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Protective capability of bicycle helmets

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Cycle helmets that meet UK and US standards have been tested. The mechanisms of energy absorption for frontal and side impacts have been analysed. A good helmet should protect the wearer for impacts up to 15 mph into a rigid flat surface.

Keywords: Bicycle helmets, protection, testing

Introduction

A recent editorial in the *Lancet* points out the need for bicyclists to wear helmets to reduce the fatality rate of 300 per year in the UK[1]. The epidemiology of head injuries to bicyclists has shown that the most frequent impact sites are the front and sides of the head[2]. A variety of helmet designs have been produced in an attempt to reduce the number of severe injuries and fatalities. At the same time, bicycle helmet test standards have been developed to identify those helmets with an adequate protective capacity.

The standards have been developed by adapting existing standards for other helmet types. Thus Bishop and Briard[3] describe the use of a modified NOCSAE American football helmet standard (1973)[4]. Hodgson describes how in this standard the NOCSAE-Wayne State University headform attempts to match the stiffness of cadaver skulls[5]. The surface struck (a flat steel plate covered with half an inch of rubber) presumably simulates the turf or other objects struck. Although this rubber covered surface would appear much more compliant than road surfaces, Bishop and Briard concluded that helmets fitted with polystyrene foam liners are superior to those with soft foam liners.

In contrast, Hurt and Thom[6] described bicycle helmet testing to the American National Standard Z 90.4 (1984)[7]. In this standard, the falling headform strikes a rigid flat steel plate or a steel hemisphere of 50 mm radius. There is no requirement for the headform rigidity to match that of the human skull; rather 'headforms shall be made of low-resonant-frequency material and shall exhibit no resonant frequencies below 3000 Hz'. The impact tests in the recent British Standard BS 6863 (1987)[8] are similar, except that the hemispherical anvil is replaced by a simulated kerbstone (a cylinder of radius 18 mm). The headform requirement is the same.

If a helmet passes one of these tests, it is a guarantee of a certain minimum level of protection. However, it is not clear what the human equivalent of a rigid headform falling one metre is, nor is it possible to infer the ultimate protective capacity of any design from the test result of a maximum headform acceleration. Therefore, the helmet test conditions have been analysed, and the performance of helmets related to the thickness, geometry and type of foam liner and shells used.

Analysis of helmet testing conditions

In a bicycle accident there are three deformable bodies; the head, the helmet and the object hit. Is it valid to approximate any of these as infinitely rigid? From a knowledge of the magnitude of the forces in helmet testing (the order of 10 kN), and the variability of test results on apparently identical helmets (a variation of ± 10 per cent is typical), it is possible to make reasonable approximations.

The object hit

A flat tarmac road surface will be more rigid than most parts of a car structure. Its impact behaviour was measured by dropping a solid aluminium headform onto it, then integrating the signal from the accelerometer attached to the rear face of the headform, using the technique of Gale and Mills[9]. *Figure 1a and b* shows that the road surface deforms by less than 0.7 mm at a 15 kN force. As this is less than five per cent of the typical liner foam crush distance of 15 mm, there will be little error in testing with a rigid steel plate in place of the road surface. Conversely, a steel plate covered with 12.7 mm of rubber is far more compliant than a road surface.

The headform

Hodgson compares the results of slow lateral compression tests of cadaver skulls with that of the NOCSAE headform[5]. The latter has a silicone rubber skin covering a hollow metal casting. The measured lateral stiffness (force divided by ear-to-ear deflection) is 1.59 kN/mm. However, McElhaney's review quotes cadaver skull stiffnesses in the range

