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Measurement of Under-Helmet Force Distribution on FMVSS 218 Headform

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ABSTRACT

An experimental method for measuring the under-helmet force distribution on the headform in a helmeted drop test has been developed. This work supports the research in developing a skull fracture criterion for motorcycle helmets. The current Federal Motor Vehicle Safety Standards (FMVSS) 218 for motorcycle helmets is a generalized safety standard based on acceleration peaks and dwell times. FMVSS 218 uses a rigid headform mounted with a unidirectional accelerometer for conducting helmeted drop tests at a specified height. However, the biomechanical basis of FMVSS 218 is not known. Recent work has validated a linear skull fracture criterion (SFC) based on skull strain correlation with fracture data, with the skull strain computed using an anthropomorphic finite element model simulating the head impact process (Vander Vorst, et al. 2003, 2004 AAAM). A direct application of the strain-based SFC to motorcycle helmets will require the simulation of the helmeted head impact, which will be impractical since it requires the modeling of the helmet. However, if the under-helmet load distribution on the headform can be measured during the FMVSS 218 test and used as inputs to the finite element model, skull strain can be computed. This approach preserves the FMVSS 218 test procedure without the need to model the helmet. A method has been developed to measure the force distribution on the headform using an array of Tekscan's FlexiForce pressure sensors attached to the FMVSS 218 headform. FlexiForce sensors have high accuracy for measuring the normal load; however, they are subjected to shear-induced errors. A technique has been developed to minimize the shear error seen by FlexiForce sensors, giving an accurate force-history profile over the entire headform. Data validating the FlexiForce sensor performance on the headform are presented. An algorithm for mapping the FlexiForce data as pressure contours on the headform for finite element model simulations was developed and preliminary finite element model simulations using helmeted headform drop test data as inputs were conducted.

INTRODUCTION

The National Highway Traffic Safety Administration (NHTSA) of the US Department of Transportation (DOT) estimates that motorcycle helmets saved 500 lives in 1998 and that 307 more could have been saved if all motorcyclists had worn helmets. Unfortunately in 2004, 4008 motorcyclists were killed in accidents and an additional 76,000 were injured. The number of motorcycle fatalities has been increasing steadily since 1996 (NHTSA, 2004). DOT introduced standards "to reduce deaths and injuries to motorcyclists and other motor vehicle users resulting from head impacts" (U.S. Department of Transportation, 2003).

Section 218 of the Federal Motor Vehicle Safety Standards (FMVSS) is the current U.S. standard for regulating motorcycle helmets. FMVSS 218 prescribes a series of tests that a helmet must pass in order to meet DOT approval (US Code of Federal Regulations, 2004) and establishes requirements for impact attenuation, penetration, and retention. The purpose of the impact attenuation requirement is to protect the head from impact shock. The penetration requirement establishes the ability of the helmet shell to resist penetration of sharp objects. The purpose of retention requirement is to keep the helmet on the head during an accident. The primary protection against head injury in nonpenetrating head impacts is offered by the impact attenuation requirement.

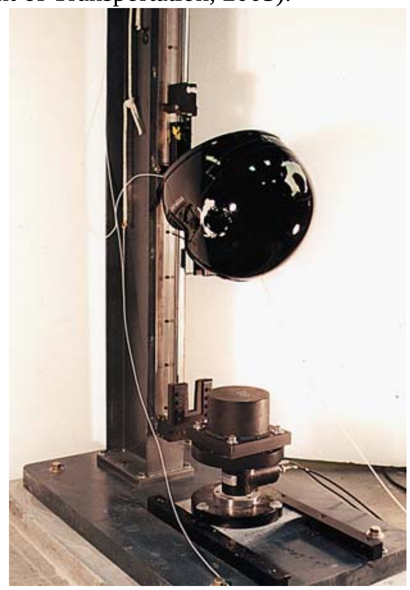


Figure 1: Helmet test drop tower.

In an FMVSS 218 attenuation test, the helmet is fitted to a metallic headform that is instrumented with a single linear accelerometer. The headform is then attached to a vertical monorail guided drop assembly, Figure 1. The standard prescribes headforms in several sizes to fit a range of helmets. The vertical acceleration of the headform is measured during the drop of the headform/helmet combination onto a metallic anvil. Tests against both flat and hemispherical anvil are required. For each helmet model and size, a total of thirty-two such drops are conducted.

Four helmets are used, each with a different environmental pre-conditioning: ambient, hot, cold and wet. Each of the four helmets is struck 8 times: two hits at each of four impact locations. The testing laboratory selects the impact locations, under the constraint that each location be separated by at least 60 degrees from the other three. To pass the impact attenuation requirement of FMVSS 218, the criteria,

$$A_{max} \leq 400 \text{ g},$$
$$T_{150g} \leq 4 \text{ ms, and}$$
$$T_{200g} \leq 2 \text{ ms,}$$

must be satisfied for each of the 32 drops. A_{max} is the peak acceleration. The dwell times, T_{150g} and T_{200g}, are defined as the cumulative time at which the acceleration vs time curve exceeds 150 g and 200 g, respectively. A graphical interpretation of each of the above three attenuation criteria is given in Figure 2.

