FACIAL PROTECTION OF MOTORIZED TWO-WHEELER RIDERS.
NEW FEATURES OF A SPECIFICATION FOR "FULL FACE" HELMET.

G. Walfisch, F. Chamouard, A. Fayon, C. Tarrière, Laboratoire de Physiologie et de Biomécanique Peugeot S.A./Renault, 132 rue des suisses, Nanterre. FRANCE.

C. Got, F. Guillon, A. Fatel, IRACBA, Hopital Raymond Poincaré, 104 Bd Raymond Poincaré, 92380 Garches. FRANCE.

J. Hureau, Laboratoire d'Anatomie, Université René Descartes, 47 rue des Saints Pères, 75005 Paris.

ABSTRACT.-

Recent accident investigations (1) (2) have shown that facial impacts account for some 31 % of the head injuries sustained by two-wheel-motorized-vehicle riders, and that the existing full face helmets have brought out no significant reduction in injuries with the exception of minor facial injuries*. In fact, they indicate some 79 % of this type of injury for non-wearers of vizors and 21 % of these same injuries for wearers of these.

However, if the injuries that are more serious than minor are considered, on the basis of these same bibliographical sources, it emerges that the degree of facial protection provided by the fittings that are standard equipment on most of the helmets available on the market enables no meaningful reduction in the frequency of occurrence and the severity of these injuries.

These reasons, added to the absence of regulations governing this area, prompted to design and produce, under a French Government contract, a prototype helmet in accordance with ECE regulation 22-02 to whose facial part (vizor and jaw part) specific investigations were devoted.

The unit composed of the vizor, jaw protector, and shock-absorbent material located in the front part of the "integral" helmet constitutes the facial protection of the prototype.

A separate investigation was devoted to each of the features listed above. The complete prototype helmet was then tested with human subjects, under the same conditions as other commercially available helmets reputed to be "satisfactory".

I - PROTOTYPE VIZOR. -

- Mathematical modelling - In order to better pinpoint and guide the choice of the mechanical and geometrical characteristics of a "satisfactory" vizor that would be adaptable to the full face prototype helmet, the so-called "finished elements" mathematical modelling was used.

(*) The injury severity scale used was the AIS (3). Minor facial injuries are classified as 1 (ocular-, dental-, and cutaneous injuries), moderate injuries are rated as 2, and serious injuries are classed in AIS $\geq$ 3.

In the present case, the problem was the modelling of the behaviour of the vizor of a helmet exposed to impact. Dynamic modelling of an impact (even in the absence of the occurrence of fracture) associated with nonlinear behaviour of the material is difficult. In this case, the object is not to determine the real values of the displacements and stresses in the elements ; rather, it is to ascertain the areas of concentration of stress and to compare various different technical solutions. It is then sufficient to consider a static loading of the vizor and to assume the material's behaviour to be linear and elastic.

The vizor is divided into 226 triangular elements, definition of the meshwork was automatic, and the node points (apexes of the triangles) were measured on the plane surfaces of the vizor.

Four types of vizor were modelled with the parameters of thickness and shapes being made to vary.

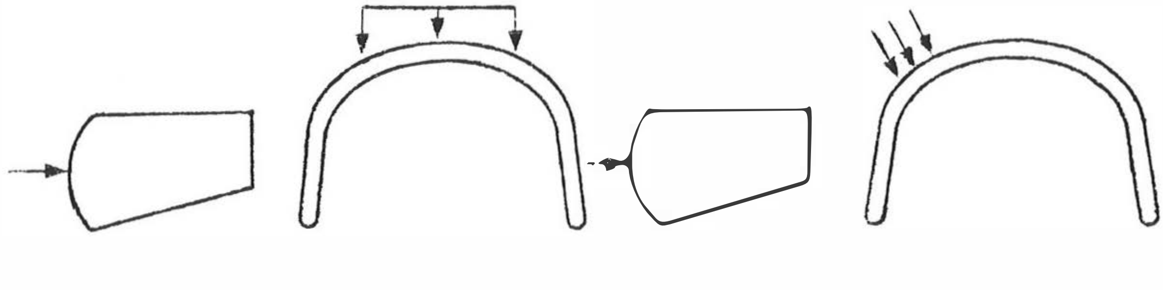
original vizor :	thickness 2.5 mm
original vizor :	thickness 4 mm
curved vizor :	thickness 2.5 mm
curved vizor :	thickness 4 mm

The curve given to the vizor was that of a curve without the vertical sections, a shape whose effect was to transform the original flat version into a "bubble"-type having two directions of curvature: one around a vertical axis due to the shape of the helmet (identical to that of the original vizor) and one around a horizontal transverse axis.

Figure 1 shows views of the two vizors after they had been cut into finished components.

The accident data referred to above (1) (2) state that two types of obstacle are most likely to be struck by the vizor, i.e. the planar and angled ones. The majority of the serious injuries were due to impacts against angles : this type of impact is what was used for the mathematical modelling.

A 100 daN resultant static load was applied to the vizor on a median horizontal plane and for two cases of loadings.



