THE DEVELOPMENT OF AN IMPROVED ATD HEADFORM WITH A FRANGIBLE FACIAL INSERT

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ABSTRACT

As part of Transport Canada's on-going occupant injury protection program, a frangible faceform has been developed to monitor for facial bone fracture in motor vehicle testing. This paper details the history of the work associated with this project. Included are the results of an extensive program of component testing as well as full scale car crash testing.

INTRODUCTION

This paper describes the completion of work on the development of a frangible facial insert. Some of the background material previously described by Newman and Gallup (1) is summarized here for completeness.

Despite the increased use of seat belts in automobiles, the head and face remains one of the more frequently injured body regions. In a Transport Canada study of 100 injury-producing frontal collisions involving 121 fully restrained occupants, 69 occupants sustained a head and/or a facial injury of AIS 2 or greater. The two predominant facial injury types consisted of 27 lacerations and 22 fractures. In addition 37 of the 69 occupants sustained concussions. It was noted that drivers are far more susceptible to facial injury than right front passengers due to the presence of the steering wheel assembly (1).

In an analysis by Tarriere et al (2) of 405 fully belted drivers involved in frontal collisions, 74 (18%) sustained a head strike against the steering wheel. The face was involved in 92% of these cases.

Gloyns et al (3) made an analysis of seriously injured restrained drivers in frontal collisions. The severity levels in this sample for the head and face region ranged from the AIS 1 to 5 level, and were predominantly at the AIS 2 level. Of these, 85% sustained soft tissue injury to the face, 22% had lacerations requiring suturing, 31% sustained a facial bone fracture, and 22% received some level of concussion. Half of the occupants with a facial bone fracture sustained a concussion. Two-thirds of the detected contacts were found on the hub and spokes of the steering wheel.

The face is defined as the anterior aspect of the head from the forehead to the chin inclusive (4). Much research on facial injuries has adressed soft tissue damage (2, 5-10). To date, emphasis has been on lacerations induced by glass rather than considering impacts to compliant surfaces.

Attempts to study and reproduce facial bone fracture started in the 1960's (11, 12). In cadaver testing carried out by Hodgson (13), it was noted that the line of action, center of load application, and the area of force application and pulse duration were all important factors when attempting to duplicate certain types of facial fractures.

Nahum and Schneider (14, 15) conducted similar tests of localized loading to cadavers. They tested the frontal, tempoparietal, zygomatic, maxillary and mandibular bones. In contrast to Hodgson, they observed that tolerances are essentially independent of pulse duration and that female bones are not as strong as those of males.

Tarriere et al (2) studied the energy absorption characteristics of the face using an impact pendulum resembling a steering wheel. Their study showed that the facial skeleton underwent elastic and plastic deformation during impact.

More recently, Nyquist et al (16) impacted the nose region of 11 unembalmed cadavers in an attempt to establish facial bone fracture tolerance and head response. 11 impacts caused nasal fractures, and thus they concluded that the nasal bones are relatively weak. The authors also found that other facial bones required larger forces to fracture, and that impact energy was a good predictor of fracture severity. More recently, Saul (17) and Zuby (18) have used Nyquist's equipment and methodology to test three current facial injury monitoring devices, one of these being the frangible device described in this paper.

In an ongoing Transport Canada and INRETS study, Welbourne and Cesari (19) are currently trying to establish tolerances for the subnasale, maxilla and nasion. As part of this research, they plan on impacting the facial insert described in this paper using the same test methodology and equipment as employed in their cadaver tests.

Development of a frangible headform system for monitoring facial lesions in automotive car crash testing was initiated in the late 1960's. Melvin et al (20) and Brinn (21) were pioneers in this area. Interest in the development of test devices capable of monitoring facial bone fracture has increased in recent years.

Based on the early work done by Tarriere (2), Petty and Fenn (22) describe the impact testing of a number of steering wheels with an energy absorbing aluminum honeycomb headform. It appears to be designed for component rather than car crash testing.

In 1979, Warner and Niven (23) proposed an idea for a segmented headform. They have further described the developmental work (24, 25). The design contained instrumented cantilevered beams in a Hybrid II headform. This has since been replaced with a non-segmented Hybrid III headform covered with a pressure sensitive piezo-electric transducer array.

Mercedes-Benz (26, 27) has developed a force monitoring system consisting of a Hybrid II headforms covered by one inch squares of Fuji pressure sensitive film.

DEVELOPMENTAL HISTORY

Based on current injury and biomechanical data, it was decided to direct Canadian efforts towards the development of a headform capable of monitoring for facial lacerations as well as fractures of the nose, zygoma and maxilla.