The FMVSS 218 criteria are based on the 1966 optional swing-away test of the American National Standards Institute (ANSI) Standard, Z90.1 (Preamble to CFR, 1973). In 1979 ANSI eliminated the swing-away test in favor of a fixed anvil drop test and omitted the dwell time requirements in favor of a single 300 g peak acceleration criterion (ANSI Supplement Z90.1b). FMVSS 218 retains the original dwell time and peak acceleration requirements of the 1966 ANSI standard, but requires a vertical guided drop onto a fixed anvil. The ANSI test conditions are also different than those of FMVSS 218. In ANSI Z90.1b, the first hit is at 6.9 m/s and the second is at 6.0 m/s for both anvils. FMVSS 218 requires that both hits are at 6.0 m/s against the flat anvil and both are at 5.2 m/s against the hemispherical one. In addition, ANSI Z90.1 requires a single 6.9 m/s hit against a 6.3 mm edge anvil, a requirement not included in FMVSS 218. NHTSA originally intended that "the performance levels for the impact attenuation requirement be upgraded to that of the Head Injury Criterion (HIC) required by Motor Vehicle Safety Standard No. 208" (Preamble to CFR, 1973).

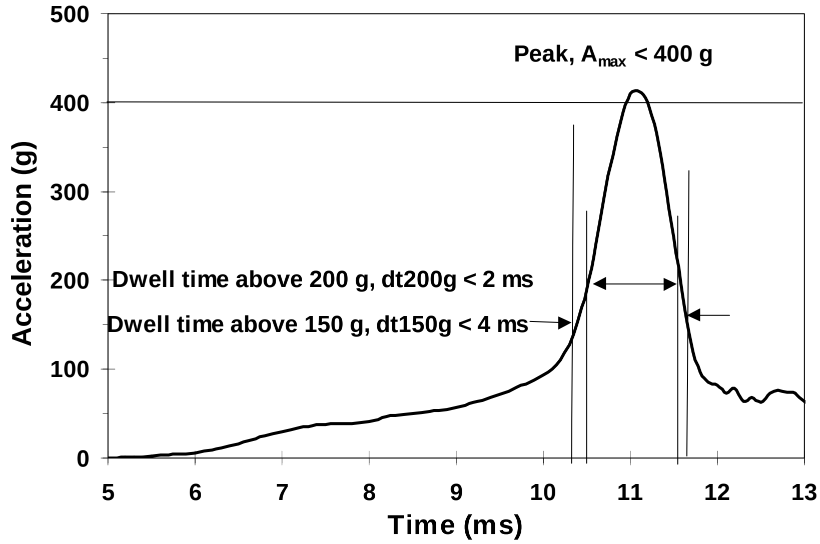


Figure 2: FMVSS 218 impact attenuation criteria.

The biomechanical basis of the various helmet criteria are not known. However, there are many methods for predicting head injury. The NHTSA SIMon finite element head model (Takhounts et al., 2003b) and the Wayne State University head injury model (Zhang et al., 2001) were developed to investigate acceleration induced traumatic brain injury (TBI). Both models were able to predict varying injury severities in real-world cases. Vander Vorst (Vander Vorst et al., 2003; Vander Vorst and Chan, 2006) developed a biomechanically-based linear skull fracture criteria called skull fracture correlate (SFC). SFC is the average headform acceleration over the HIC15 time interval. SFC was validated using post mortem human subjects (PMHS) data from the historical Hodgson and Thomas tests (1971, 1973) and recent data from Medical College of Wisconsin. The PMHS data was correlated with Hybrid-III headform tests and finite element model simulations. The first work (2003) demonstrated that the skull strain calculated by a finite element model (FEM), the fracture data and SFC all correlated well with one another with well defined confidence bands, hence validating the biofidelity of SFC. The following work (2004) expanded the validity of SFC to lateral impact using more newly obtained PMHS data.

Previous exploratory results show that the FMVSS 218 risk factors of 150 and 200 g dwell times are poor correlates with skull strain while the peak accelerations are good correlates (Vander Vorst and Chan, 2006). These results come from a series of simulations of bare headform drops onto flat samples of a material typically used in helmet liners. The headforms reached accelerations comparable to helmeted head drops. The favorable performance of the surface pressure sensor methodology suggested that it can be used for other types of head impact tests for measuring surface pressures during impact, namely helmeted headform impact attenuation tests.

The objective of this research is to evaluate the biofidelity of helmet criteria using validated skull fracture criteria. The approach used to meet this objective is:

1. Develop instrumentation to measure headform surface pressure during drop tests.
2. Predict helmeted skull fracture with FEM simulations.
3. Evaluate FMVSS 218 against predicted skull strain.

This paper reports results of the development and validation of instrumentation to measure the pressure-history on the DOT headform and verification of the computational procedure using headform pressure data as input.

METHODS

To determine the biofidelity of the motorcycle helmet criteria, each of the kinematic risk factors (peak acceleration, 150 g dwell time, and 200 g dwell time) were correlated with skull strain as computed from an anatomical finite element model. This was accomplished through three stages: 1) Development of instrumentation to measure the pressure contour on the headform during the impact attenuation test; 2) Mapping of impact attenuation pressure data from the headform to the finite element skull fracture model and calculation of peak skull strain; and 3) Statistical analysis to determine correlation between skull fracture and FMVSS 218 kinematic risk factors. The statistical analysis will be performed at a later time after more head drop data has been gathered.

Instrumentation

To predict the efficacy of a particular helmet using an anatomical model purely from finite element calculations would require a validated structural model of the helmet. This task is impractical for each helmet model to be tested. However, if during a drop test, the pressure applied by the helmet to the headform were measured, and this pressure applied to the anatomical finite element model to compute the peak strain, then the probability of skull fracture could be predicted for the specific helmet. To accomplish this, instrumentation to measure the pressure-history on the headform was developed.

Tekscan's Flexiforce sensors were chosen to measure the interfacial pressure between the helmet liner and the headform. Extensive tests were conducted to characterize the FlexiForce force sensors. The sensors were found to have acceptable drift, repeatability, and linearity when a normal force was applied. A drop in signal voltage was observed when the sensor was subjected to shear force. This negative voltage was proportional to the normal force acting on the sensor and was repeatable.