Symmetrical loading Lateral loading

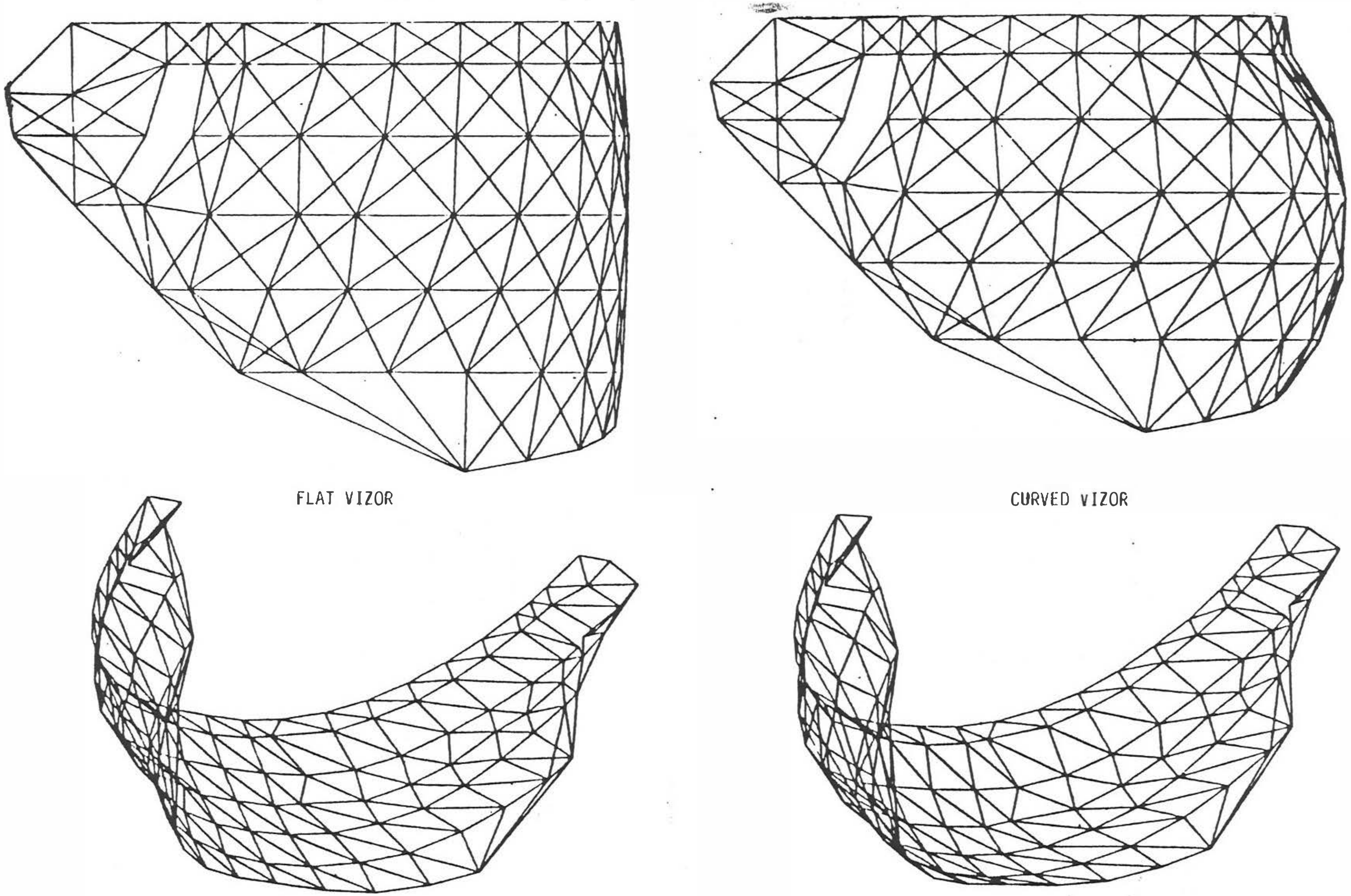


FIG 1 : MATHEMATICAL MODELLING - FINISHED ELEMENTS -

The force was applied onto three node points of the meshwork. The vizor wal held in place on the helmet, and the helmet supports and anchorage supports were introduced onto the model.

The Young's module of the material was taken to be equal to 240 daN/mm^2.

- Results of modelling - For each element, the calculation program yielded the principal stresses, the reactions to support points and to fixture-embedment points (forces, moments), the displacements and rotations of the meshwork node points, etc.

In order to judge the various responses of the vizors according to their thicknesses and shapes, the expedient criterion chosen was the VON MISES maximum : the higher it is, the higher is the state of the stresses in the elements under consideration. The following table summarizes the results obtained in terms of the reduction of the VON MISES maximum criterion when vizor thickness was increased from 2.5 mm to 4 mm.

Table 1 - Coefficient of reduction of VON MISES in the element the most acted upon.

		Flat vizor	Curved Vizor
Coefficient of reduction of the VON MISES	Symmetrical loading	1.98	2.39
	Lateral loading	1.78	1.89

- Concerning the influence of vizor thickness - The preceding table shows that the reduction of the stresses is more than proportionate to the reduction of the thicknesses.

$$\frac{4 \text{ mm}}{2.5 \text{ mm}} \simeq 1.6$$

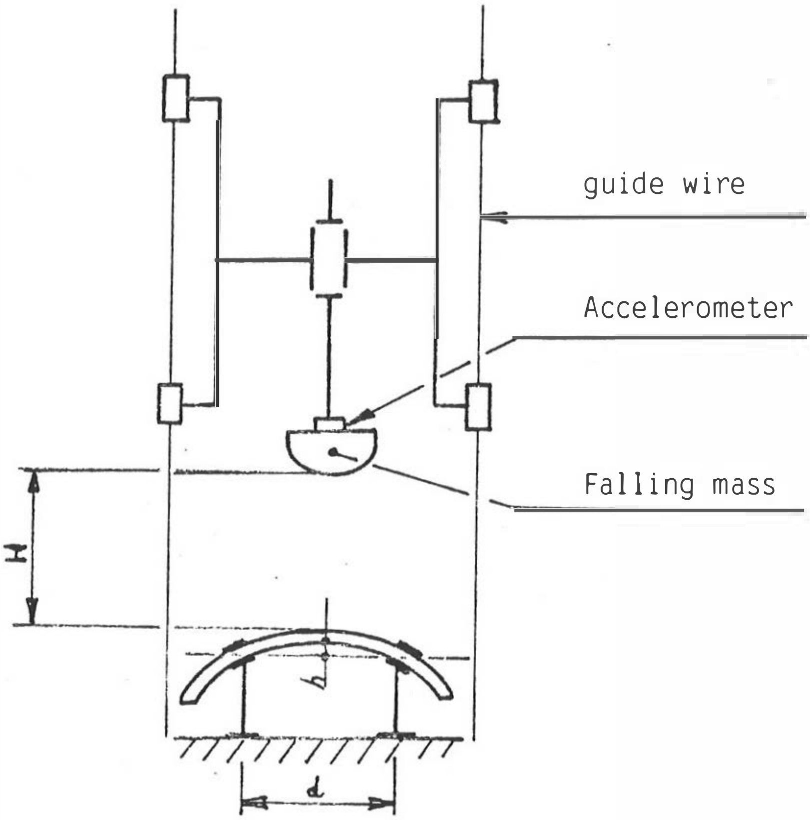
The increase in thickness therefore appears to be a satisfactory parameter for increasing vizor resistance.

- Concerning the influence of vizor curve - A considerable reduction in stresses appears when the curvature increases.

The figures listed here should, however, not to be taken at their face value in order to judge the effect of the curvature. In fact, when impact occurs, the physical magnitude input is not the force of the impact, as it is here in the calculation ; rather, it is the energy of impact. Increasing the curves however, leads to increasing the stiffness of the vizor ; for a given energy, the forces can be greater.

An experimental investigation using the device shown hereafter was performed for the purpose of showing that the force variation at constant energy was very slight when the vizor was curved.

The vizor was held rigidly between two supports. Its curve radius was adjustable, as was the center distance of the axes of the supports. Two experiments were performed at several different drop heights.



1. Center distance of axes 190 mm (d) h = 11 mm
   (radius of curve R ≃ 415 mm)

2. Center distance of axes 190 mm (d) h = 20 mm
   (radius of curve R ≃ 235 mm)

The findings are listed in the table below.

Table 2 -

	Maximum acceleration	maximum Force
Drop height (H)	h = 11 mm	h = 20 mm
0.50 m	18 g/ 80 daN	14 g/ 63 daN
1.00 m	30 g/136 daN	34 g/154 daN
1.50 m	44 g/196 daN	48 g/218 daN

The above findings show that, for the kind of experiment involved and for the type of material tested, a considerable reduction in the vizor's curvature radius fails to bring out any major increase in the levels of forces and stresses, by failing to lower the fracture threshold, and with the opposite effect even seeming possible.