The initial design was based on the modification of a Hybrid II headform. The frontal portion of the aluminum skull, corresponding to the facial bones under study was removed and replaced with a frangible facial insert supported on a molded rubber base. The basic design was subsequently transferred to the Hybrid III headform.

Early attempts were made to match local tolerances by varying the thickness of the facial inserts. This proved ineffective. To resolve this problem, the insert was modified to a uniform thickness and the vinyl skin cover thickness was correspondingly altered over the specified facial bones. The frangible skull assembly is illustrated beside a human skull in Figure 1.

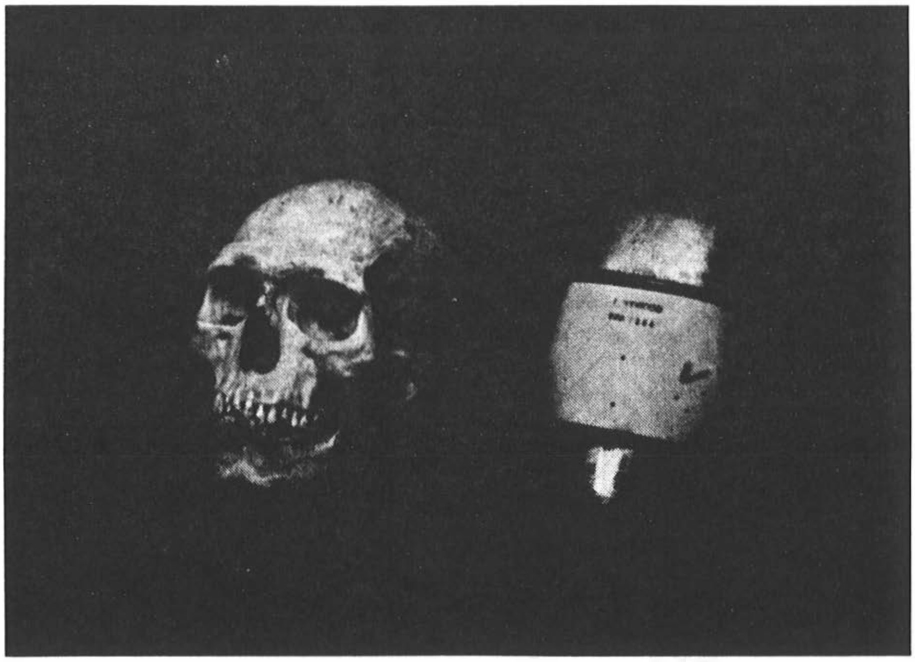

Figure 1: Human Skull and Frangible Skull Assembly

Ward and Schneider (29) had shown that impacts to the Hybrid III chin produced accelerations almost twice as great as those found in cadaver mandible impacts. To address this in the design, attempts were also made to articulate the Hybrid III aluminum mandible. This proved effective but not durable. The final solution consisted of removing approximately 1.25cm of the aluminum from the bottom of the mandible ,replacing the space with vinyl. This modification proved adequate.

FRANGIBLE HEADFORM SYSTEM

Overall Assembly

The present frangible headform system consists of a modified Hybrid III headform. Fracture levels depend on facial insert thickness, the rubber backing stiffness, and the thickness and stiffness of the vinyl skin cover. These parameters are all critical in terms of tolerance response thresholds.

The modified headforms are ballasted to meet mass and center of gravity specifications for a Hybrid III headform as specified in the GM drawing package (30).

A cross-section of the headform system is illustrated in Figure 2. Each portion of the system is further described in the following sections.