During the impact attenuation test, the FlexiForce sensors attached to the headform would be subjected to shear forces, causing error in the experimental data. In order to get the true force from the sensors, the shear force seen by sensor would either have to be eliminated or accounted for mathematically. It was decided to solve this by lowering the coefficient of friction between the sensor and the helmet/target, thereby reducing the shear force.

A series of tests were conducted to find the best method to remove the shear error. Tests were performed by attaching a sensor to a load cell, then applying a static weight to it. A mallet was used to strike the weight causing it to move across the sensor. Various techniques for reducing shear error were tried, including applying grease, petroleum jelly, and Teflon strips. The setup for this experiment is shown in Figure 3. It was found that placing a thin layer of petroleum jelly on the sensor, then covering it with two layers 0.005 inch thick Teflon strips reduced the signal error to near zero.

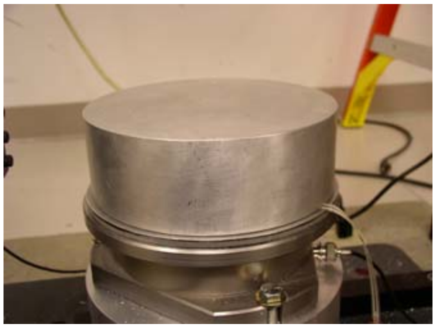


Figure 3: Setup for measuring FlexiForce shear error.

Once the best method for reducing shear error was found, an array of sensors was glued to the crown of a FMVSS 218 medium size headform. The initial array included 21-sensors in a 3x7 pattern. After the first set of experiments, two more outside rows of 3 sensors each were added, forming a 27-sensors cross pattern. These final 6 sensors were added to complete the sensor coverage on the sides of the head. The sensors were attached using silicon adhesive sealant then the petroleum jelly and Teflon strips were applied. The fully treated and instrumented headform is shown in Figure 4.

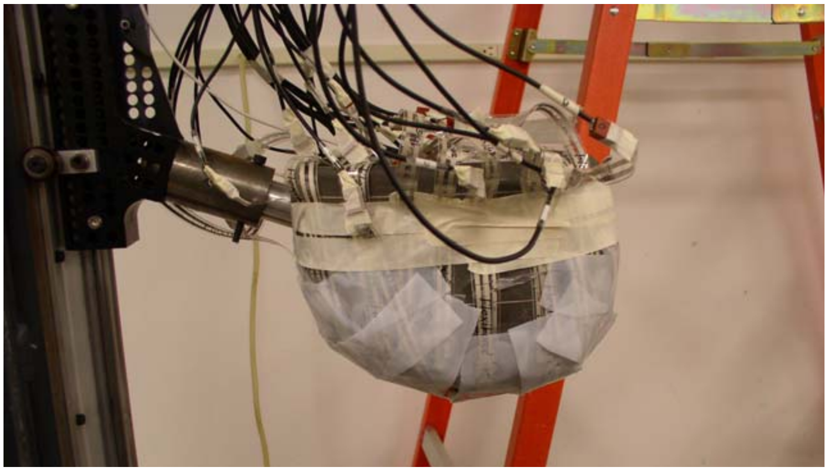


Figure 4: Fully instrumented headform.

Impact Attenuation Tests

Nine drop tests were conducted to test the instrumentation setup and to gather input data for the finite element model. Impact attenuation tests were performed according to specifications given in FMVSS 218. The helmets were dropped against a flat anvil at a speed of 6 m/sec. In each test, the helmet was dropped so the crown of the helmet impacted the anvil. This was done because the current setup of the sensor array had the best coverage when the impact occurred on the crown.

The acceleration of the headform was measured using a single axis accelerometer placed at the center of gravity of the headform. The anvil was bolted to a Kistler 925M113 load cell connected to a Kistler 5118B2 power supply / coupler. Headform acceleration, load cell force, and FlexiForce pressure data was taken by LabView version 7.0 on a BSI FieldGo Pentium 4 computer.

Two helmets were used in the tests, Helmet A and Helmet B. The Helmet A had a continuous lining, while the Helmet B lining had holes in it. The two helmets can be seen in Figure 5. For the initial tests, each helmet was dropped multiple times. This was done to save helmets for the actual helmet tests to be done at a later time. The data gathered using these two helmets was still viable for validation purposes.

Helmet A

Helmet B

Figure 5: Helmets used in Impact Attenuation Tests.

The contact area between the headform and the helmet was assumed to be the area between the reference plane of the headform and its apex. To compensate for the much smaller area covered by the FlexiForce sensors, each sensor is assumed to cover its own area plus a portion of the area around it. This area was calculated by taking the original sensor area times the ratio of the impact area to the total sensor area. This modified sensor area will be used in all calculations of total measured force.

Skull Fracture Finite Element Model

The maximum principal skull strain was calculated for each impact attenuation test using a refinement of the anthropomorphic, medical imaging based, finite element model of Vander Vorst et al. (2004), Figure 6. The baseline model was composed of 24,000 elements and resolved the outer and inner tables, diploe, brain, scalp, and face. The mass of the baseline model was 4.54 kg. The skull components were modeled using fully integrated thick shells and the brain, scalp, and face were modeled with fully integrated bricks. Since this model was based on CT imaging of a PMHS, the skull shape and thickness are anatomically correct. The thickness of the compact skull tables was set to be 1 mm uniformly, since they were too thin to be resolved from the CT scan. The 1-mm value was based on measurements of photographic cross-sections from the Visible Man project (National Library of Medicine, 2000). The properties of the biological materials were taken from the open literature. The elastic properties of compact skull bone were from Wood (1971). Diploe was taken to be linear elastic (Khalil and Hubbard, 1977). The linear viscoelastic properties of the brain were from Takhounts et al. (2003a). Scalp was assumed to be viscoelastic with properties calibrated by Vander Vorst et al. (2003). All finite element model simulations were performed using Version 9.70 of LS-Dyna3d software [Livermore Software Technology Corporation, 2003].