In addition, an increase in the vizor's curvature induces the following :

- The moving of the head farther away from the obstacle, and thereby in the event of impact allowing the head to have a longer stopping distance,
- Increased facial rigidity of the helmet by thus enabling the vizor to better participate in impact absorption.

In conclusion, on the basis of the constraints of optical quality (prismatic effect), aerodynamics and style, we were led to propose a pronounced curvature of the vizor, both around the vertical axis and around a horizontal axis.

- Choice of vizor material - For reasons of high cost, we selected the material on the basis of existing vizors that would interface with the prototype helmet.

The material chosen was the one whose penetration resistance proved to be the highest in dynamic tests of the free fall of a 5-kg corner. (height of free-fall = 1 meter).

These tests were performed in accordance with the conditions defined in the procedure set out for French norm N.F. 72304 (see Figure 2), at different temperatures.

Two vizors were tested as follows :

- One made of acetobutyrate, with two curvature directions and a thickness of 2.5 mm,
- One made of polycarbonate, with one curvature direction and the same thickness.

Two tests were performed for each test condition. The following table shows the findings.

Table 3 -

Temperature 0° C	Nature of material	Distance face/punch (corner) (mm)	Observations
+ 20° C	Acetobutyrate	0 0	Vizor pierced and broken
+ 20° C	Polycarbonate	11 10	No cracking of vizor
+ 50° C	Acetobutyrate	0 0	Puncturing of face with cracking of vizor along 50 mm
+ 50° C	Polycarbonate	10 10	No cracking
- 20° C	Acetobutyrate	0 0	Vizor pierced and broken
- 20° C	Polycarbonate	12 11	No cracking

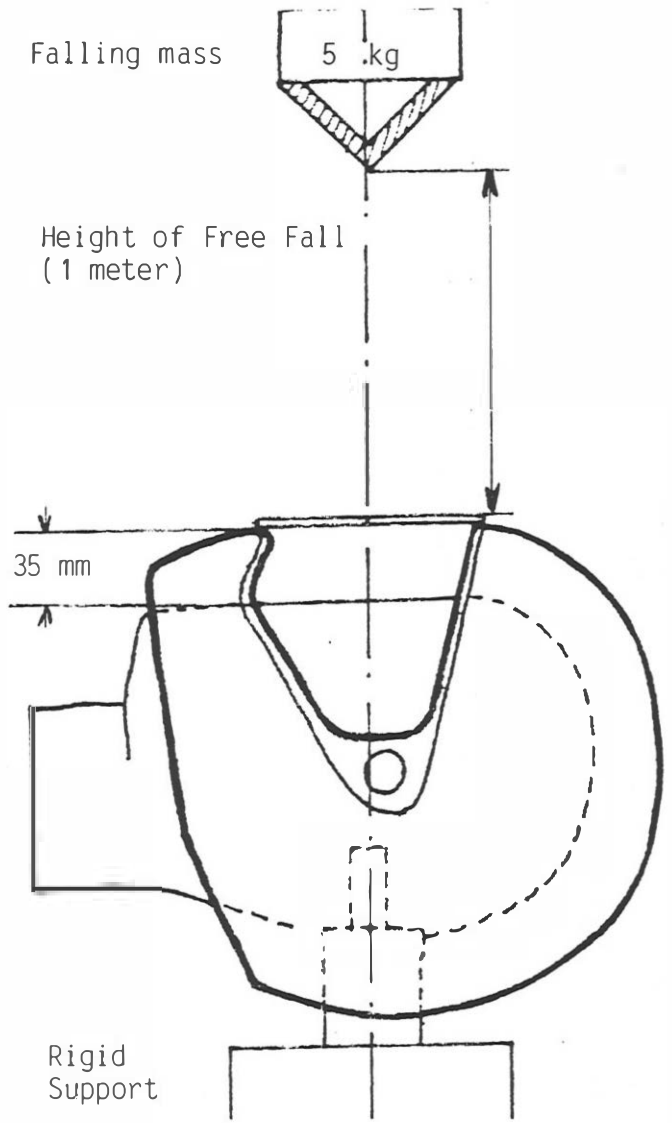


FIG 2 - VIZOR PENETRATION TESTS

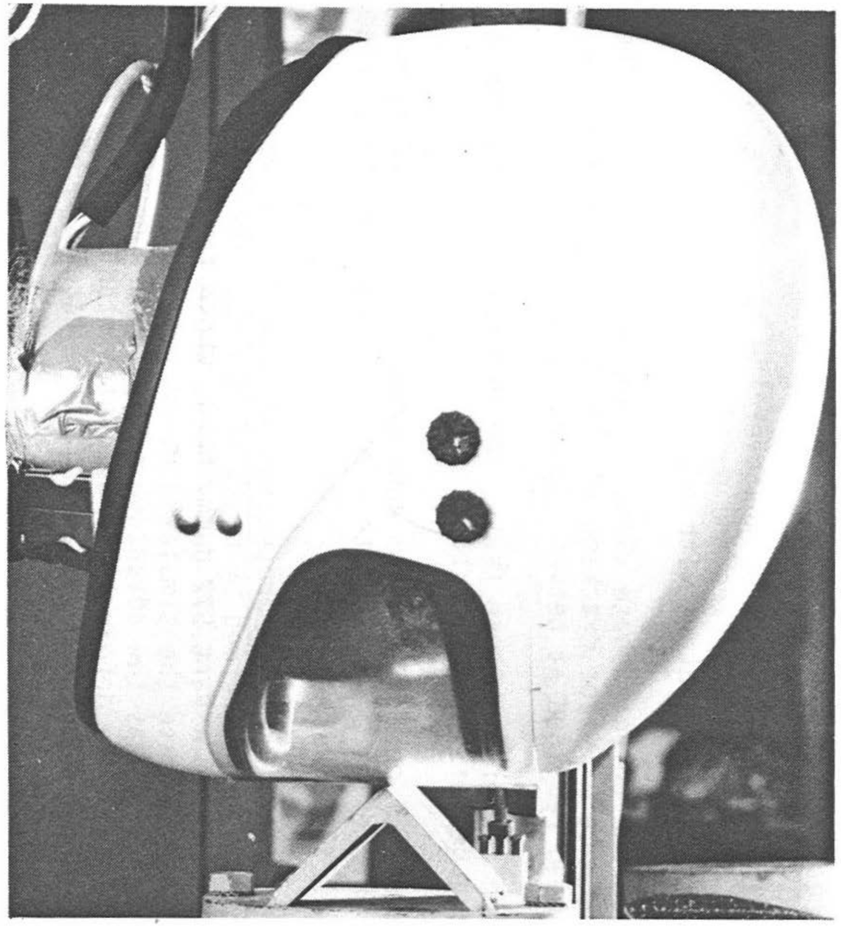


FIG 3 - EVALUATION OF THE IMPROVED PROTECTION AFFORDED BY THE VIZOR

TEST CONFIGURATIONS

Analysis of the table clearly shows that the polycarbonate resists penetration much better than the acetobutyrate.

