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Development of Face Surrogate for Impact Protection Design for Cyclist

Sanga Monthatipkul, Pio Iovenitti, and Igor Sbarski

***Abstract*—**Bicycle usage for exercise, recreation, and commuting to work in Australia shows that pedal cycling is the fourth most popular activity with 10.6% increase in participants between 2001 and 2007. As with other means of transport, accident and injury becomes common although mandatory bicycle helmet wearing has been introduced. The research aims to develop a face surrogate made of sandwich of rigid foam and rubber sheets to represent human facial bone under blunt impact. The facial surrogate will serve as an important test device for further development of facial-impact protection for cyclist. A test procedure was developed to simulate the energy of impact and record data to evaluate the effect of impact on facial bones. Drop tests were performed to establish a suitable combination of materials. It was found that the sandwich structure of rigid extruded-polystyrene foam (density of 40 kg/m^3 with a pattern of 6-mm-holes), Neoprene rubber sponge, and Abrasaflex rubber backing, had impact characteristics comparable to that of human facial bone. In particular, the foam thickness of 30 mm and 25 mm was found suitable to represent human zygoma (cheekbone) and maxilla (upper-jaw bone), respectively.

***Keywords*—**Facial impact protection, face surrogate, cyclist, accident prevention

I. Introduction

THERE is a growing popularity of bicycle usage for exercise, recreation, and commuting to work. An Australian survey result shows that pedal cycling is the fourth most popular activity with 10.6% increase in participants between 2001 and 2007 [1]. In many countries, bicycling has become an important mean of transportation and the number of bicycle sales has grown far more rapidly than that of the new cars [2], [3]. However, as with other means of transport, accident and injury becomes common although safety regulation and an enactment of mandatory bicycle helmet wearing have been introduced. Currently, helmet is the only protection against HI (Head Injury) including brain damage that has strong potential to cause long-term disability or even death.

Many studies in effectiveness of bicycle helmet agree on wearing helmet to reduce the risk of severe head and brain injury. This is especially true when impact occurs at the helmet. However, for impact at other region – facial impact, the brain may not be effectively protected because current helmet design does not cover the face. Harrison and Shepherd [4] supports this by pointing out that there is an association between HI and facial impact – that is facial skeleton may not absorb enough impact energy to keep the brain safe. Additionally, Thomson and coworkers [5], [6], and Harrison & Shepherd [4] infer that current helmet does not prevent facial injury by showing that the central facial zone (nose, upper lip, and upper-jaw bone) received the most frequent injuries - haematoma, abrasion, laceration, dental injury, and bone fracture. In addition, facial injury may cause loss of function, loss of facial expression due to facial nerve damage, poor cosmesis, and loss of personal identity [7]. Facial fractures, especially in children, can lead to growth disturbances and condylar joint ankylosis [8], [9]. Recovering from facial injury can become complex and costly that eventually contributes to the cost of the community as a whole.

In order to have a meaningful facial-injury assessment, the bio-fidelity of the test device is critical. The current bicycle-helmet-testing headform, intending for impact test on skull, is usually made of hard materials [10] whose dynamic responses are very different to that of human face, specifically, it has many times as much stiffness as that of human facial bone. Thus, impact testing on these materials tends to give unrealistically high impact force that does not seem meaningful, especially, when both of the protective material and facial bone forms a sandwich structure that participates in impact-energy absorption. Conversely, provided that a suitable facial surrogate is used, the generated impact forces and pressures can be meaningfully assessed against the available biomechanical data.

II. Research in Related Field

Currently there are extensive researches in energy absorbing characteristics of a variety of materials and helmet design, but the number of research on facial protection to reduce severe facial injuries specifically for pedal cyclist is very limited or non-existent. The helmet design and relevant Australian standards [10]-[13] aim to reduce head deceleration during impact on the skull without considering impact on the facial region and facial injury prevention

Although a number of researches in skin penetration assessment can be found in forensic sciences and safety glass industry, these studies usually focus on ballistic impact (low mass with high velocity) and laceration caused by impact on

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sharp objects. The subject seems too complex to apply to blunt impact (high mass with low velocity) associated with bicycle-helmet-related testing.