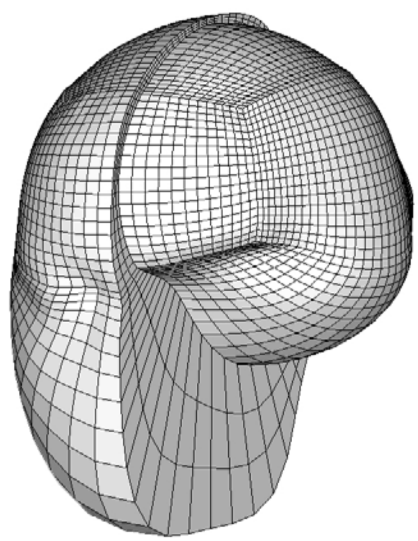


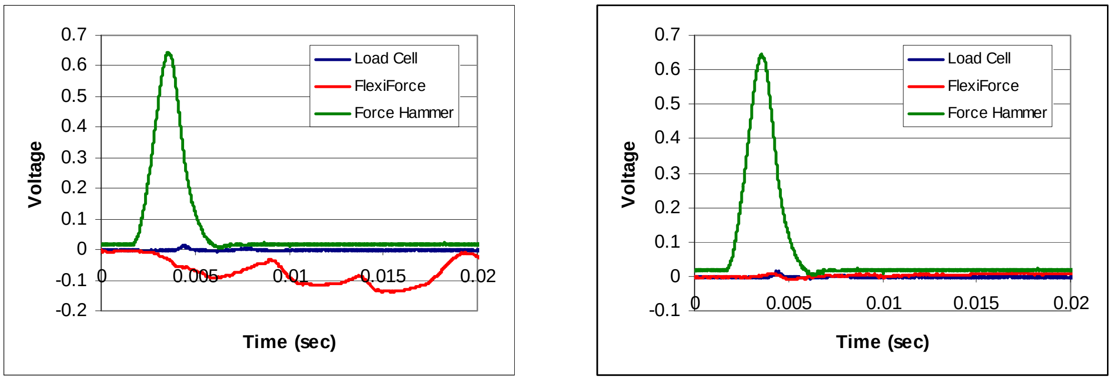
Figure 6: Anthropomorphic CT-based head model showing skull face and brain.

The sensor locations on the headform were mapped directly to the scalp elements of the skull fracture FEM. For example, if the headform had a line of seven sensors equally spaced from the anterior to posterior reference line, the location of the reference plane on the skull fracture FEM would be determined and the seven sensor locations would be equality spaced similar to the headform. The area of applied pressure for each sensor on the FEM was the same as the modified area calculated from the ratio of contact areas. The maximum strain in either the inner or outer table of the skull would be found and used in the statistical analysis.

RESULTS

Instrumentation

Applying only a shear force to a FlexiForce sensor gave a false signal as seen in Figure 7a. In this figure, a force hammer was used to hit a weight resting on the FlexiForce sensor to cause horizontal movement (Figure 3). The bottom load cell signal shows that no vertical force was applied to the FlexiForce sensor. The FlexiForce sensor reports a negative signal when subjected to shear force. It was found that using a thin layer of petroleum jelly on the sensor then covering it with two strips of 0.005 inch thick Teflon, the FlexiForce shear error was reduced to near zero (Figure 7b). Further investigation showed that the Teflon treatment did not affect the sensor output when normal force was applied to the sensor.



(a) FlexiForce with shear error **(b) FlexiForce with no shear error**

Figure 7: Validation of shear error elimination method.

To confirm this technique would work on sensors attached to the headform, helmeted drops were performed using an unmodified headform, a headform with a thick layer of petroleum jelly, and the Teflon/petroleum jelly modified headform. Five drops of each type were conducted. The unmodified headform showed a maximum total force of 1.48 N, the jelly coated headform was 1.79 N, and the maximum force of the Teflon treated headform was 1.98 N. There was a significant difference between the maximum force of the untreated and jelly treated headform and the untreated and Teflon treated headforms, p=0.015 and p=0.0004, respectively (Figure 8).

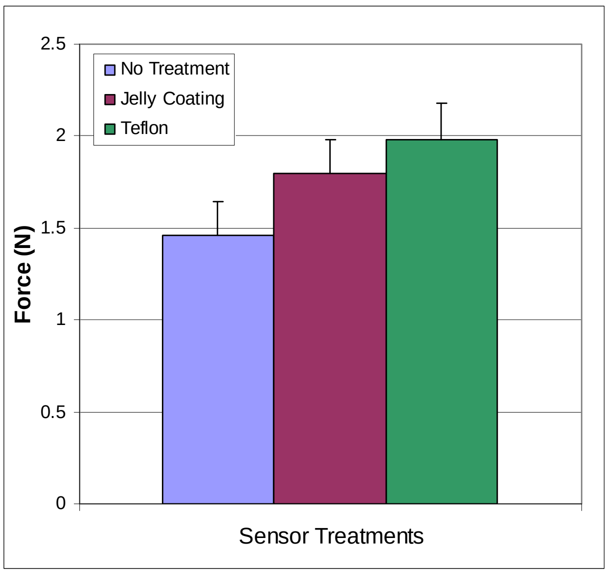
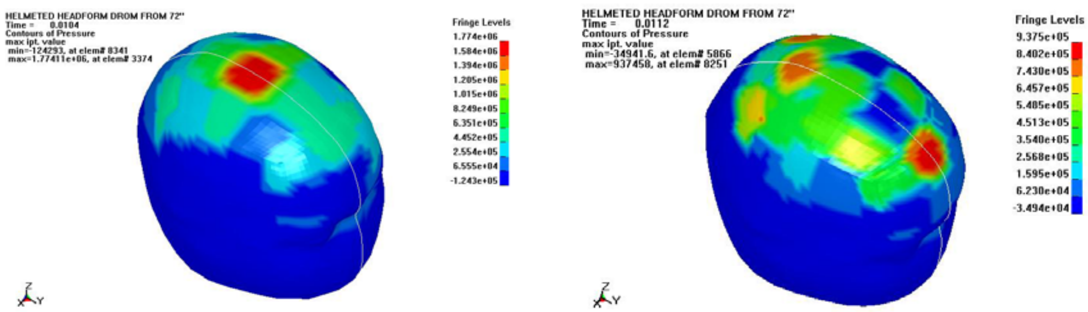


