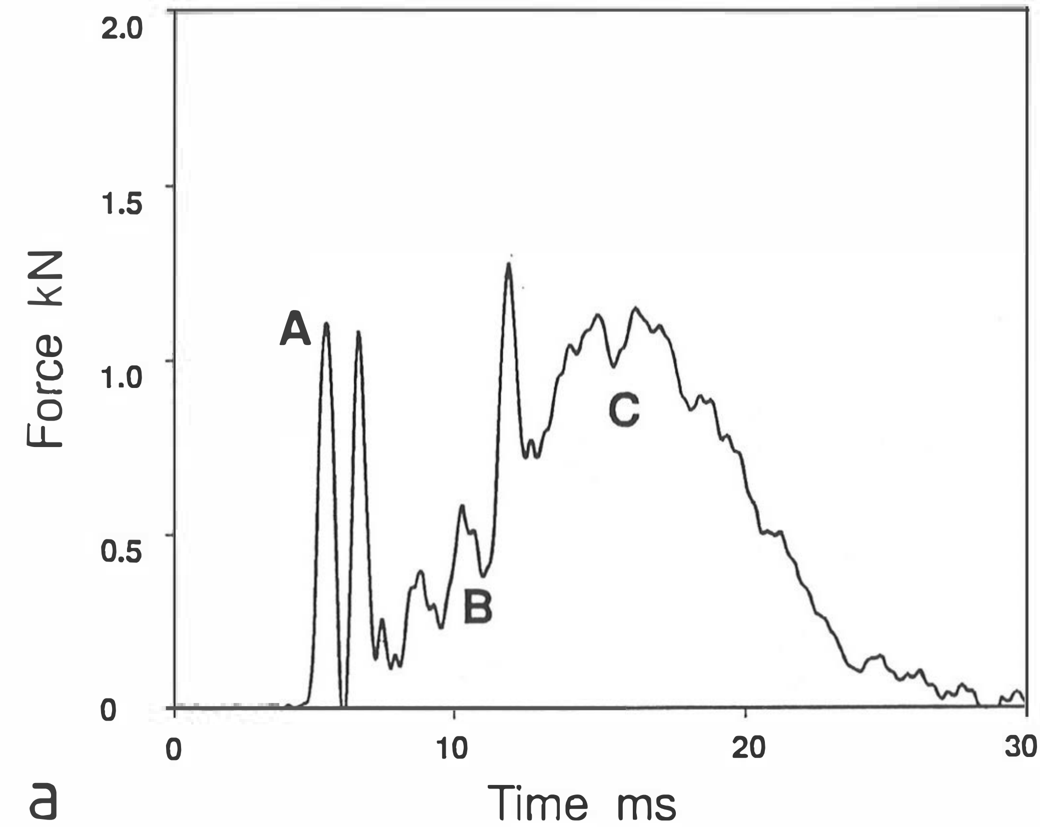
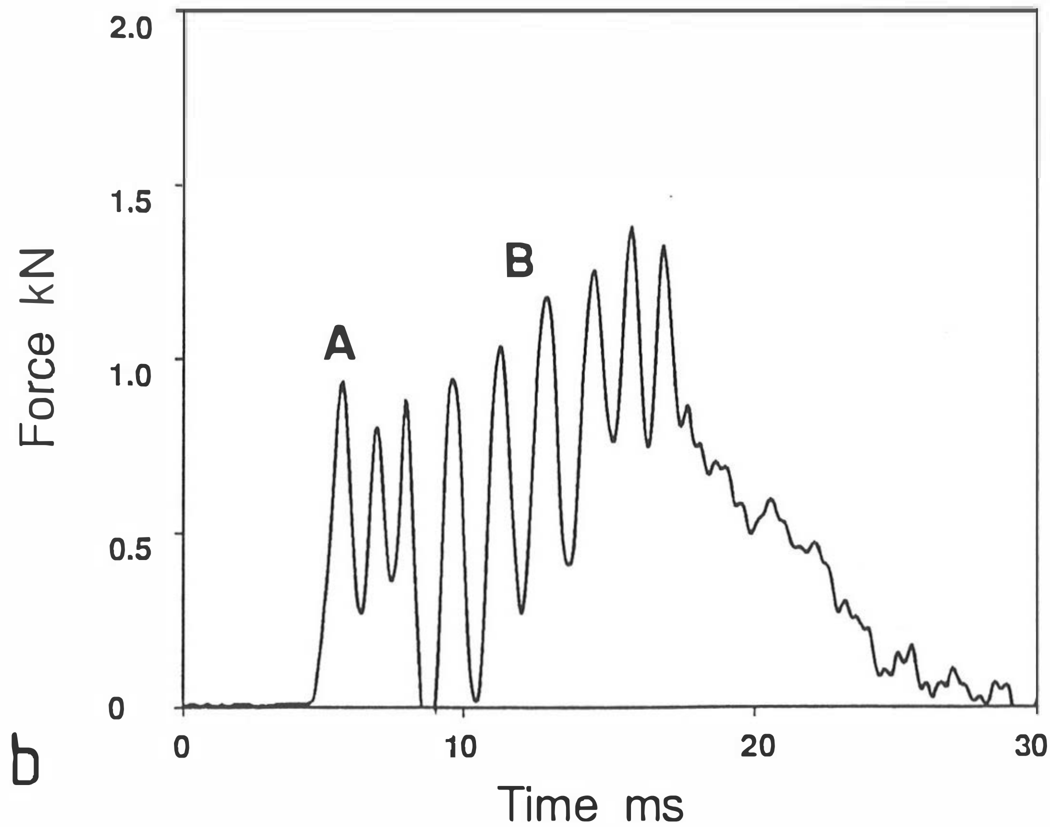
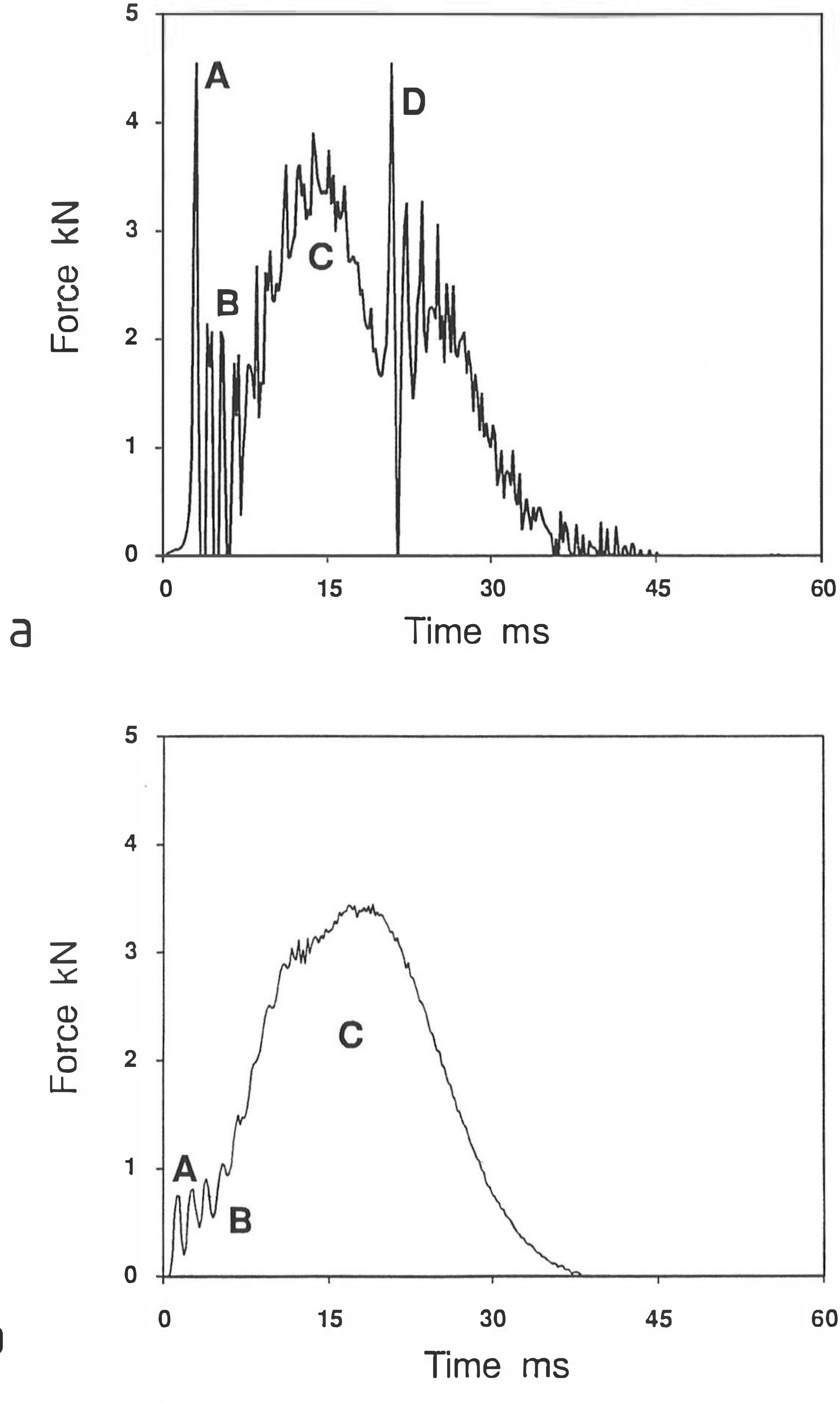


Fig.4. The chin strap path in a no - shell bicycle helmet, with the webbing strap passing around the polystyrene foam.





5. Experimental load cell force versus time for ANSI Z90.4 cycle helmet test with a 350 g stirrup mass and a) HDPE foam 4, b) LDPE foam 3 of Table 3.



6. Experimental load cell force versus time traces for BS 6658 motorcycle helmet test on a fullface thermoplastic shell with a 350 g stirrup mass and a) LDPE foam 3 , b) HDPE foam 4 of Table 3.