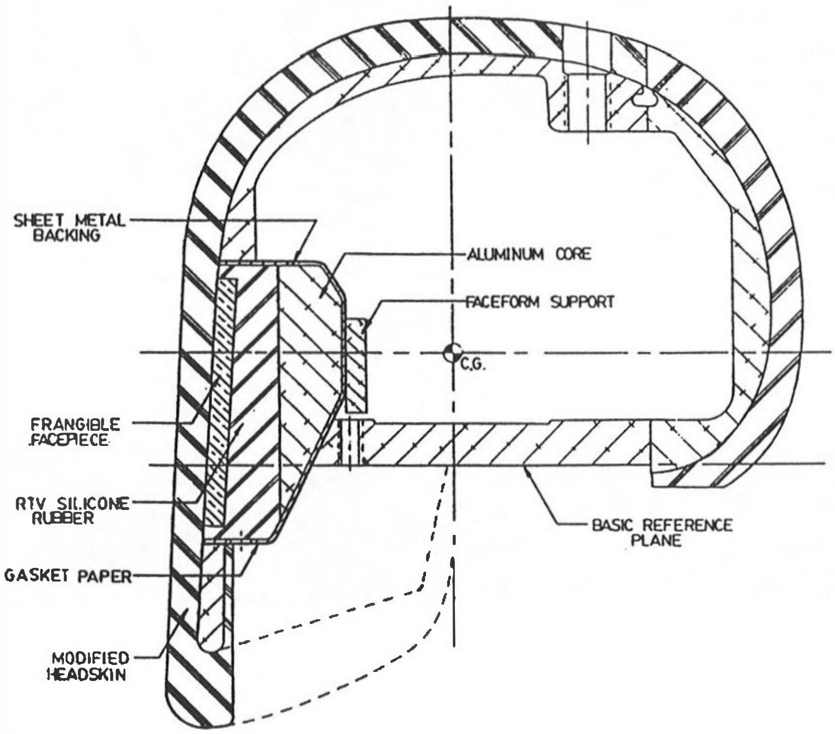

Figure 2: Headform Cross-Section

Skull Design

A modified Hybrid III headform has been employed for the skull. The frontal region corresponding to the facial bones being studied is removed. The cavity is lined with a 0.16 cm thick aluminum sheet supported on a 0.05 cm thick gasket paper. A specially contoured aluminum core block is attached to a support member running laterally through the skull behind the sheet metal. The shape of the aluminum core approximates the curvature of the facepiece and thus ensures a uniform RTV rubber backing thickness. RTV silicone rubber (General Electric blue RTV - 664) is poured into the cavity through pre-drilled holes under the chin. The RTV is subsequently cured at an elevated temperature. Temperature curing may be necessary in order to obtain acceptable stiffness and thereby gain desired fracture levels.

Facial Insert Design

The frangible nature of the facial insert is achieved by utilizing a cross-linking, self-curing acrylic resin. This brittle material, methyl methacrylate, is registered under the trademark of Kerr Formatray.

The exterior surface and dimensions of the facial insert are similar to the original facial surface of the Hybrid III skull, with the exception that the eyes and depression in the nose region have been filled in to smooth the outer surface. The design wall thickness of the facial insert is uniformly 0.6 cm. It has eight 2mm diameter stress raisers drilled in it. These serve to increase repeatability as well as accuracy of fracture levels. A technical drawing is provided in Figure 3.

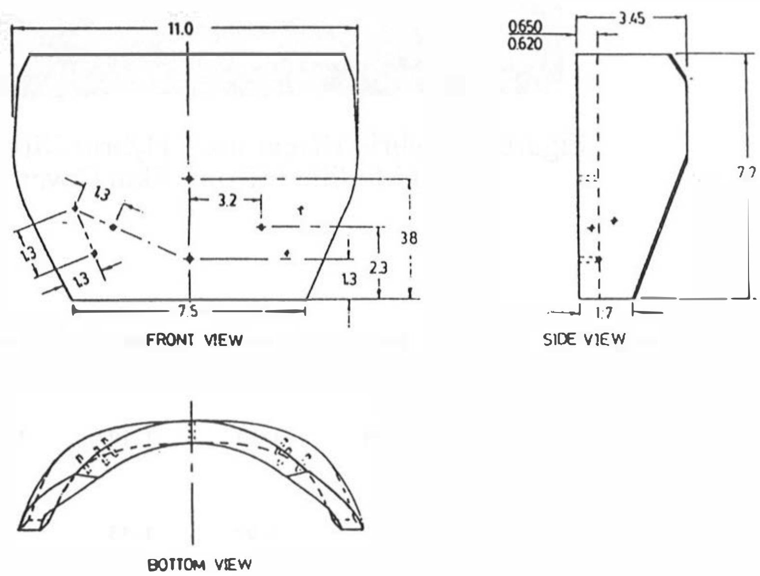

Figure 3: Frangible Facial Insert

Skin Design

Early testing of the Hybrid III skin cover indicated a lack of repeatability in facial fracture response. This was improved by removing the dominant facial features. The remaining exterior anthropometry was unmodified.

Testing of the skin material established a relationship between the fracture tolerance and skin thickness. Skin thickness was specified to give the desired fracture levels at each facial region (Table 1). The modified skin, the Hybrid II, and Hybrid III skins are illustrated in Figure 4.