Figure 8: Comparison of maximum force from untreated and treated helmeted drop tests.

Impact Attenuation Tests

A total of nine helmeted drops were performed. The first five tests were conducted on Helmet A with a 21-sensor FlexiForce array. The remaining four tests were performed on Helmet B with a 27-sensor FlexiForce array. Each helmet had a different pressure distribution pattern. Helmet A showed peak pressure on the crown of the headform, while Helmet B showed peak pressure at the anterior and posterior curves of the head. Helmet B showed some sensors with no change of signal. The pressure distribution for each helmet is shown in Figure 9.

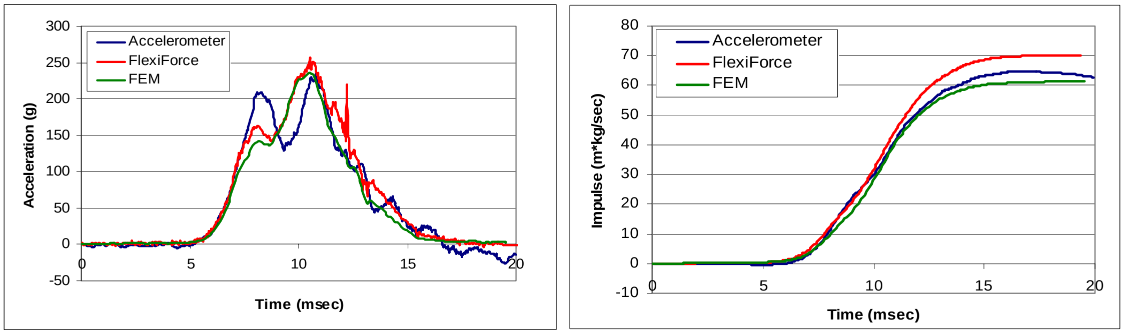


Helmet A **Helmet B**

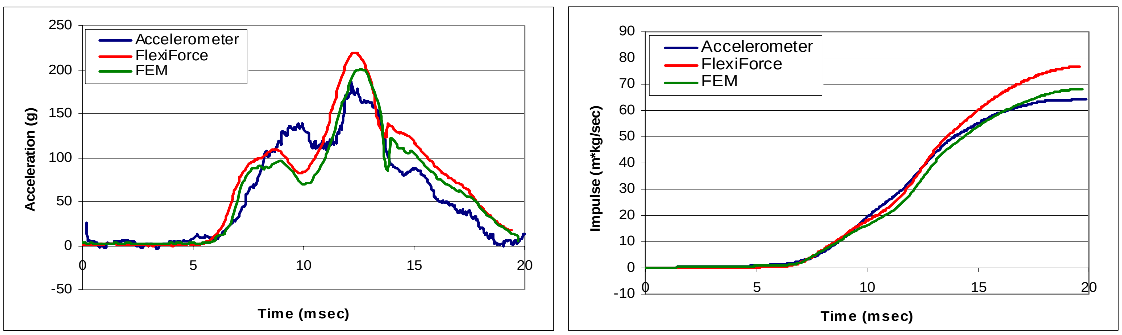
Figure 9: Headform pressure distribution data.

The FlexiForce data was validated against the headform accelerometer data. The total vertical component of the force from the FlexiForce sensors was computed and divided by the weight of the head to get the acceleration. Figure 10 shows the comparison of FlexiForce data and accelerometer data. The impulse of the headform during the impact attenuation test was also calculated. If the impulse between the accelerometer data and the FlexiForce data were not equal, a factor was multiplied to the FlexiForce pressures to preserve the accelerometer measured impulse at the peak acceleration. The impulse factor ranged from 0.92 to 1.25 with an average value of 1.15. This factor was applied to the pressures at each sensor and this impulse preserved pressure was used for the finite element calculations.