In fact, in all the tests, and at whatever the temperature, the acetobutyrate vizor was consistently broken and punctured by the corner which, after the test, was still in contact with the surrogate head.

However, with the polycarbonate vizor, under the same impact conditions, there was no occurrence of vizor cracking and the distance between the corner and the head remained at between 10 and 12 mm.

In conclusion concerning these tests, the material selected for the prototype full-face helmet was polycarbonate.

For the reasons of cost noted, for equipping the prototype helmet we chose the 2.5 mm thick flat polycarbonate vizor with one curvature direction (in relation to the vertical axis).

- Evaluation of the improved protection afforded by the vizor -

This evaluation was performed by means of dynamic free-fall tests (as shown in Figure 3) of a Part 572 dummy head, whose facial part had been modified so as to incorporate the simulated human face designed by Leung et al. (4,5) This simulation has the advantage of having a honeycomb structure (see Figure 4), of which the deformation correlates with the severity of the bone injuries that would have been sustained by the face of a human being struck under the same impact conditions.

Several different drop heights were used. The findings are set out in the following table, which also lists the data obtained with a reputedly "satisfactory" commercially available helmet, tested under the same impact conditions (identified as helmet "G" in the present report).

Thishelmet has a polycarbonate vizor like that of the prototype helmet. The vizor's curve, its dimensions, the surface area of its supports on the "G" helmet, and its mass are closely similar to those of the prototype helmet. Vizor's thickness is 2 mm.

Table 4 -

Drop height (m)	Depth of imprint of the honeycomb structure of the substitute face (mm)
1° / Prototype helmet	
1.5	1.5
2	4
2.5	7
2° / "G" helmet	
1.5	9
2	9
2.5	13

Figure 5 illustrates these findings

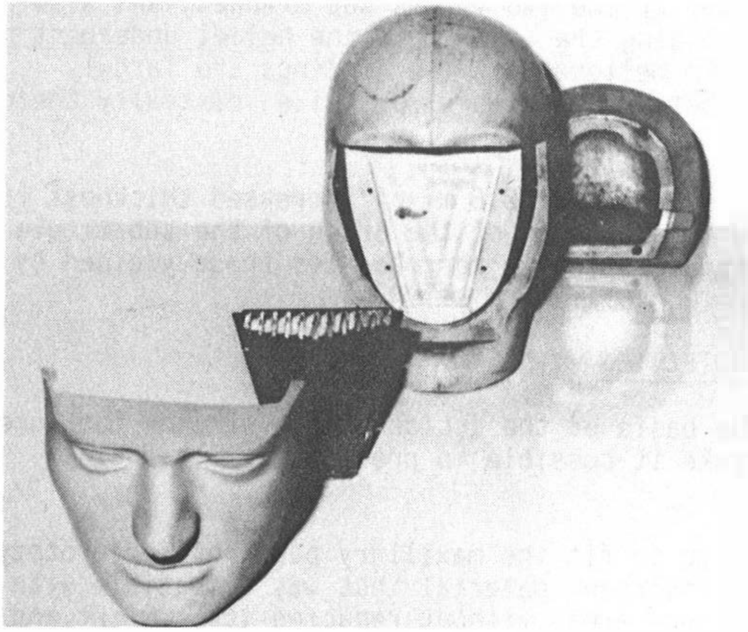
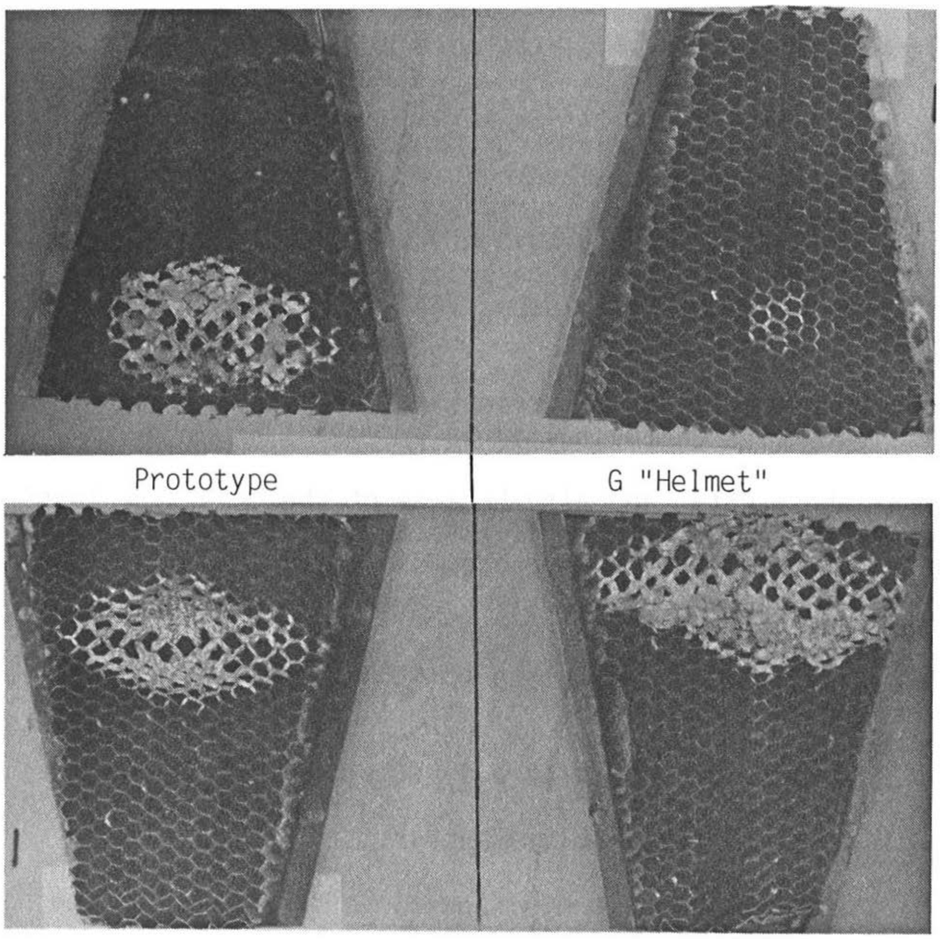


FIG 4 - HUMAN FACE MODEL



Impact speed
5,4 m/S

Impact speed
7 m/s

FIG 5 - FACIAL DEFCRMATIONS OF THE HUMAN FACE MODEL

Since, in addition, neither of the two vizors was cracked, and also since the fixation components holding the vizor onto the helmet underwent no deterioration, there is reason to believe that the findings are largely attributable to the difference between the two vizors, i.e. basically their thicknesses.