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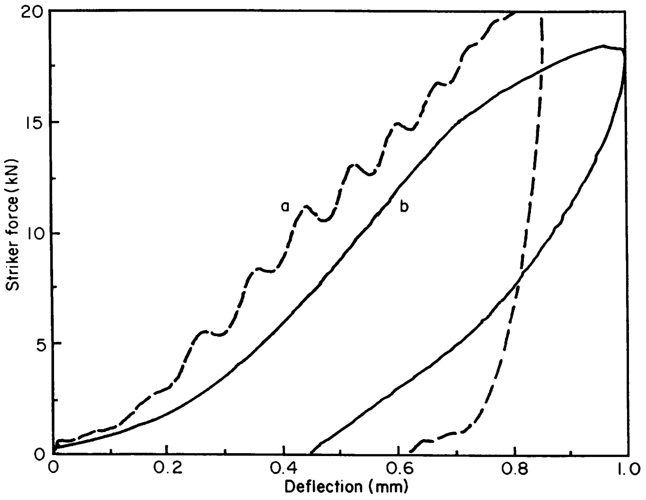

Figure 1a and b. Force deflection relationship for a) the crown of an aluminium headform hitting a tarmac surface and b) the crown of a filled polyurethane Med-Eng headform hitting a flat steel plate

1.4–3.6 kN/mm for anterior-posterior tests, and 0.7 to 1.8 kN/mm for lateral tests[10]. It is clear that the compliant skull absorbs a variable amount of energy on impact. The difficulty with using a compliant headform is that its impact stiffness must be carefully specified, otherwise test results from different test houses will not be comparable. The relatively low impact kinetic energies (50 J in BS 6863) and high allowable forces on the headform (the 300 'g' failure level for a five kg headform represents a 15 kN force) means that a high compliance headform could pass the test without much of a helmet being present.

Figure 1b shows the impact force versus headform deflection for the crown of a Med-Eng headform hiting a flat steel plate. These headforms were made in Ottawa from polyurethane hard rubber filled with silica and are used by BSI for motorcycle and bicycle helmet testing. The slope k of the linear loading curve can be used to calculate the energy E absorbed or stored by the headform at a force level F, using

$$E = F^2/2k. \qquad (1)$$

The slope $k = 20$ kN/mm in *Figure 1b* shows that only 5 J is absorbed by the headform when $F = 15$ kN. Other more compliant headform designs such as the NOCSAE headform could absorb a high percentage of the impact energy. Therefore, in the following impact tests a rigid solid aluminium headform has been used to ensure that only the helmet can absorb energy.

Testing of helmets

No attempt is made here to provide comparative test results of a comprehensive range of helmets, as such surveys were done by Bishop and Briard[3], Hurt and Thom[6] and in various cycling magazines by Glaskin[11] and Balderston[13]. A limited amount of testing done for a consumer protection department showed that helmets not manufactured to a UK or US standard often offered minimal head protection. The aim is to provide insights into the mechanisms of protection.

The test equipment has been described by Gale and Mills[9]. In it an instrumented steel striker with either a flat or a kerbstone shaped face and falls vertically onto the fixed headform and helmet. The solid aluminium headform can be adjusted in position on a ball joint so that the impact site can cover the range specified in BS 6863 (*Figure 2*). The impact forces can either be measured from the acceleration of the 5 kg striker, or from the output of a quartz load cell beneath the headform mount.

In the first set of tests, some typical helmets were impacted with the same kinetic energy as if a 5 kg headform plus the helmet mass fell one metre. The impact sites were with a flat striker at the front at the point B 20° above the horizontal AA′ plane on the headform, and at the side on the AA′ plane with flat and kerbstone strikers. *Table 1* gives the test results for impacts at 20°C. When the striker acceleration data is numerically integrated, it provides graphs of the striker force versus the helmet deflection.

Figure 3 shows this for the three types of impact on a helmet that has a uniform liner thickness and smoothly curved shell. It is noticeable that the loading part of the response is linear, so the slopes of these loading stiffnesses are also given in *Table 1*. The theory described later predicts that the loading stiffness for impacts with a flat surface should be proportional to the radius of curvature of the shell at the impact site, assuming that the foam liner has no holes or grooves in it. The front of helmets 3 to 5 in *Table 1* are approximately spherical with a radius about 100 mm, whereas the radius at the side is 140 to 150 mm. Helmets 1 and 2 have flat areas on the front, and in the case of helmet 1 there is a large area of ventilation slots. In three cases in *Table 1* the loading stiffness is higher at the side by 10 to 130 per cent but in one case it is 30 per cent lower.