Head Acceleration **Head Impulse**

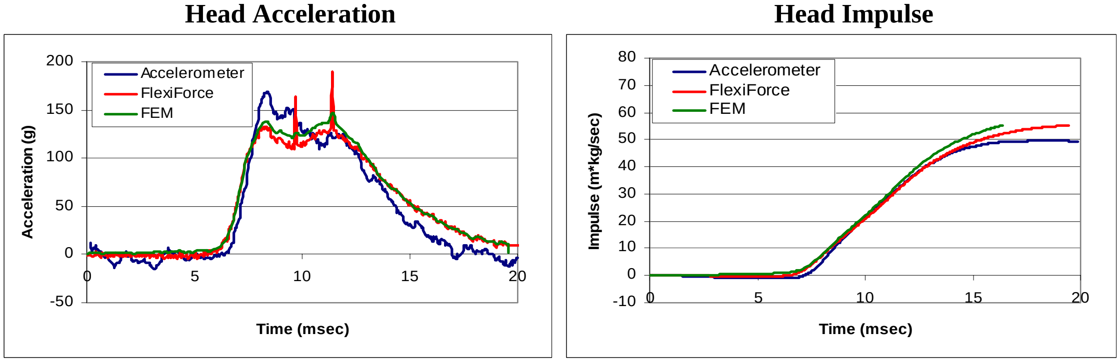


(a) Drop 21-3

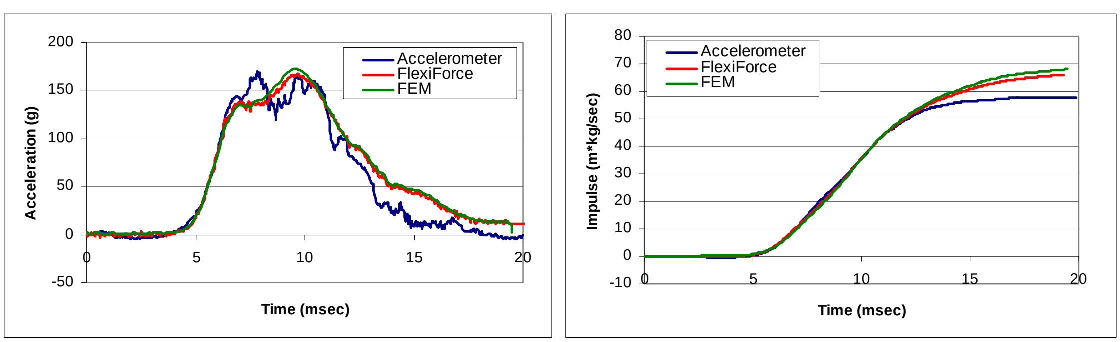


(b) Drop 21-5

Head Acceleration **Head Impulse**



(c) Drop 27-1



(d) Drop 27-4

Figure 10: Head Acceleration and Impulse Data Comparison.

Skull Fracture Finite Element Model

A finite element model simulation was performed for each impact attenuation test using the pressure data from the experiment. The simulation was run to 20 msec. From these simulations, the maximum principle strain in the inner and outer tables was determined. The maximum principle strain for each drop is shown in Table 1.

Table 1. Maximum Principle Strain.

Test ID	Maximum Strain (%)
21-1	0.112
21-2	0.122
21-3	0.125
21-5	0.105
21-7	0.104
27-1	0.077
27-2	0.110
27-3	0.113
27-4	0.090

A time history of the pressure applied to the scalp with its accompanying time history of the principle strain in the skull is shown in Figures 11 and 12. The FEM head acceleration and head impulse closely matched the experimental results (Figure 10). In each case, the maximum principle strain is seen away from the impact location. The maximum strain occurs near the sphenoid and temporal bone interface. A time history plot of the strain at the location of maximum strain is shown in Figure 13.