This means that with the vizor used, 0.5 mm of increased thickness (i.e. 25 %) enabled a 50 % reduction in the depth of the crush of the substitute face. This is an interesting finding, and it corroborates those yielded by the mathematical modelling.

II - IMPROVEMENT OF MAXILLAR PROTECTION -

As stated earlier, on the basis of the accident data already mentioned, the full face helmets do not make it possible to prevent maxillo-facial fractures (AIS $\geq$ 2).

We consequently endeavoured to fit the maxillary parts of the prototype "integral" helmet with a shock-absorbent material that was compatible with the fracture tolerance of this body area, without reducing its comfort and without detracting from the correctness of its fit onto the head.

Under these conditions, the space available in the prototype helmet was about 25 mm.

With this space occupancy requirement, the object, then was to absorb a maximum amount of energy with a shock-absorbent material that would make it possible to remain below the jawbones' fracture tolerance. Evaluation was performed on the basis of existing bibliographical data (6). When the forces were transmitted to the two jawbones in the anteroposterior direction, a force somewhere between 200 and 300 daN seems to be established at the tolerable threshold.

In addition, anthropometrical measurements showed us that the presumed maxillary support surface area on the helmet is 40 cm2.

In the light of these data, and also because of the objective involved, we selected shock-absorbent materials whose particular feature was that they were crushable under an appreciably steady pressure of from 5 to 7.5 daN/cm2.

Four materials were selected :

- "ELF isolation" with a density close to 50 g/l and 60 g/l : this a rigid, crushable polyurethane foam.

- "Styrofoam", a polyester foam with a density of about 30 g/l.

- "Rohacell 31", a copolymeric polymethacrylic.

- In addition to the above, we used expanded polystyrene foam having a density of about 30 g/l for purposes of comparison, making this choice because this material is a very commonly employed substance, is easy to install in a helmet, is also inexpensive.

- Test conditions - The testing method chosen involved the free-fall of a substitute head weighing 4.7 Kg, encased in the prototype helmet and falling onto a flat, rigid anvil, as illustrated by figure 6, at a level of the jawbone part of the helmet.

Impact velocity for all these tests was 5.5 m/s. Table 5 lists the principal measurement findings.

The accelerations were measured at the center of gravity of the surrogate head, and force was measured on the anvil.

It should here be noted that the forces transmitted to the jawbones are necessarily lower than those measured on the anvil because of the inertia of the helmet in the beginning of the impact.

Two tests were performed with each material. Figure 7 illustrates the principal findings.

All the tests were performed with helmet chinstraps unattached, so as to pinpoint more accurately the effects of the prototype shock-absorbent features installed in the maxillary part of the prototype integral-design helmet in place of the "comfort" foam padding.

- Findings - Table 5 lists the principal measurements.

- Test N°. 1 relates to the "G" helmet, which, it will be recalled, is a commercially available full-face helmet reputed to be "satisfactory".

- Tests N°. 2 and 3 relate to a prototype-design helmet whose maxillary part was, like that of helmet "G", fitted with "comfort" foam padding only.

These three tests served as references for assessing the improvement in maxillary protection provided by the shock-absorbent feature selected.

Under the conditions of the tests performed, if we use the reduction in maximum accelerations (or in maximum forces transmitted to the maxillaries) to judge the shock-absorbent characteristics of the materials employed, comparison between the findings of the reference tests (tests 2 and 3 of table 5) and those of the other tests -specifically of tests 9 and 10- point to an attenuation of impact with the prototype helmet which ranges between 60 % and 70 %.

It will be further noted that, as compared with the "G" helmet (test 1), the prototype helmet that was fitted with 25 mm of "ELF isolation" 50 g/l (tests 9 and 10) enabled a nearly 90 % reduction in maximum accelerations to be achieved.

These findings are especially signifiant because the shock absorbers did not always "perform" under optimum conditions : some of them either partially or totally burst during the tests. In these cases, an envelopping skin would have improved the energy-absorption capacity.

It should also be noted that the expanded polystyrene, density ~ 30 g/l (test 12), although it was intrinsically less effective than the