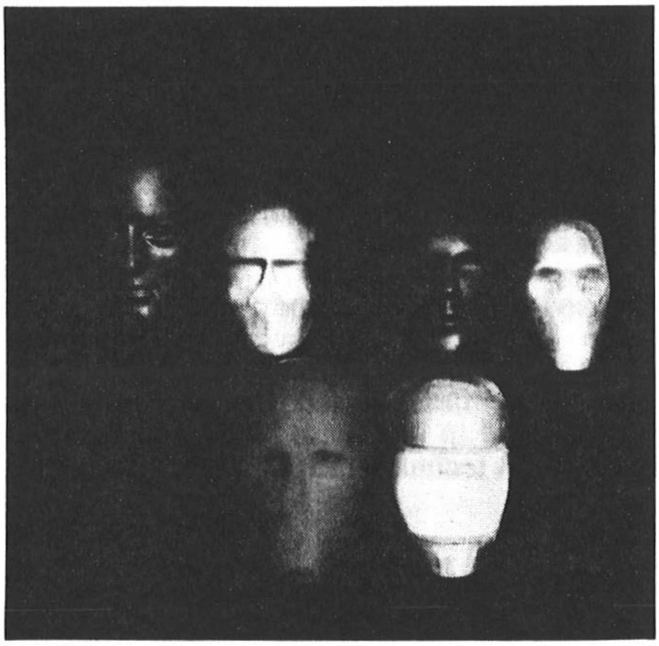

Figure 4: Hybrid II(rear left), Hybrid III(rear right) and Modified (front) Skin Covers

Skin	Nasion	Zygoma	Maxilla	Subnasal	Nose
Modified Skin (AR11)	1.00	1.10	1.10	1.05	1.10
Hybrid III	1.55	1.09	1.13	*	*

Table 1: Skin Thickness (cm) at Various Facial Locations

IMPACT LOCATIONS

Anthropometry of the Face

Bone contours of a human skull were traced onto the facial skin of a Hybrid III headform and then transferred to a facial insert (figure 5). From the tracing it is evident that the facial insert includes all the upper face (distance between the nasion and the stomion). The specific bones included are: the zygomatic bone, the maxilla, the nasal bone, the small portion of the frontal bone at the level of the fronto-zygomatic suture, and the supraorbital margin.

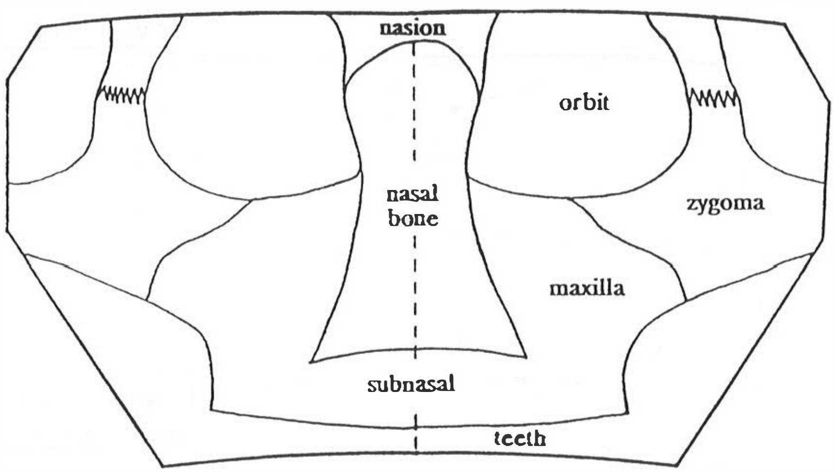

Figure 5: Human Bones Outlined on a Facial Insert

Tolerance Data

The procedure used to establish tolerance levels for the facial insert system was based on existing cadaver data for given locations. The target energy levels for the facial insert fracture were set slightly above the highest energy levels at which no fracture was recorded. The lowest fracture levels observed from cadaver results were considered to be unrepresentative of the general population.

The test device and a methodology approximated those employed by Nahum and Schneider (14, 15) . The methodology was however altered so that the headform was rigidly attached to a base plate as opposed to being supported on foam. This decreases the energy required to fracture by approximately 30% (15) and was confirmed in testing at Biokinetics (28). The previously published target levels were reduced correspondingly and the modified data can be found in Figure 6.

Other regional tolerance levels not investigated by Nahum and Schneider were established through interpolation of Swearingen (12) and Hodgson's (13) data.