Interestingly, automobile industry has been aware of facial injury assessment and conducting a number of researches on biomechanical studies on facial injury assessment including bone fracture tolerances, impact characteristics of cadaver face, and development of Anthropometric Test Device (ATD). In particular, Perl [14] and Melvin [15] bring up an interesting concept of simple sandwich structure consisting of non-recoverable foam sheet (representing facial bone) layered with soft rubber sheet (representing facial skin). The structure is shown to have dynamic responses comparable to those of human zygoma (cheekbone) and maxilla (upper-jaw bone), which are based on blunt-impact cadaver data published by Allsop [16] and Nyquist [17]. In this case, the "zygoma" includes the crushing and fracturing of facial skin, nose, and left and right cheekbones altogether, whereas the "maxilla" includes those of facial skin and the upper-jaw-bone (below the nasal bone, but above the upper lip).

Perl used rigid polyurethane foam to represent both cheekbone and upper-jaw bone. Foam density was not clearly stated, but it was weakened by hole-pattern to reduce its stiffness in order to comply with Allsop's cadaver data. Fracture force compliance and force-time history were not mentioned.

Melvin used rigid extruded-polystyrene of high-density type (56 kg/m^3) with weakening hole-pattern. The cheekbone data from Allsop and Nyquist were extensively analyzed, and Force-Time response corridor (FT-Corridor) was established along with Force-Deflection response corridor (FD-Corridor). Both stiffness and fracture force were taken into account. However, the high-density type foam is not commonly available and not easy to obtain in small quantities.

III. Aim of Research

The research aims to develop a simple sandwich structure that has comparable dynamic responses to those of human facial bone under blunt impact. The focus is on the central facial zone, in particular, the cheekbone and upper-jaw-bone. The structure – facial surrogate, will serve as an important test device for further development of facial-impact protection for cyclist.

IV. Methodology

Impact Energy

All impact testing was carried out by drop tests. In order to have a meaningful dynamic-response comparison between facial surrogate and cadaver data, the impact energy used by Allsop et al [16] was simulated. This included a steel-cylindrical-bar impactor (cross-sectional radius 11 mm, 7.6 kg) attached to the 1.65-kg aluminium-drop carriage (Fig. 1). Consequently, the total weight of 9.25 kg was to drop from a height of 720 mm onto the investigated facial surrogate. Thus, the total drop energy was approximately 65 Joules (J).

Fig. 1 Aluminium-drop carriage and steel cylindrical impactor

Data Acquisition System

Installed at the drop carriage, a charge accelerometer (B&K 4371) and an amplifier (B&K Type 2635) were used to generate impact signal, which was recorded by an oscilloscope (oscill_1, Tektronix TDS 2024) at the sampling rate range of 25-100 kHz. The oscill_1 stored data directly onto a compact flash (CF) card. The impact velocity was measured by 2 LED detectors placing 100 mm apart and the time was recorded by another oscilloscope (oscill_2, Tektronix TDS 210). A USB card reader was then used to transfer all data from the CF card to a personal computer installed with spreadsheet software that was later used to calculate additional data for analysis of the test results. The drop tower was shown in **Fig. 2**.