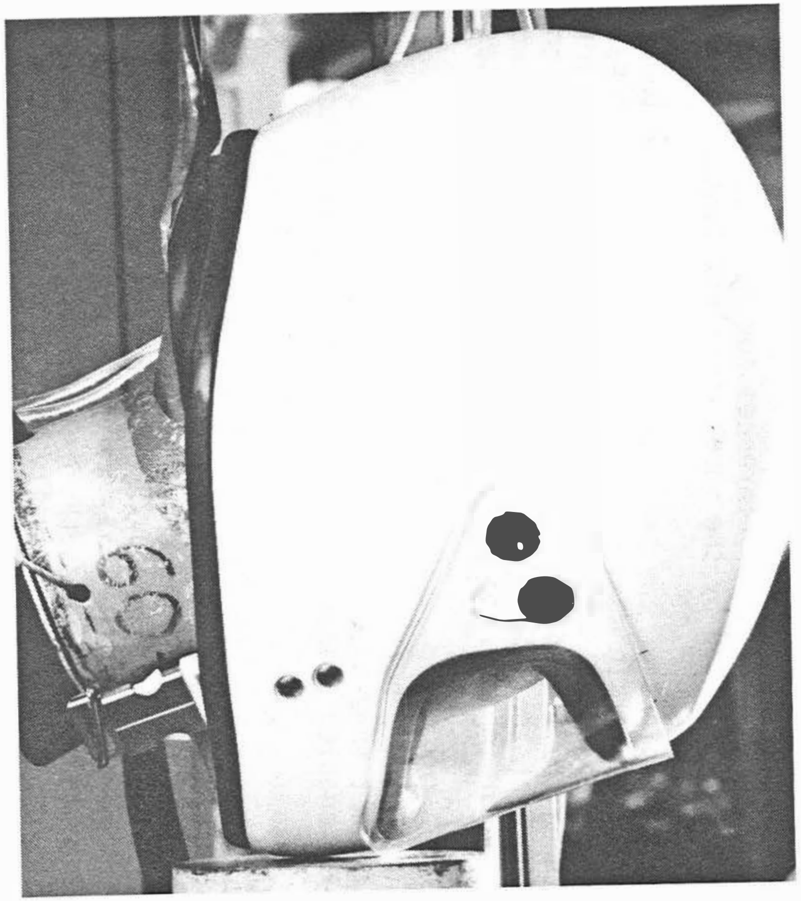


FIG 6 - JAW BONE TEST CONFIGURATIONS

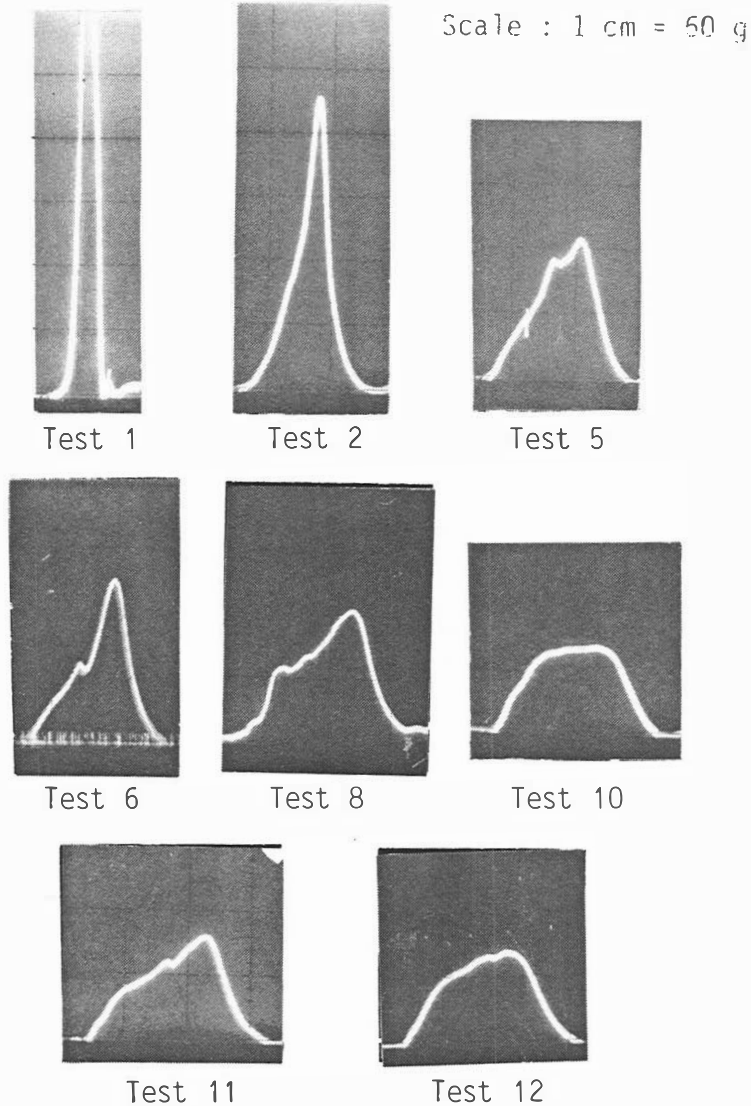


FIG 7 - MAIN ACCELERATION CURVES JAW BONE IMPACTS
(See table 5)

"ELF isolation" (tests 9 and 10) yielded highly satisfactory results. Since this is a material which is easily installed in a helmet, which requires no envelopping skin, and which, in addition, is inexpensive, we decided to use it for padding the maxillary part of the prototype full-face helmet.

Remark : We also endeavoured to evaluate the possibility of shock-absorption by means of the chinstrap in instances when this is snugly fitted below the lower maxillary. For this purpose, and using the same test procedure, we performed two additional tests (13 and 14) with prototype full-face helmets whose maxillary part was upholstered only with "comfort" foam padding. The findings are summarized in the table below and are compared with those of tests 2 and 3 in Table 5.

Table 6 -

Test N°.	Maximum resulting acceleration (g)	Maximum load (daN)	Observations
2	223	1068	Chinstrap unattached
3	204	967	
13	140	873	Chinstrap attached
14	134	706	

All other things being equal, it can be noted that with the helmet used, under these testing conditions the chinstrap enabled nearly a 35 % reduction in impact violence (if we consider the reduction in the maximum resulting acceleration).

This is a significant finding, and it shows that the chinstrap of a given helmet can be an element in the improvement of facial protection. The parameters to be considered are : the material of which it is made, the location of the points of its attachment onto the helmet and its orientation in relation to impact direction.

III - EVALUATION OF THE MAXILLO-FACIAL PROTECTION PROVIDED BY THE PROTOTYPE FULL-FACE HELMETS -

Evaluation of the maxillo-facial protection provided by the prototype "integral" helmet was effected via comparisons between, on the one hand, the facial injuries observed on human cadavers * fitted with reputedly "satisfactory" full-face helmets ["B" helmet in (2)] and, on the other hand, the absence of facial injuries to human cadavers fitted with the prototype full-face helmet; the impact violences of the tests performed with the commercially available "satisfactory" helmet [helmet "B"] were less than or equal to those of the tests performed with the prototype helmet.

(*) These cadavers were those of individuals who had specifically bequeathed their bodies to Science.

Note : the "B" helmet was fitted with the so-called "comfort" foam in its maxillary part only.

- Methodology - Testing conditions - The human cadavers - those of recently deceased individuals, unembalmed, prepared and instrumented in accordance with procedures already described in the scientific literature (7) (8) (9) - were held in place horizontally, with their heads in the prolongation of the thorax, as shown in Figure 8 ; they dropped in free-falls onto a flat, rigid dynamometric platform that was not covered with shock-absorbent material.

The drop heights and the principal anthropometric data concerning these subjects are set out in Table 7. Table 8 lists the values achieved by the various physical parameters measured as well as the descriptions of the facial injuries observed : Figure 9 illustrated these.

- Analysis of facial injuries (see Table 8) - With the "B" helmet, at a drop height of 1.83 meters, the human subject sustained a nose fracture. At 2.5 meters and 3 meters, the facial fractures were multiple and very severe (see figure 9) [Lefort I, II and III, depending on cases.]

However, with the prototype helmet, the faces of the two subjects tested remained intact although impacted under the most severe impact conditions of all those tested (drop height 3 meters).

This is a highly interesting finding and although obtained on the basis of only two tests, it is significant of the improvement brought about in facial protection.

- Measurements findings - These measurements findings are not the basic purpose of this report. However, certain points deserve to be noted, specifically as concerns the head's accelerations. In fact, the levels achieved in tests 94 and 95 (see Table 8) and those achieved in tests 309 and 310, all of which were performed at a 3-meter drop height, are quite close, whereas the facial injuries are, respectively, very severe in the first two tests, and nonexistent in the other two.

In the light of this small number of tests, the temptation is to conclude that there is no correlation between the resulting accelerations at the head's center of gravity and the severity of facial injuries. Actually, it is the crushing forces applied to the face itself that brings about the corresponding injuries. In the two pairs of tests compared above (i.e. 94/95 versus 309/310), we know only that the sum of the forces applied to the head is roughly the same, but we have no measured indication of the distribution of the forces of contact between the forehead and the actual face. In all likelihood, for tests 309 and 310, the lower maxillary part of the face was subjected to forces sooner and more violently.