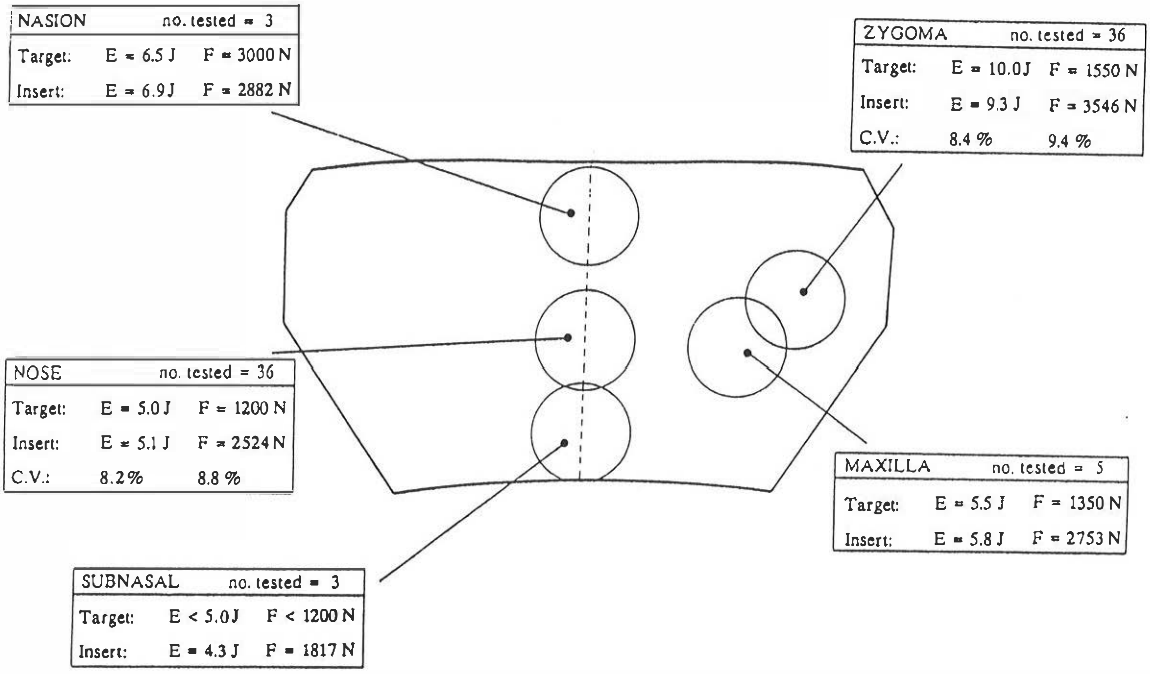

Figure 6: Mean Fracture levels

Impact Testing

The impact testing is accomplished with a guided drop frame assembly with a mass of 1.46kg. The impacting anvil is circular with a diameter of 2.5cm, and is similar to the one employed by Schneider et al (15). The impactor is also fitted with a uniaxial accelerometer for force estimation. The kinetic energy at impact is calculated by measuring the velocity, by means of a velocity gate, at the instant that the drop frame strikes the surface of the headform. Using an assortment of base plate configurations, the headform can be impacted at any of the locations of interest with the axis of the anvil perpendicular to the center surface of the headform. Figure 6 illustrates these impact sites.Figures 7 and 8 illustrate test set-ups for the nose and zygoma , respectively.