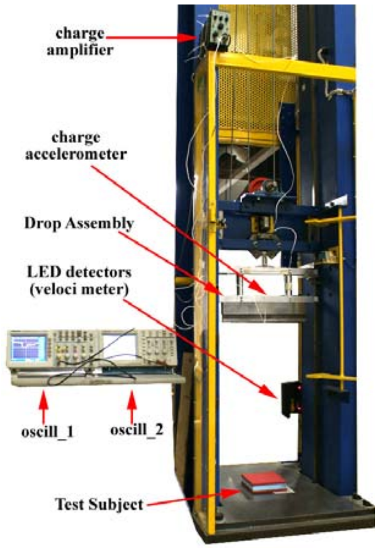


Fig. 2 Drop tower

Validation on equipment accuracy was done by comparing the momentum value of a drop test with that calculated from Newton's Second Law of motion ($\mathbf{F}\cdot dt = m\cdot d\mathbf{v}$). A drop test was done by dropping a mass of 9.25 kg from the height of 720 mm onto a piece of recoverable foam. Comparison was made between the start of impact (measured impact velocity = 3.57 m/s) and the fully crushing of the foam (velocity = 0 m/s). The resultant momentum (in Fig. 3, shaded area = 33.3459 kg·m/s) compared well with the calculated value (9.25 x 3.57 = 33.0225 kg·m/s) resulting in a very small percentage error of 0.98%.

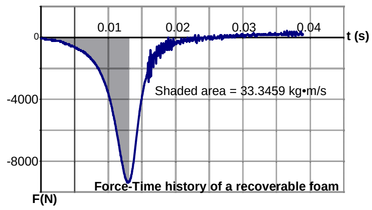


Fig. 3 Momentum change for equipment validation

Test Subject

Sandwich structures of non-recoverable foam sheets and soft rubber sheets were to be tested. Another rubber sheet (rubber backing) was positioned at the bottom layer to prevent damage to the drop assembly. Table I listed candidate materials for facial-surrogate experimentation.

TABLE I
CANDIDATE MATERIALS FOR FACIAL-SURROGATE EXPERIMENTATION

Material	Commercial Name	Properties	Purpose	Supplier
Rigid extruded-polystyrene foam	Styrofoam LB	Density 30 kg/m^3	facial bone	Styrapak Aust Pty Ltd
Rigid extruded-polystyrene foam	Styrofoam RTM	Density 40 kg/m^3	facial bone	Styrapak Aust Pty Ltd
Rigid polyurethane foam	PUR60WIN	Density 60 kg/m^3	facial bone	Australian Urethane & Styrene Pty Ltd
Soft rubber	Abrasaflex	Shore A Durometer hardness of 40	Facial skin, rubber backing	Complete Rubber Pty Ltd
Gum rubber	Pure gum	Shore A Durometer hardness of 40	Facial skin, rubber backing	Complete Rubber Pty Ltd
Sponge rubber	Neoprene sponge	Shore A Durometer hardness of 15	Facial skin, rubber backing	Complete Rubber Pty Ltd

All materials were cut to sizes of 150 x 150 mm (for cheekbone) and 150 x 75 mm (for upper-jaw bone) with various thicknesses (Fig. 4). No adhesive was applied between the skin and bone in order to minimize friction as suggested by Bowman [18]. In addition, patterns of 6-mm-hole (pattern-1 and pattern-2) with different hole-densities (Fig. 5) were to be experimented should all foam types were found too stiff. Fig. 6 listed symbols and descriptions of the test subjects. When they were layered in a sandwich structure, the combination of symbols was used to represent the structure, as illustrated in Fig. 7.

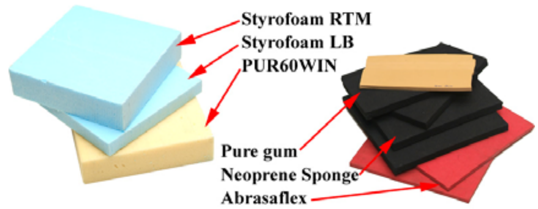


Fig. 4 Materials for test subject

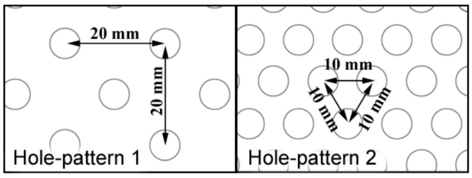


Fig. 5 6mm-hole-pattern

Symbol	Description	Thickness (mm)
	Abrasaflex	5
	Pure Gum	5
	Neoprene Sponge	9.5
LB20	Styrofoam LB	20
LB30	Styrofoam LB	30
RTM20	Styrofoam RTM	20
RTM20PA1	Styrofoam RTM with hole pattern-1	20
RTM20PA2	Styrofoam RTM with hole pattern-2	20
RTM25PA2	Styrofoam RTM with hole pattern-1	25
RTM30PA1	Styrofoam RTM with hole pattern-1	30
RTM30PA2	Styrofoam RTM with hole pattern-2	30
PU60-20	PUR60WIN	20
PU60-30	PUR60WIN	30