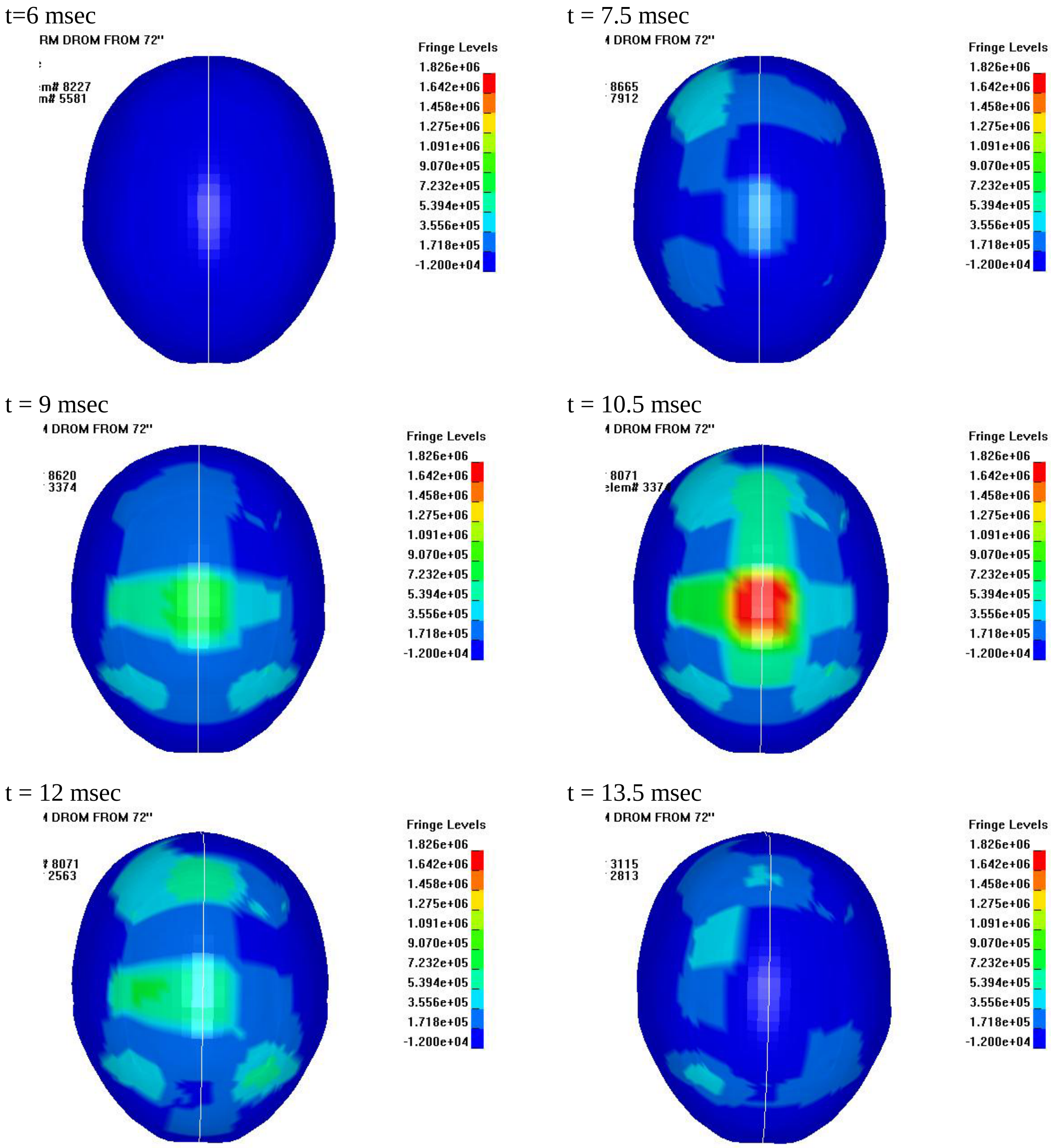


Figure 11: Time history contour of the pressure applied to the scalp (Crown view), test 21-1.

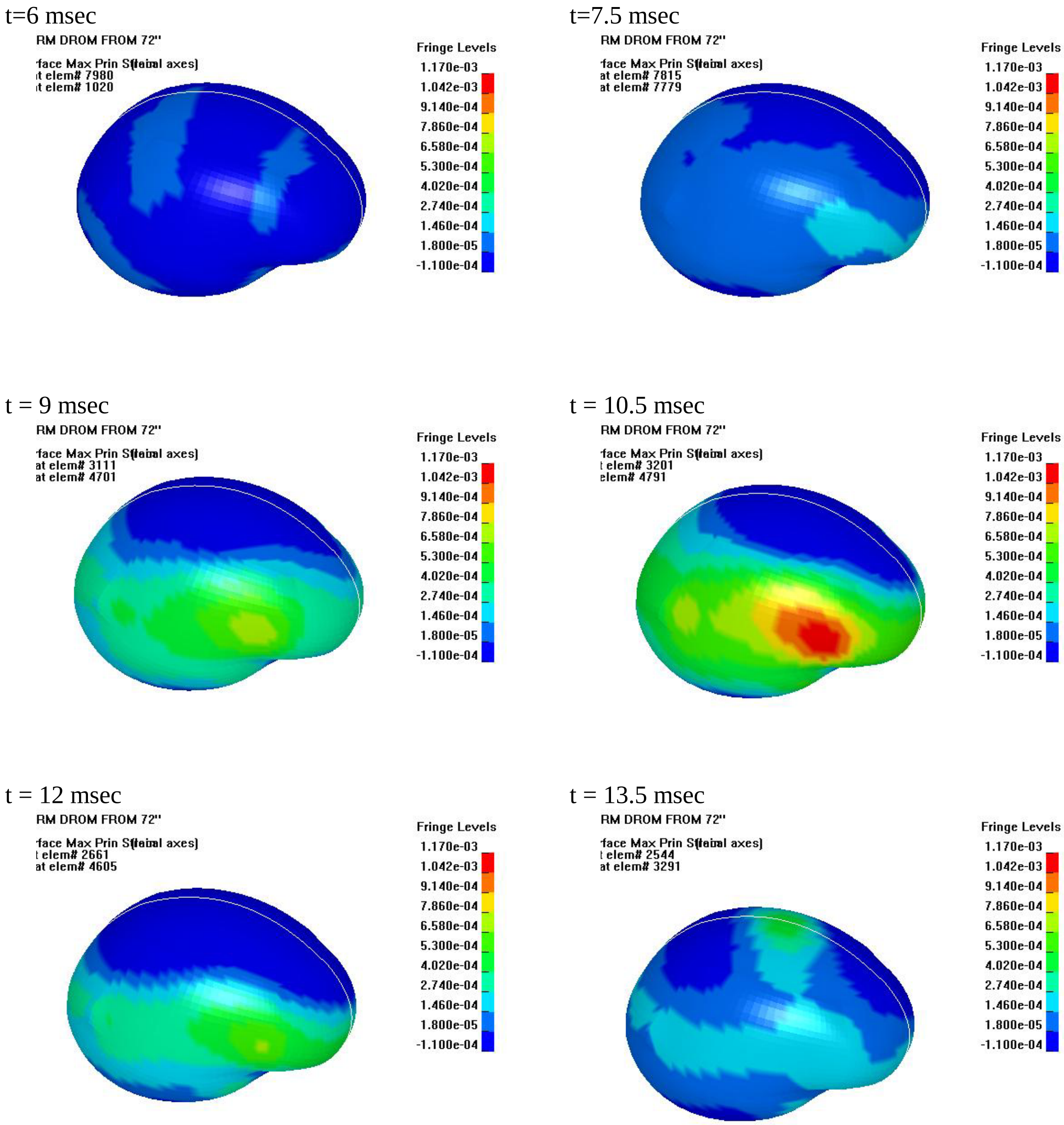


Figure 12: Time history contour of the maximum principle strain in the outer table of the skull (Side view), test 21-1.