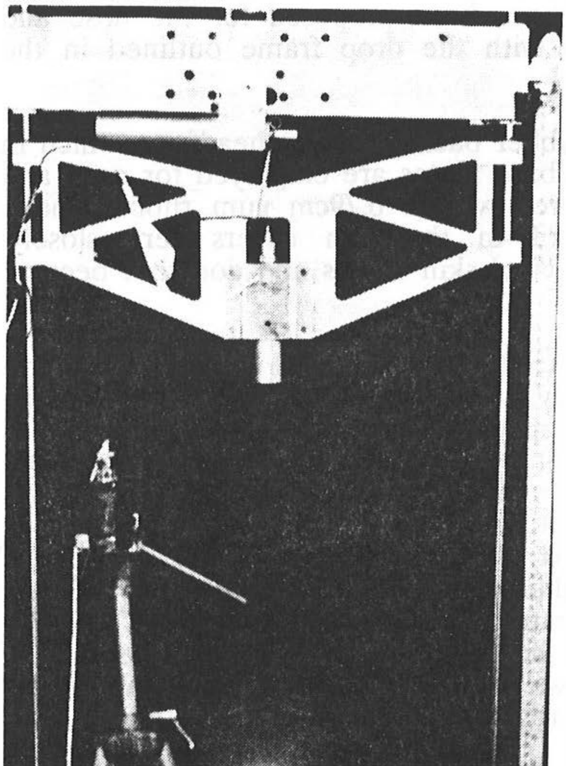

Figure 7. Nose Impact

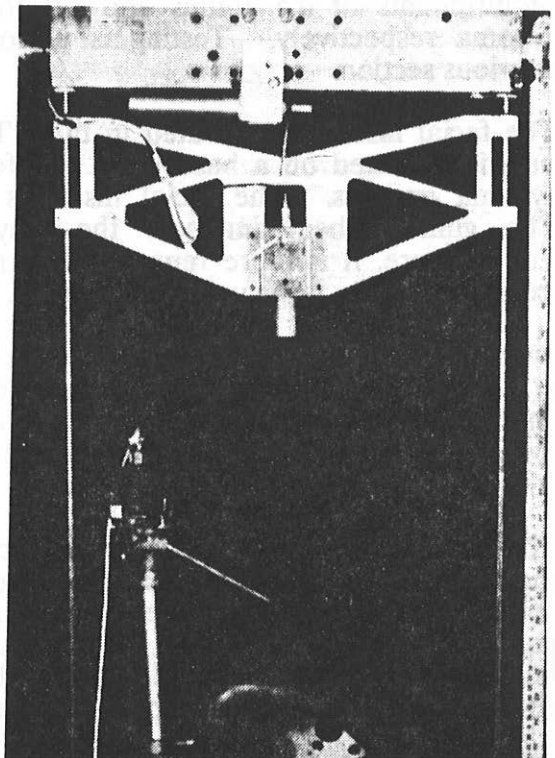

Figure 8. Zygoma Impact

CERTIFICATION TESTING

Ideally, the facial inserts should break at energy levels set by human fracture tolerance data. Calibration of the facial insert is less straightforward than with other dummy components since the application of energy capable of producing a human facial fracture would also produce a fracture in the facial insert. This renders that particular insert useless for further testing.

Certification testing is thus accomplished by impacting the inserts at a lower threshold level at which they may not break and a higher threshold level (subsequent to car crash testing) at which they must break.

In order to eliminate unacceptably weak facial inserts, lower certification requirements of 4.5 Joules and 8.0 Joules have been proposed for the nose and zygoma respectively. Testing is performed with the drop frame outlined in the previous section.

The facial inserts are located in the RTV rubber backing of the headform which in turn is mounted on a base plate. Different base plates are employed for nose and zygoma impacts. The facial insert is covered with a 0.79cm gum rubber sheet. The gum rubber simulates the vinyl used in the skin covers very closely. Furthermore, it is more repeatable than the vinyl skin covers and does not become exhausted with a large volume of testing.

Subsequent to use in a car crash test, the facial insert is tested at the upper limit at which it must break. The inserts can only be broken at one test region so the choice of this final upper limit test region may be dependent upon observations from crash film data. The upper limit is set at 6.0 Joules for the nose and 11.5 Joules for the zygoma.

The amount of energy required to fracture is greatly influenced by the stiffness of the RTV rubber backing. The backing is thus certified with a Durometer reading and dynamic impact response at the nose location. A Durometer Shore 'A' reading must fall between 60-70. The dynamic certification requirement consists of impacting the RTV rubber directly at the nose with the drop frame. For an impact energy of 6.4 Joules, the acceptable range of g-response is 250-280 g's.

The skin covers have to be certified for car crash testing. The skins are mounted on a solid aluminum headform that has the same shape as the modified Hybrid III headform when fitted with a frangible insert. Acceptable g-response obtained by impacting the skins at the nose are presented in table 2 , the corresponding response corridor is illustrated in figure 9.

Impact Energy J	Response Min. (g's)	Response Max. (g's)
3.80	190.0	210.0
6.40	284.0	306.0
8.75	379.5	404.5