Fig. 6 Symbol and description of the test subject

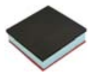
Symbol	Photos	Description
RTM20		Skin layer: 1 sheet of Neoprene Sponge Bone layer: 1 sheet of 20mm-thick RTM foam Rubber backing: 1 sheet of Abrasaflex

Fig. 7 Example of symbol and photo of a sandwich structure

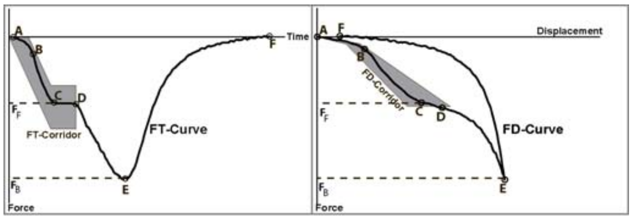


Fig. 8 Expected FT and FD Curve

Dented + fracture Separated Badly crushed

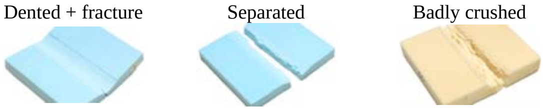


Fig. 9 Samples of foam damage

Test Procedure

For the type of impact test in this study, the expected Force-Time history (FT-Curve) and Force-Displacement curve (FD-Curve) were illustrated in Fig. 8. The main interest of this study was the "rising portion" (AB-line, BC-line, and CD-line), which included the following information:

- Foam Stiffness (or Bone Stiffness) that was represented by the slope of BC-line on the FD-Curve. The unit was in Newton per millimeter (N/mm).

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- Fracture force (F_F), whose unit was in Newton (N)

For cheekbone, the BC-lines (on FT- and FD-Curve) should fall within the corresponding corridors (FT-Corridor and FD-Corridor, Melvin [15]), whose stiffness and F_F ranged 160 – 218 N/mm and 2,260 – 3,710 N, respectively. The FD-Corridor could be offset to the left or right while maintaining its slope since the primary interest was in the Bone Stiffness. Further interpretation of the curve can be found in Table II. For upper-jaw bone, stiffness and F_F should comply with the cadaver data published by Allsop [16], whose stiffness and F_F ranged 80 – 250 N/mm (average 120 N/mm) and 1,000 – 1,800 N, respectively.

Before each test session, test on a piece of recoverable foam was performed 3 times and force-time data were recorded and compared to check equipment readiness. Then, each test was repeated at least 3 times in order to ensure consistent result. The study also expected to visualize the foam damage (Fig. 9) after the impact. The satisfactory BC-line and F_F were to be obtained by experimenting on the following variables:

- Combination of foam and rubber in the sandwich structure
- Foam density (foam types and hole-pattern)
- Rubber hardness
- Foam thickness