- Problems linked to the defining of facial protection criteria - The preceding remarks confirm that the measurements of the head's acceleration, in the case of a distributed fronto-facial impact do not make it always possible to gauge the severity of possible facial injuries and hence the degree of protection provided by full-face helmets. In addition, more localized facial impacts (against angles, for example) would tend to lead to the

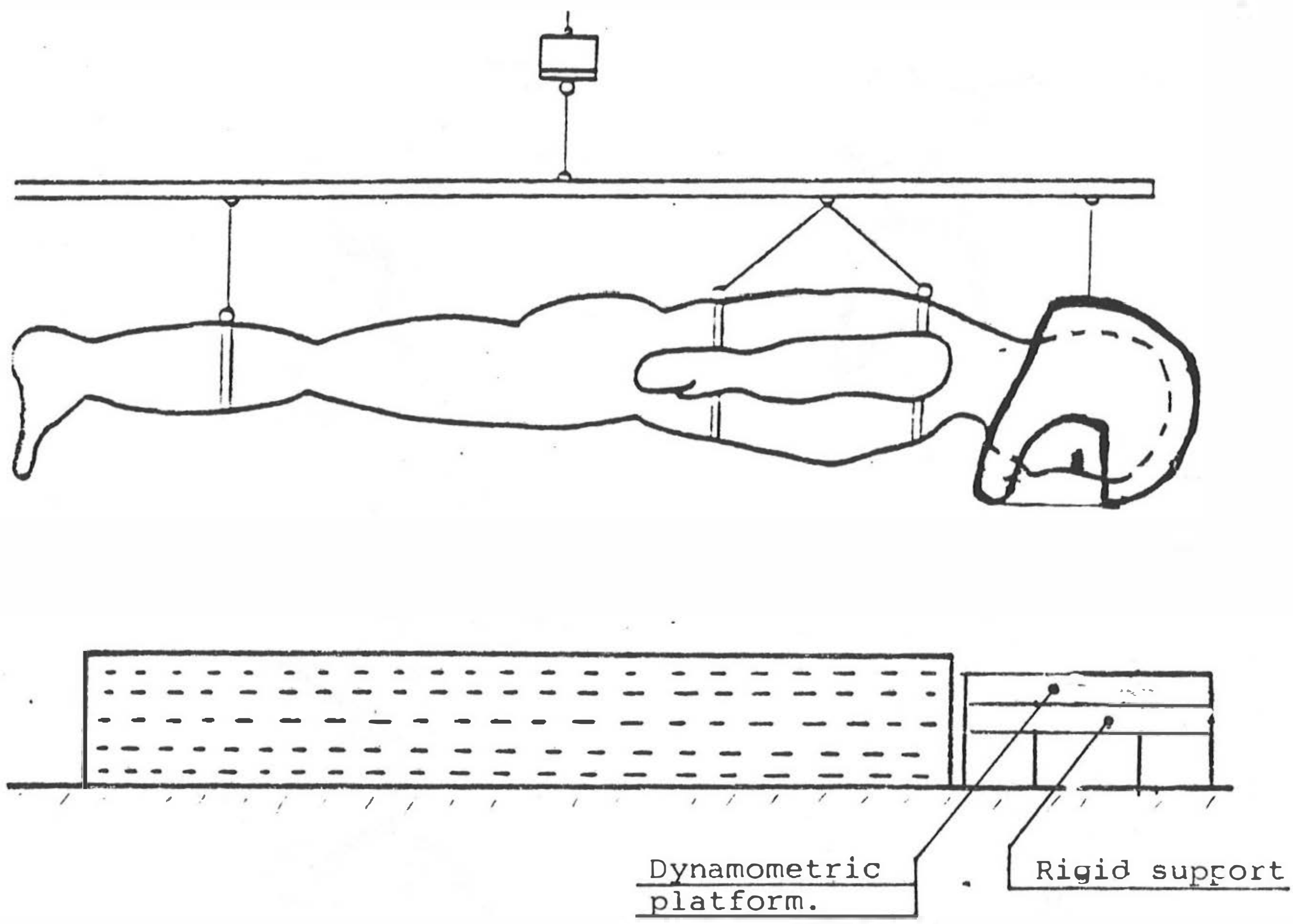


FIG 8 - PRINCIPLE OF CADAVER TESTS

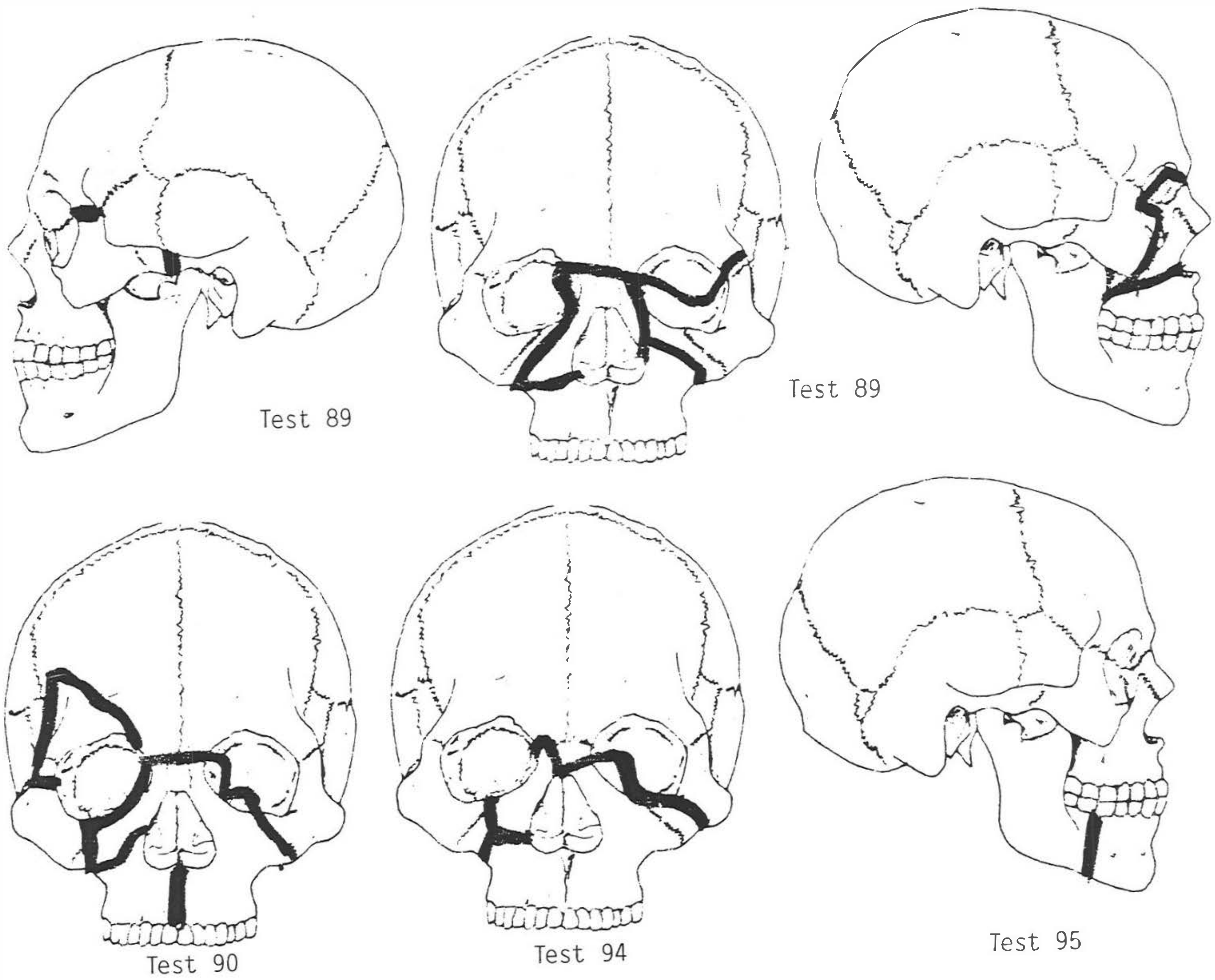


FIG 9 - CADAVER TESTS - FACIAL INJURIES

same conclusions. It is hence reasonable to believe, in the perspective of all facial-protection investigations, that it will be necessary to fit the rigid surfaces of the anthropomorphic dummy heads with the proper modelization of the human face, of the kind designed by Leung et al. (4,5) the constitution of which was noted.

- Analysis of brain injuries - The occurrence of brain injuries was frequently observed without the levels achieved by the physical parameters measured (acceleration and force) or the severity of facial injuries making it possible a priori to evaluate their severity. On the other hand, analysis of the high-speed films revealed kinematics of the head in relation to the thorax, and amplitudes of these various movements, depending on the tests, that could be related to the occurrence of brain injuries.

The comparison between tests 309 and 310, which were performed with the same type of helmet and under the same impact conditions, is from this standpoint significant. In fact, for test 309, analysis of the film revealed only a very slight traction on the neck ; a slight extravasation of the injection liquid was found in the microscopic examination of the brain (AIS 2 or 3).

On the contrary, for test 310, analysis of the film revealed a considerable elongation of the neck accompanied by a forward rotational movement of the head. In this case, the brain injuries observed were multiple and quite severe (injuries to the brain-stem and brain lobes, in-depth). Similarly, considerable elongations of the neck (without the occurrence of injury at this level) were observed in the films for subjects 88 through 95, who frequently sustained brain injuries (see table 8). All the movements of the head in relation to the thorax and the associated brain injuries suggest mechanisms of a type implying involvement of the brain mass at the level of foramen magnum.

Complementary investigations performed with human subjects tested under the same conditions as those described above, but with observation of the nonoccurrence of elongation of the neck, should make it possible to understand more thoroughly the effects of the head's kinematics in relation to the thorax in the total picture of encephalic injuries.

SUMMARY AND CONCLUSIONS

At the conclusion of this investigation, a prototype full-face helmet was designed while including criteria of cost and production.

The various features that constitute maxillo-facial protection (vizor and maxillary part) were investigated via a preliminary approach by calculation. They were designed and selected on the basis of biomechanical data, and were then tested dynamically.

Overall validation of the prototype integral helmet was subsequently carried out by means of tests performed on human subjects.