Table 2: Skin Certification Results

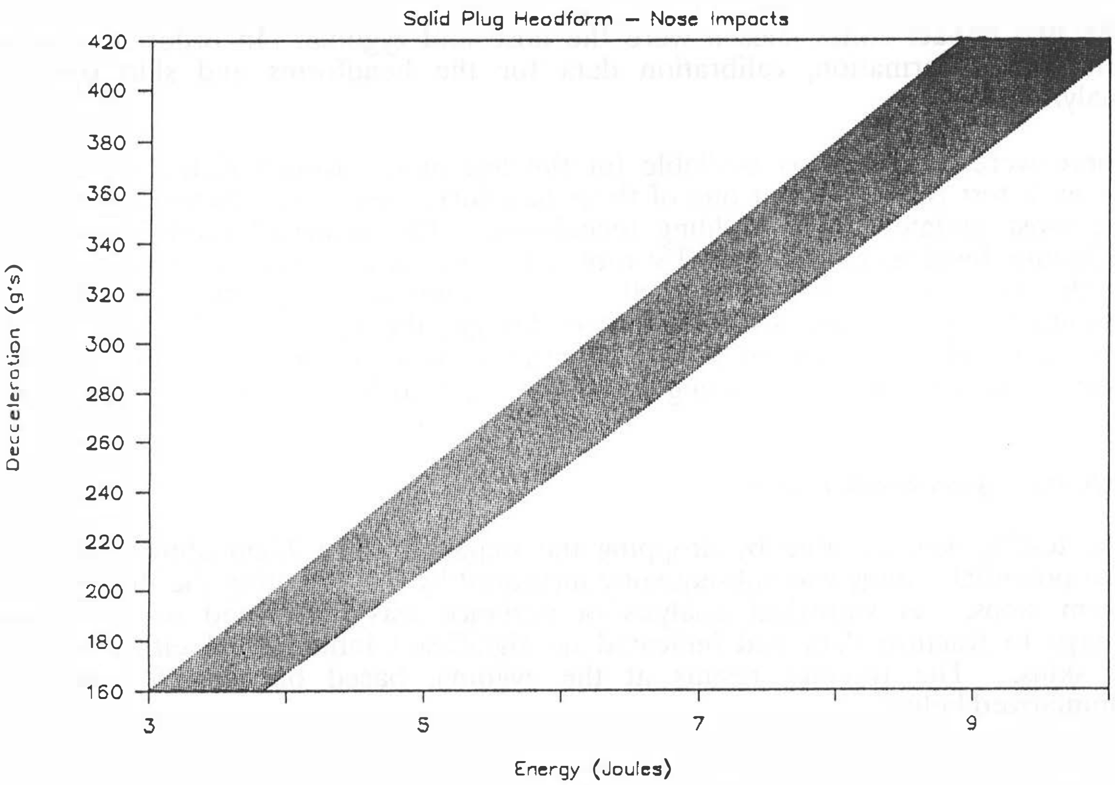

Figure 9: Skin Response Corridor

Other Requirements

Test bar specimens are molded simultaneously with each facial insert. The specimens are notched and tested in a modified Izod plastics material tester. A material specification has been established from the results of these tests.
The assembled headforms are also tested by performing standard Hybrid III forehead drop tests.

REPRODUCIBILITY TESTING

Methodology

A reproducibility study was performed on the headform system utilizing the drop frame assembly previously outlined. In order to examine the reproducibility of the headform system, the variability of each of the main system components, namely headform (RTV rubber backing), frangible insert, and skin cover had to be taken into consideration.

The test matrix completed to date encompasses two test impact locations, two headforms and six facial skin covers. A 30 minute delay was observed between consecutive impacts on any one skin cover, according to recommended practice. Each test setup was performed for three inserts, requiring destructive testing of a total of 72 inserts.

The two impact zones chosen were the nose and zygoma. In order to gain some prior test information, calibration data for the headforms and skin covers was analyzed.

There were 5 headforms available for the test matrix from which 2 were selected for each test zone. All but one of these headforms were manufactured according to the most updated RTV molding techniques. The principal modification in this technique involves curing the RTV rubber backing at an elevated temperature. This results in a stiffer headform. It was of interest to establish whether these manufacturing changes could be traced through the reproducibility testing. Thus one new and one old (and softer) generation headform were chosen for the test matrix. Similarly, 6 skins spanning the softest to the stiffest were chosen.

Zygoma Reproducibility Tests

The testing was initiated by dropping the impactor from 72cm above the zygoma. The potential energy was subsequently increased by incrementing the drop heights in 3 cm steps. A statistical analysis of variance was performed on the required energy to fracture data and indicated no significant influence of either headforms or skins. The fracture results at the zygoma, based on the 36 samples, are summarized below:

E_{zyg}	= 9.35 J ± C.V. = 8.4%	F_{zyg} =	3546 N ± C.V. = 9.4%
E_{max}	= 11.09 J	F_{max} =	3881 N
E_{min}	= 8.22 J	F_{min} =	3308 N

Nose Reproducibility Tests

Testing was continued at the nose location. It became apparent after testing only 6 inserts and skins on the softer headform that these results were different from those with the stiffer headform. The results obtained with the stiffer headform were closer to the tolerance target levels set for the nose. At this point a decision was made to reject the softer old generation headform. Another of the new generation of headforms was tested on the nose with 18 additional facial inserts.

A statistical analysis of variance performed on the data based on the new headforms revealed no statistical influence of skins or headforms. A statistical analysis of variance did indicate a large difference between these headforms and the softer, old generation headform.

The population statistics for the latest generation headforms, based on 36 samples, are shown below.