It is not clear why the standards do not test at the front of the helmets at sites as low as the AA′ plane, since this is a frequent impact site in accidents.

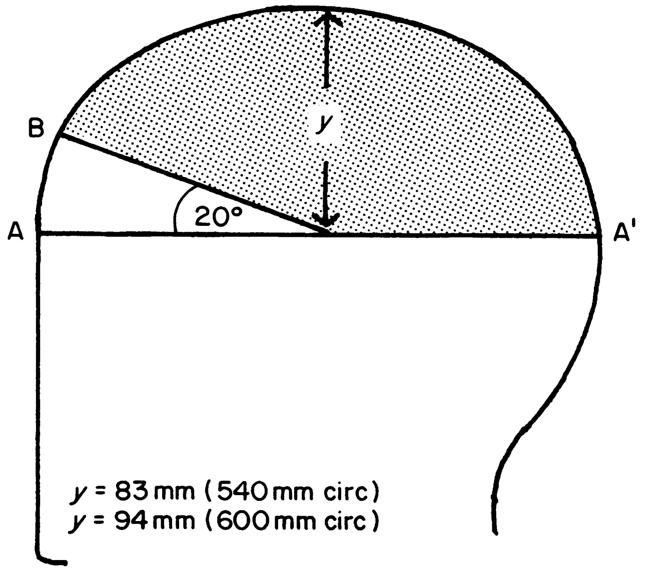

Figure 2. The shaded area shows the impact sites in the BS 6863 standard relative to the headform. The distance from the crown to the AA′ plane varies with headform size.

Table 1. Helmet impacts equivalent to a 1 m drop

No	*Make*	*Std*	*Foam density kg/m³*	*Peak 'g' values Flat Front*	*Flat Side*	*Kerb Side*	*Loading stiffness N/mm Flat Front*	*Flat Side*	*Kerb Side*
1	Nolan N12	ANSI	59	87	98	74	168	298	160
2	Kiwi K25	ANSI	70	137	86	84	459	308*	212
3	Scott Aspen	AUS	91	154	138	103	621	600	242
4	Centurion	BS		125	115	93	309*	711*	276*
5	Brancale SP4	ANSI		145	132	93	550*	610*	200

*Traces show a step and plateau before linear region

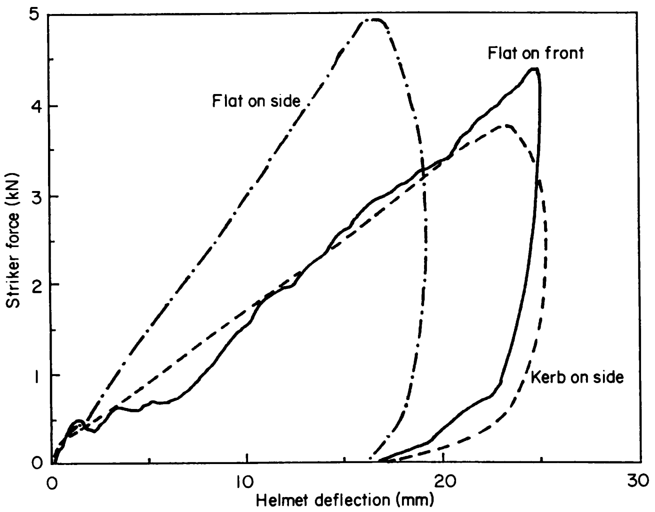

Figure 3. Force vs deflection graphs for a Centurion helmet impacted with 50 J energy in three ways