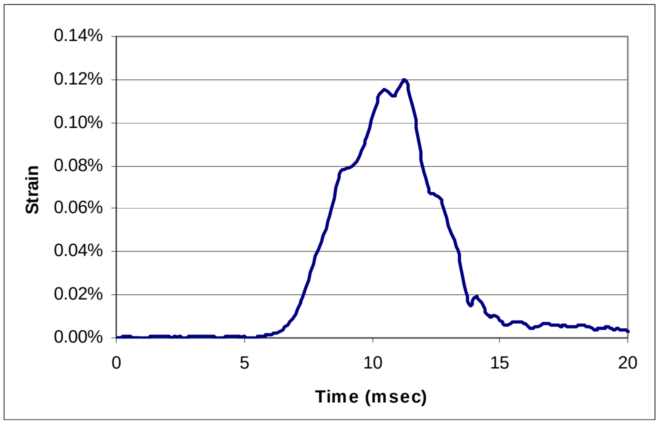


Figure 13: Time history plot of the strain at location of maximum strain, test 21-1.

DISCUSSION

The Teflon treatment on the FlexiForce sensors was able to reduce any shear error and allowed results from the FlexiForce sensors to match closely with the accelerometer and load cell. During the drop test, it was found that the different linings of the helmets affected the sensor readings. It is suspected that the holes in the Helmet B lining disrupted the contact between the helmet and the sensors on the headform. To counteract this, a denser 46 sensor array will be used.

The maximum principle strain occurred away from the impact location. This can be explained by considering the helmet acts to transfer the impact energy across the whole of the skull, not at a single location seen in focal fractures. Historical studies by Messerer (Yoganandan and Pintar, 2004) demonstrated that by compressive loading of the skull in one direction resulted in tensile deformations in the other perpendicular direction. Fractures were associated with the least out-bending curvature.

The limitation of this work is that the impacts studied were from helmets that were dropped multiple times at the same location. The sensor array on the headform might not have been large or dense enough to capture the total pressure distribution on the headform. In future work, these techniques will be used to fully establish the biofidelity of helmet standards. The sensor array will be expanded to 46 sensors. Drop tests will be conducted using new helmets, impacting at different locations according to FMVSS 218. Also a much larger sample size will be used for statistical analysis, up to a total of 20 helmets with 8 tests each.

CONCLUSIONS

Instrumentation and experimental protocol was developed to measure the contact force on a FMVSS 218 headform during an impact attenuation test. A technique for mapping experimental force data from the headform to a FEM skull was developed. The FlexiForce data and computational results were validated against the headform data. This methodology developed is being applied to validate the biofidelity of motorcycle helmet criteria.

ACKNOWLEDGEMENTS

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The views and opinions expressed in this paper are those of the authors and not those of the National Highway Traffic Safety Administration.

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DISCUSSION

PAPER: **Measurement of Under-Helmet Force Distribution on FMVSS 218 Headform.**

PRESENTER: ***Paul Rigby, L-3 Communications/Jaycor***

QUESTION: *Dan Thomas*

How do you validate item 2 up there: "Surface data were successfully used as inputs to FEM simulation to calculate skull strength?" You're using some sort of mechanical device to make measurements on it and then you put it into a model, and then you calculate skull strength?

ANSWER: Yes.

Q: And, you think that represents what would happen to a human skull if their head was inside that helmet?

A: Well, the FEM we're using has been validated. It's been published a number of times.

Q: How is it validated?

A: It's validated with Hodgson and Thomas data, NCW impact data, skull fracture impact data and--

Q: From cadaveric experiments?

A: Yes.

Q: But, how do you transmit from this headform over and make inputs for that?

A: Well we know--

Q: I don't see—I don't see how it works.

A: We know where on the skull—We know what the pressure is at certain points on the skull and by putting that over on the FEM as our inputs, we can—

Q: Suppose I use a different headform and instrument it the same way. Can I get the same results on the estimates of skull strain?

A: If you use a different headform, yeah. All it is—You just map the headform where the sensors are on the headform over to the FEM model. It might have a different—

Q: And all this is independent of whatever headform I use?

A: Yes. Yes, it is.

Q: Okay.

Q: *Guy Nusholtz, Daimler Chrysler*

You made the comment that one of the problems that you had was in modeling the helmets and that you couldn't do it because that was very difficult and the implication is: It's easier to model a head than it is to actually model a helmet. [chuckle]

A: Yeah, well that's because we already had the head, the head FEM already—

Q: I think there's problems there. With respect to the model: Have you attempted to try and vary things like skull thickness within the range that we typically see? You're making this long chain of: You got the headform you measure pressure, you don't really know whether the pressure you're going to see on the model actually represents the pressure if it was a head, and then once you put that strain on, you don't know because you've got different thicknesses and different properties and different people.

A: Yeah.

Q: What you might want to do to resolve those particular items is try and look at a range of what might be possible, and then what you get is you'll get an uncertainty or a confidence level as to how good your results are.

A: Okay. Thank you.

Q: And then when you go to your actual biomechanics, you'll have some statistical justification as opposed to trying to do it in a deterministic way where you say, "The head is exactly like the human head and then the model is exactly like the—"

A: Okay.

Q: So that might address your problem. Your results that you've gotten now are probably somewhere in that range, but precisely what that range is and what it looks like is not determined.

A: Okay. Yeah. Just so—I forgot to mention: The FEM we are using, it was created using CT scan data.

Q: Okay.

A: It's from a couple papers from Michael Vander Vorst and it's sponsored by NHTSA. It's been going on for about two, three or four years—our skull strain fracture model.

Q: A point I'll make: I've done quite a few autopsies and skull thicknesses vary quite a bit. I've gone from about 1.2 millimeters to almost 1.2 centimeters. So you've almost got a factor of 10, at least in the subjects that I've seen.

A: Uh huh. Okay.

Q: Okay. So, there could be quite a bit of difference in the strains that you see. Obviously for this type of thing, you're trying to figure out what your average strain would be. You don't want to say, well, what's the extremes, but this way it just gives you a range.