E_{nose} = 5.10 J $\pm$ C.V. = 8.2% F_{nose} = 2524 N $\pm$ C.V. = 8.8%
E_{max} = 6.30 J F_{max} = 2950 N
E_{min} = 4.35 J F_{min} = 1962 N

OUTSIDE TESTING

VRTC

In an effort to compare different facial injury assessment schemes, Zuby at the Vehicle Research and Test Center (VRTC) evaluated the facial insert (18). The evaluation was done in two parts. The first was done using Nyquist's (16) 32 kg rigid bar impactor at the nasal location at three different velocities. From the rigid bar tests, it was noted that all facial inserts broke at both upper energy levels (7.0m/s, 3.5m/s) but did not at the lower level (1.75 m/s). It was also noted that the number of broken pieces of the frangible insert increased with higher energy impacts.

The second test series comprised impacts to the steering wheel rim and hub of two vehicles, at two velocities. The results of the steering wheel impact tests show that the deformation of the steering wheel rim absorbed a great deal of energy and the inserts did not fracture . Impact with the hub, however,usually fractured the inserts.

Car Crash Tests

Fourteen facial inserts have been tested to date at the Transport Canada Motor Vehicle Test Centre. The modified dummy was employed in both the driver's and passenger's configuration in full scale 48km/h frontal barrier crash tests. Each test was with a car of different model.Three of the facial inserts fractured. Head resultant accelerations and HIC values for all these crashes are presented in Table 3.

Vehicle Number	Occupant Seating Position	Contact Region From Film	Peak Resultant Head Acceleration (G's	@ Time)	Fracture of Facial Insert (Y/N)	Head Injury Criterion, HIC Time Interval (ms) Any	<=36 ms	<=15 ms
1	Driver	Steering wheel hub	129	70 ms	Yes	516	516	411
2	Driver	Steering wheel hub	96	78 ms	No	877	868	666
3	Driver	*	131	69 ms	No	551	542	392
4	Driver	*	127	89 ms	No	1056	1056	741
5	Driver	AIR BAG	58	67 ms	No	465	458	294
6	Driver	*	195	80 ms	No	947	948	927
7	Driver	Steering wheel	91	101 ms	No	719	719	574
8	Driver	Top steering rim	121	82 ms	No	762	762	621
9	Driver	Steering wheel hub	197	73 ms	Yes	873	873	706
10	Driver	Steering wheel hub	122	98 ms	No	797	795	578
11	F.R. Passenger	**	43	72 ms	No	494	349	158
12	Driver	*	141	83 ms	No	1065	1065	1065
13	F.R. Passenger	**	49	104 ms	No	556	511	233
14	Driver	Steering wheel hub	194	87 ms	Yes	926	926	926

* Data not available.
** Not applicable.

Table 3: Frontal Barrier Test Results

All three cases of fracture correspond to a steering wheel hub (not rim) impact ,as expected from the VRTC test results (18).

As can be seen, neither the peak resultant head acceleration nor the HIC are adequate indicators of facial bone fracture. This is because both are poor indicators of contact force distribution.

DISCUSSION

Efforts over the last two years in connection with the further development of the facial insert have been directed largely at ensuring that site-to-site variations in fracture levels across the facial region are faithfully and repeatably represented. The results obtained from the current series of tests suggests that this objective has been achieved at least in terms of energy levels required to fracture the insert. Only a limited number of reproducibility tests have been completed for the nasion, the maxilla, and the subnasal region. Additional testing in these regions is required to confirm the preliminary findings.

In the testing to date, the impactor employed produces loading conditions which are far more concentrated in terms of force distribution than those generally induced from contact with either the hub or the rim of an automobile steering wheel. The testing program currently in progress at INRETS will provide much needed data on the reliability of the facial insert under more representative loading conditions.

The level of reproducibility presently achieved with the present design (of the order of 8% coefficient of variation), compares favorably with levels of reproducibility achieved with other ATD components subject to certification testing. It must be recognized that in the case of the facial insert, the measured response (ie. fracture) and the associated failure criterion for testing purposes are one and the same. In the case of other ATD components, such as the head, the levels of repeatability or reproducibility are expressed in terms of responses which differ from the actual performance index employed in actual testing. For example, relatively small variations in the acceleration time history of the head can produce large variations in the computed values such as HIC. Such difficulties are avoided with a facial insert.

Evidence suggests that the severity of a facial impact could be assessed with an insert by taking into account the number of insert fragments produced during an impact. Such a relationship, if it exists, would largely be fortuitous as the insert was designed to support a simple pass/fail criterion. However, such a capability could possibly be developed further with relatively minor changes to the design of the insert and the location of the stress raisers.

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