TABLE II
INTERPRETATION OF FT- AND FD-CURVE IN FIG. 8

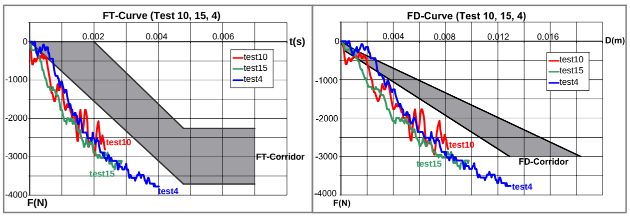
Item on curve	Interpretation
AB-line	Crushing of rubber skin that absorbed very little impact energy resulting in a small slope. For cheekbone, this portion was comparable to the crushing of facial skin and nasal bone altogether. For upper-jaw bone, this portion was comparable to the crushing of facial skin.
BC-line	Crushing of rigid foam and was approximately linear with steep slope. For cheekbone, this portion was comparable to the crushing of both left and right cheekbones.
CD-line	Fully crushing and fracturing of the rigid foam. If the foam was torn and separated, this curve might show irregular shape. On the other hand, if no fracture or small fracture occurred, this curve might not be distinguishable from the BE curve.
DE-line	Bottoming-out of the structure where the remaining impact energy was transferred to the floor (test platform).
EF-line	The impactor bounced back (upwards)
F_F	Fracture Force that initiated foam fracture (comparable to bone fracture).
F_B	Bottom-out Force that might be more or less than the F_F depending on the remaining impact energy.

V. RESULTS AND DISCUSSION

Cheekbone: Series-1 to -6

Series-1: Experimentation on rubber thickness

Series-1 focused on materials that had closest properties to those used in relevant studies [15], [18], [19]. The foam density 40 kg/m^3 (RTM foam) and rubber hardness 40 (Abrasaflex) layering in different combinations were attempted and it was found that increasing the skin thickness tended to increase stiffness, F_F, and severity of the foam damage. However, the effect was not significant. In addition, the missing of the skin crushing (AB-line) implied that the Abrasaflex's hardness might be too high. All tests in this series give unfavourable results – all curves fall outside the corridors indicating that structures are too stiff (Stiffness ranged 255-392 N/mm; F_F ranged 2,700-3,800 N). A set of results was shown in Fig. 10.

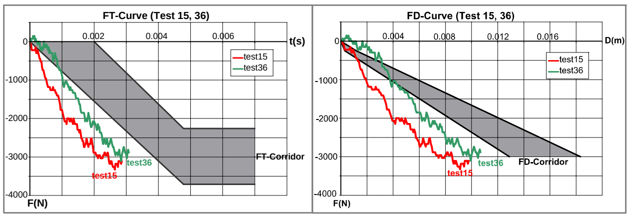


Test	Structure	F_F (N)	Stiffness (N/mm)	Foam damage
10	RTM20	2,800	347	Dented + slight fracture
15	RTM20	3,100	372	Separated
4	RTM20	3,800	392	Separated

Fig. 10 Series-1 results

Series-2: RTM and LB comparison

Since series-1 results suggested that the foam density 40 kg/m^3 was too stiff, testing on a less density foam – Styrofoam LB (density 30 kg/m^3) was attempted in series-2 with Abrasaflex. As expected, the LB structure had less F_F and less stiffness. However, the stiffness is still too high (Fig. 11).

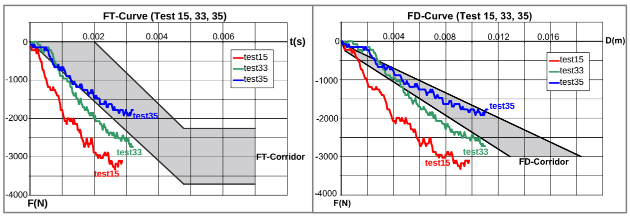


Test	Structure	F_F (N)	Stiffness (N/mm)	Foam damage
15	RTM20	3,100	372	Separated
36	LB20	2,900	298	Separated

Fig. 11 Series-2 results

Series-3: RTM with hole-patterns comparison

The series-2 results indicated that both RTM and LB were too stiff. To further reduce the stiffness, hole patterns (Pattern-1 and Pattern-2 in Fig. 5) were drilled through RTM foam and experimented. Abrasaflex was still used in this series. The result (Fig. 12) showed that pattern-1 reduced F_F and stiffness by 16% and 17%, respectively, whereas pattern-2 did by 39% and 51%. Pattern-2 potentially has acceptable stiffness (182 N/mm) but the F_F is too low.