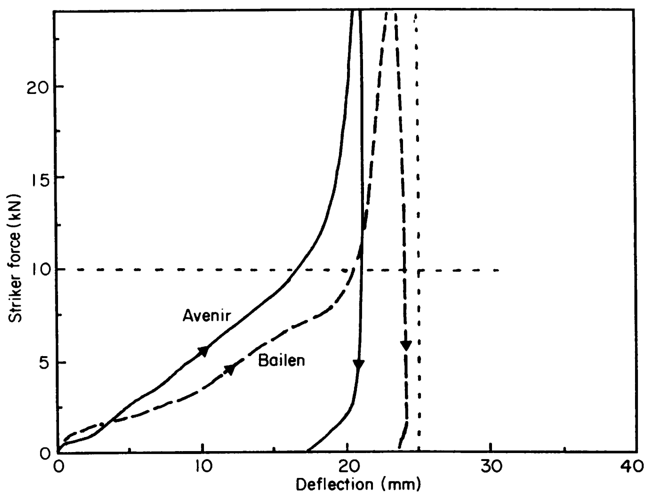

Figure 4. Force vs deflection graphs for 150 J impacts with a flat striker on the front of two helmets at the level of the AA' plane. The dashed lines represent a force limit of 10 kN and a foam thickness of 25 mm

Therefore, some impacts were performed at this site with much higher impact energies of about 150 Joules, rather than the 50 Joules in the ANSI or BS standards. *Table 2* gives the results, and *Figure 4* shows the force–deflection graphs.

The linear part of the loading curves have similar loading stiffness to those in *Table 1*, so there is no reason to suppose that they would not pass the ANSI impact test at this site. However, the force rises rapidly once the deflection is of the same order as the liner thickness. The reason for the larger peak deflections is that there is also some soft comfort foam inside the helmet and the shapes of the inside of the helmet liner and the headform do not match exactly.

Energy absorption mechanisms in the helmet

Quasi-static analysis for side or frontal impacts

There are two main mechanisms by which energy is absorbed in a helmet. *Figure 5a and b* shows these in relation to a lateral impact site. The first load path to the head is through the yielded foam that is below the contact area with the object impacted. The second is via the elastically deformed shell to surrounding areas of un-crushed foam, and hence to the head. The shape, material and thickness of the shell at the impact point will determine the proportions of force transmitted or energy absorbed via the two routes. In some circumstances, such as a motorcycle helmet hit

Table 2. Frontal impacts on a flat surface with 150 J energy

No	*Make*	*Std*	*Peak 'g' value*	*Peak deflection mm*	*Liner thickness mm*	*Loading stiffness N/mm*
6	Avenir	ANSI	583	21	17	585
7	Bailen	ANSI	387	24	19	499

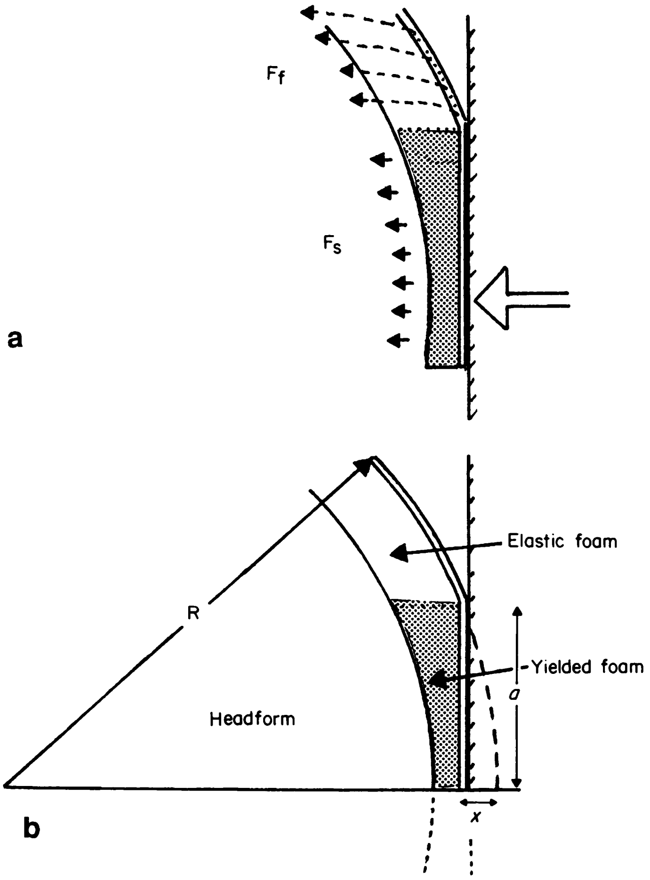

Figure 5a and b. a) The side of a cycle helmet in contact with a flat surface, showing how forces are transmitted to the head b) Contact geometry between a flat surface and the helmet. R is radius of spherical liner, *a* is radius of contact area, *x* is foam crush distance