The overall findings have been set out ; they show the improvements provided by the prototype helmet and the technological solutions chosen.

The matter of the application of these findings to maxillo-facial protection was also investigated, and it reveals the value of using a proper simulation of the dynamic behaviour of the human face for assessing the degree of protection afforded by helmets.

The use of such simulation of the face also emerges as worthwhile if we consider the maxillo-facial protection of motor vehicle occupants.

ACKNOWLEDGEMENTS

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Opinions and conclusions are those of the authors.

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Table 5 - Findings for Localized Impacts Onto the Maxillary Parts of the Prototype "Full Face" Helmet With Various Shock-Absorbent Materials.

Testing conditions			Findings of measurements		
Test no.	Type of helmet used	Material situated in maxillary part of helmet	Resultant maximum acceleration (g)	Maximum force (daN)	Observations
1	"G"	Original "comfort" foam padding	620	>2000	
2	prototype	"Comfort" foam	223	1068	
3	prototype	"Comfort" foam	204	967	
4	prototype	Copolymer polymethacrylic ref. 31	136	761	Bursting of material into several fragments
5	prototype	Copolymer polymethacrylic ref. 31	105	629	Bursting of material into several fragments
6	prototype	Rigid, deformable polyurethane foam, density 45 g/l	126	733	Material partially burst and reduced to powder
7	prototype	Rigid, deformable polyurethane foam, density 60 g/l	106	603	Material partially burst and reduced to powder
8	prototype	Rigid, deformable polyurethane foam, density 60 g/l	101	607	Material partially burst and reduced to powder
9	prototype	Rigid, deformable polyurethane foam, density 50 g/l	75	431	Bursting of material
10	prototype	Rigid, deformable polyurethane foam, density 50 g/l	65	397	Bursting of material
11	prototype	Polyester foam, density 30 g/l	84	466	Bursting of material
12	prototype	Expanded polystyrene foam, density 30 g/l	74	463	Bursting of material

Table 7 - Fronto-Facial Impacts of Heads of Human Subjects - Testing Conditions, Anthropomorphic Data Concerning the Heads

			Dimensions (cm)			Mass (kg)	
Test No.	Helmet type	Drop height (meters)	Circumference	Length	Width	Head and neck	Head alone
88	B	1.83	55.2	18	15	3.9	2.9
89	B	2.5	55	17.5	13.7	4	3.21
90	B	2.5	58	19.6	14	5.28	4
94	B	3	55.3	17.8	14.6	4.56	3.60
95	B	3	55.5	18.5	14	4.37	3.53
309	prototype	3	56	18.9	15	5.1	4
310	prototype	3	53.5	18.6	14.6	4.42	3.4

Table 9 - Fronto-Facial Impacts of the Human Subjects' Heads - Measurement Findings - Record of Injuries

	Measurement Findings				Injuries	
Test No.	Acceleration (g) Maximum	3 ms	HIC	Impact Force (daN)	Facial Injuries	Other Injuries
88	129	95	565	1040	Fracture of nose bone	Brainstem injuries
89	150	95	540	1080	Multiple fractures, so-called Lefort I, Lefort II, Lefort III	Corpus callosum injury
90	176	125	1185	1560	Multiple fractures, so-called Lefort I, Lefort II	
94	169	136	1500	800	Nose fracture + fracture of upper maxillary	Brainstem injury
95	185	125	1150	--	Fracture of mandible + dislocation of maxillar	Brainstem injury + cortical contusion
309	-	-	-	940	No injury	Very slight injury to 4th ventricle
310	180	158	1600	740	No injury	Brainstem injuries + many injuries in the cerebral hemispheres