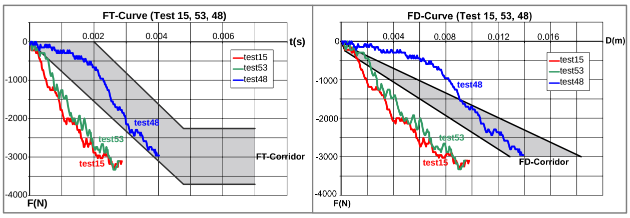


Test	Structure	F_F (N)	Stiffness (N/mm)	Foam damage
15	RTM20	3,100	372	Separated
33	RTM20PA1	2,600	309	Separated
35	RTM20PA2	1,900	182	Separated

Fig. 12 Series-3 results

Series-4: Rubber skin comparison

From series-1 to -3, the missing AB-line implied that the Abrasaflex's hardness might be too high. Series-4 attempted to confirm this by testing on different rubbers – Neoprene sponge, and Pure gum. The RTM was still used in this series. The result (Fig. 13) showed that the Neoprene sponge was soft enough to make AB-line visible, and the FT-Curve complied well with the FT-Corridor. The stiffness was also reduced by about 10%, however, it was still too high – more than 32% higher than the upper-limit (218 N/mm) of the FD-Corridor. Consequently, the Neoprene sponge was to be used as skin for the rest of the tests.

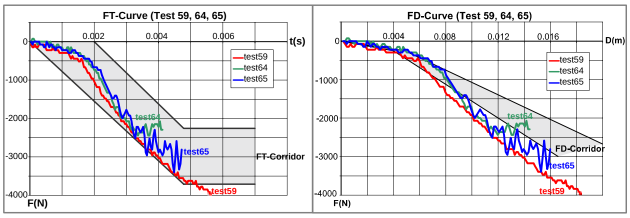


Test	Structure	F_F (N)	Stiffness (N/mm)	Foam damage
15	RTM20	3,100	372	Separated
53	RTM20	3,200	364	Separated
48	RTM20	3,000	321	Dented

Fig. 13 Series-4 results

Series-5: Foam comparison under Neoprene skin

Since the Neoprene skin helped the FT-Corridor compliance and reduced the stiffness of the structure, it was tested again with polyurethane (PUR60WIN) and LB foam in an effort to avoid using hole-pattern. The results (Fig. 14) showed that, although with higher density, PUR60WIN was 21.5% less stiff than RTM. However, it seemed difficult to manage PUR60WIN and to visualize its damage since it was very dusty and easily shattered. Thus, no further test was done on polyurethane foam. Interestingly, the 30-mm-thick LB (test 59) had the stiffness (236 N/mm) close to the upper-limit of the FD-Corridor. Nonetheless, the F_F could not be measured since there was no sign of fracture (BC-line not clearly visible).

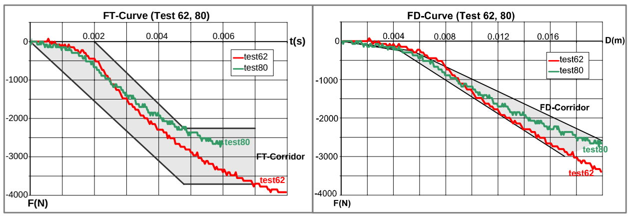


Test	Structure	F_F (N)	Stiffness (N/mm)	Foam damage
59	LB-30	-	236	Dented
64	PU60-20	2,400	252	Badly crushed
65	PU60-30	2,700	254	Badly crushed

Fig. 14 Series-5 results

Series-6: RTM with hole-patterns under Neoprene skin

All results so far suggested that the Neoprene skin and hole-pattern-2 RTM foam were potentially suitable for cheekbone surrogate. Test 35 and 48 were used as benchmarks for further modification. Test 35's fracture force was to be raised by an increase in foam thickness, whereas test 48's stiffness was to be reduced by hole-pattern. As expected, the 30-mm-thick RTM with hole pattern-2 (test 80) gave acceptable result – fracture force (2,700 N) and stiffness (165 N/mm) fell within the corresponding corridors as shown in Fig. 15. Note that it was acceptable to offset the FD-Corridor to the left to accommodate the FD-Curve since the interest was on the stiffness and this study lacked the crushing of the nose feature as opposed to those of the cadaver tests conducted by Allsop [16] and Nyquist [17]. Consequently, this study concluded that the structure of the test 80 was suitable for a cheekbone surrogate, whose photo was shown in Fig. 17.