near the crown, the doubly convex shape of the shell with thickness of about 4 mm means that it takes a high force in the region of 2 to 4 kN to buckle the shell inwards. It is then expected that the shell absorbs 30 to 40 per cent of the impact energy[9]. However, here we are concerned with thinner shells and with impact sites that lie at the front or sides. In this case, the rigid foam liner will be expected to absorb most of the energy, as the unconstrained lower edge of the shell allows it to deform easily.

The energy absorption or storage mechanisms are:

In the yielded foam liner

The contact geometry between a flat impactor and the spherical outer surface of the foam liner is shown in *Figure 5b*. So long as the amount of liner crush x is much less than the radius of curvature R of the spherical outer surface, then the contact area A is given by

$$A = 2\pi Rx. \qquad (2)$$

It is assumed that the foam yields over an area A, of radius a, and has a constant yield stress σ_y. In reality the yield stress will be highest in the centre of the contact area where the strain is highest. Consequently the force transmitted by the foam is

$$F_f = 2\pi R\, \sigma_y x. \qquad (3)$$

so long as the strain is increasing. Once the foam begins to unload, the force drops rapidly as the cell walls do not fully recover from their buckled state. Substituting typical values of R = 160 mm σ_y = 0.7 N/mm^2 for the side of a cycle helmet liner into equation 3 gives an effective foam spring constant on loading of

$$K_f = F_f/x \approx 700\,\text{N/mm}. \qquad (4)$$

Nearly all this energy is absorbed by polystyrene foam; typically less than five per cent is returned to the rebounding head.

In the bent shell and elastic part of the foam liner

It is difficult to make a precise estimate of the force transmitted this way, but this will not matter if the value is much less than that in the yielded foam liner. One method is to repeat the impact test with an area of foam liner removed under the impact point. The difficulty here is that the cutaway area should increase as the test proceeds. Another approximate method is to perform slow compression tests of the complete helmet between two parallel plates without any headform being present. The difficulty with the latter is that the stress distribution in the shell differs from that in a side or front impact.

However, the values of the static loading stiffness K_s, given in *Table 3*, show that these are much smaller than either the foam crushing spring constant K_f of the last section, or the stiffness of cadaver skulls measured in slow tests. The values in *Table 3* should be doubled to produce the stiffness between the contact point and the centre of the headform/helmet in order to be comparable with the K_f values. After doing this they are less than 10 per cent of a typical K_f value, and less than three per cent of the mean lateral cadaver skull stiffness.

The Centurion shell is made of a high density polyethylene, has a small area of ventilation holes, and varies in thickness from 3.2 to 4.5 mm. The OGK shell is made of polycarbonate (a stiffer glassy thermoplastic), has a medium area of ventilation holes, and is 2.5 to 3.2 mm thick. These constructions are typical of many bicycle helmets.

Dynamic effects in impacts

It has been found for crown impacts on both industrial helmets and motorcycle helmets that the impact forces are strongly affected by dynamic effects[12]. This is because the shell is stiffest when loaded at the crown, and the considerable shell mass

Table 3. Compressive stiffness of cycle helmets loaded slowly between parallel plates

Helmet	Stiffness N/mm at 30 mm deflection Fore – Aft	Lateral
Centurion	19.8 (4.8)	19.6 (5.2)
OGK	(2.0)	(3.9)

Values in brackets are without the liner present is separated from the headform either by a suspension cradle of stiffness about 200 N/mm or by 5 to 10 mm of soft comfort foam. The dynamic effects are clearly seen by measuring both the force on the headform and the striker, then plotting the difference between these forces versus time. The result is a damped sinusoidal oscillation. Although the bicycle helmet shells are of similar mass of about 300 g as industrial helmet shells, when they are hit at the side or front only a small percentage of the shell mass is suddenly accelerated by the impact. Thus the effective mass of the shell is low, perhaps 50 g. Consequently, the dynamic effects are small.