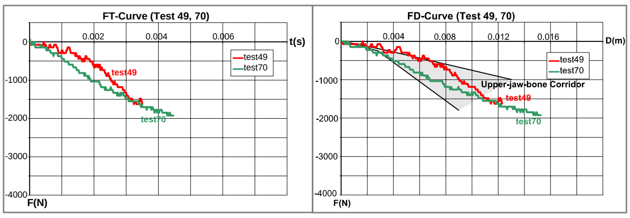
Test	Structure	F_F (N)	Stiffness (N/mm)	Foam damage
62	RTM30PA1	-	194	Dented
80	RTM30PA2	2,700	165	Dented + fracture (almost separated)

Fig. 15 Series-6 results

Upper-jaw bone: Series-7

Series-7: Upper-jaw bone surrogate

Consulting the facial-bone-fracture tolerances [16], [17], [20] revealed that the cheekbone had higher F_F and stiffness than those of the upper-jaw bone, whose surrogate might be obtainable by reducing the foam thickness used in the test 80. Two thicknesses – 20 mm and 25 mm, were tested and it was found that the 25-mm thickness (test 70) gave satisfactory outcome (Fig. 16). The stiffness of 134 N/mm fell well within the FD-Corridor (created from Allsop's data) and was close to the average value (120 N/mm) suggested by Allsop [16]. The fracture force of around 1,900 N, however, was near the higher limit (1,800 N). It was possible to have a more compliant upper-jaw bone surrogate by testing on the foam thickness between 20 – 25 mm, although it might be too trivial to conduct further validation. As a result, the study concluded that the structure of the test 70 was suitable for an upper-jaw bone surrogate (see photo in Fig. 18).



Test	Structure	F_F (N)	Stiffness (N/mm)	Foam damage
49		1,600	204	Separated
70		1,900	134	Separated

Fig. 16 Series-7 results

Cheekbone foam	Cheekbone surrogate	Foam damage after impact (Test 80)

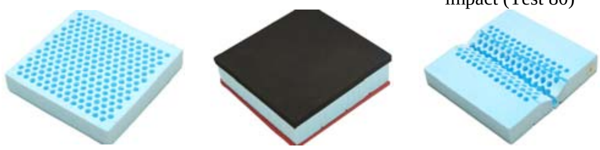


Fig. 17 Cheekbone surrogate structure

Upper-jaw bone foam	Upper-jaw bone surrogate	Foam damage after impact (Test 70)

Fig. 18 Upper-jaw bone surrogate structure

VI. Conclusion

The aim of the research was to develop a simple sandwich structure, referred to as the face surrogate, that has comparable dynamic responses to those of human facial bone under blunt impact. A test procedure was developed to simulate the energy involved in an impact of the face of a cyclist on a hard surface. A drop tower test set up was used to conduct impact tests to establish the face surrogate materials to represent the human face.

The face surrogate consisted of a combination of foam and rubber materials to represent the facial cheekbone and upper-jaw bone. The study found that a common rigid extruded-polystyrene foam sheet (blue Styrofoam) with hole-pattern was suitable to represent cheekbone and upper-jaw bone when used with Neoprene sponge as the skin and Abrasaflex as rubber backing. The surrogates in this study seemed only valid for blunt impact (high mass, low velocity) whose impact area was large enough to cover the hole-pattern.

In conclusion, the results of this study presents an important step as a basis for further investigation into facial protection for cyclist, in particular, when both of the protective material and facial structure form a sandwich structure that participates in impact-energy absorption.

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