Interpretation of the impact test results

It has been concluded previously in this paper that the loading force–deflection graph from impacts to the side or front of bicycle helmets will be dominated by the polystyrene foam crushing response. This is confirmed by the linear traces in *Figure* 3, and the fact that the slope for the frontal tests is lower than for the side impacts on flat surfaces as shown in *Table 1*. In some cases there is a step at the start of the force–deflection trace indicating some dynamic contribution to the striker force.

Thus for 50 J impacts for which ANSI 90.4 or BS 6863 helmets are designed, the simple model works well. The maximum deflections are close to the liner thickness but do not exceed it. Some helmets with relatively uniform design are stiffer at the side impact site because of the greater radius of curvature there. Other designs, by having more ventilation holes and/or grooves in the sides of the liner, have roughly equal loading stiffnesses at the front and sides. Whether or not this was intentional, these are better designs.

The limits to the protective capacity of helmets are shown in *Figure* 4. The force rises rapidly once the total deflection exceeds the foam thickness. Therefore, a pair of constraints can be placed on the impact diagram:

> That the force does not exceed an injurious level, or
> $F \leq F$ max
> That the deflection does not exceed the foam thickness t or
> $x \leq t$

Polymeric foams provide at best linear loading graphs. Hence the largest input area in *Figure 4* corresponds to the case where the slope of the graph is F_{max}/t. From this we conclude that for an impact of 100 Joules energy with a flat surface, F_{max} = 10 kN, and a foam thickness of 20 mm the loading curve has an optimum slope of 500 N/mm.

Discussion

The impact tests on bicycle helmets have been analysed to show that the main energy absorption mechanism for impact with a flat surface is the crushing of the polystyrene foam below the contact area. Other mechanisms, such as the bending stiffness of the shell and unyielded liner can be ignored. The linear loading curves while the deflection is less than the liner thickness allow estimates of the maximum protective capacity to be made. Once the foam is more than 90 per cent compressed it bottoms out and the force on the head rises rapidly. It therefore hardly matters if the pass/fail criterion in the test standard is 200, 300 or 400 'g'. Most manufacturers have aimed for a performance in 20°C tests of less than 200 'g', to allow some leeway for foam variability and to pass tests at −10°C and 50°C. The performance limit then depends on the thickness of liner allowed by consideration of weight, aesthetics, and aerodynamics. If the liner is kept of uniform thickness, then 20 mm seems a likely upper limit on thickness. This allows for impacts of up to 100 Joules energy on a flat surface before the head acceleration reaches 200 'g'. Some manufacturers have chosen to make the liner thicker at the front, perhaps upto 40 mm (helmets 1 and 2 of *Table 1*, and some 'no-shell' types). In this case they can reduce the foam loading stiffness at the front to about 250 N/mm by having large ventilation passages, and possibly achieve protection for impacts up to 200 J energy.

Finally, let us consider the total energy absorption in the head/helmet/road system and the limiting impact speeds for protection. For a front impact we should compare the helmet loading stiffness of say 500 N/mm with double the mean cadaver skull anterior-posterior stiffness of 2500 N/mm. McElhaney interprets his mechanical impedance measurements on the front of a cadaver skull with a skull stiffness of 8800 N/mm[10]. As the helmet liner and the skull transmit the same forces, the energy which they absorb is inversely proportional to their stiffness. Therefore, if the helmet can absorb 100 J, then the skull only absorbs between 10 and 6 J. Because of the flexibility of the neck, it is reasonable to treat the head, of mass about five kg, as being unrestrained by the motion of the torso. Thus a 110 J kinetic energy of the head means an impact velocity of 6.6 m/s or 15 mph. This limit applies to component of velocity normal to a rigid surface such as the road or heavy beam on a truck. The conclusion is that a bicycle helmet to a recognised standard provides very valuable protection for the majority of accidents, but it cannot protect the head in a high velocity direct impact.

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