

Fracture Modeling Inputs for a Human Body Model via Inference from a Risk Curve: Application for Skull Fracture Potential

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ABSTRACT

A three-step process was developed to estimate fracture criteria for a human body model. The process was illustrated via example wherein skull fracture criteria were estimated for the Ford Human Body Model (FHBm) - a finite element model of a mid-sized human male. The studied loading condition was anterior-to-posterior, blunt (circular/planar) cylinder impact to the frontal bone. In Step 1, a conditional reference risk curve was derived via statistical analysis of the tests involving fractures in a recently-reported dataset (Cormier et al. 2011a). Therein, Cormier et al. authors reported results for anterior-to-posterior dynamic loading of the frontal bone of rigidly-supported heads of male post mortem human subjects, and fracture forces were measured in 22 cases. In Step 2, the FHBm head was used to conduct some underlying model validations relative to the Cormier tests. The model-based *Force-at-Peak Stress* was found to approximate the test-based *Fracture Force*. In Step 3, models of Cormier's setup with assumed fracture criteria were made such that they produced the experimentally-observed spread of fracture forces. Moreover, iteration was conducted on the model-based stress and strain fracture criteria (viz., σ_{ult} and ϵ_{ult}). The outcomes were analyzed via the same statistical approach applied in Step 1, and subject to $\sigma_{ult} \approx 125$ MPa and $\epsilon_{ult} \approx 2.2\%$, the model-based risk curve nearly identically recovered the reference test-based risk curve (i.e., $P_{FE-based} \approx 1.03 P_{reference}$ and $R^2=0.99$).

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INTRODUCTION

The ultimate goal of human body modeling in vehicle crash research is to predict injury potential for a given load case. Progress has been steady towards that goal, moving from one- and two-dimensional lumped-mass models of various body regions in the early 1960's to whole-body three-dimensional finite element models in the early 2000's. With the advent of finite element approximations (FE), geometries have become more realistically represented. For example, hundreds of thousands of elements are used in present-day whole-body models. Each of those elements is assigned a material model to represent biomechanical strength. Material models accordingly get us closer to the aforementioned goal. (See Yang et al. 2006 for a review of human body models.)

In contemporary finite element codes, fracture potential can be roughly approximated via the material model. For example, in Radioss, failure stress and failure strain can be prescribed, and those failure criteria approximate fracture potential. However, such fracture modeling presents

challenges, as failure stress and failure strain are often not measured in tests of specimens/post mortem human subjects (PMHS). Moreover, when these fracture data are estimated, they often demonstrate considerable variation. For example, Kennedy et al. (2004) reported failure strains of 0.3 - 2.0% for the femur; Kemper et al. (2005, 2007) reported 0.2 - 6.6% for the ribs.

Yet, risk curves incorporate human variation. Specifically, a risk curve relates a predictor variable to the probability of sustaining injury via statistical or cross-correlation methods. (See Mertz et al. 2003 for a comprehensive review of various risk curves for various body regions.)

The objective of the present study was to use iteration on model-based fracture criteria to acceptably recover a test-based risk curve. This approach will be applied via a three-step process for the skull in the Ford Human Body Model (FHBm) - a finite element model of a mid-sized human male. In Step 1, a conditional reference risk curve will be derived via statistical analysis of the tests involving fractures in a recently-reported dataset involving blunt cylindrical impact to the frontal bone of rigidly-supported heads of male PMHS. In Step 2, the head of the FHBm will be used to conduct some underlying model validations relative to the underlying PMHS tests and to assess which model-based measures of force approximate test-based fracture force. In Step 3, models of the experimental setup with assumed fracture criteria were made such that they produced the experimentally-observed spread of fracture forces. Moreover, iteration was conducted on the model-based stress and strain fracture criteria (viz., σ_{ult} and ϵ_{ult}). The outcomes were analyzed via the same statistical approach applied in Step 1. The introduction, analysis, and results pertaining to each step will be self-contained in the following sections.

STEP 1: DERIVATION OF REFERENCE RISK CURVE

Risk curves are often derived from statistical analyses of datasets involving post mortem human subjects (PMHS). In the present study, we considered the PMHS dataset developed by Cormier et al. (2011a). Therein, the authors reported results for anterior-to-posterior dynamic loading of both the left and right aspects of the frontal bone of rigidly-supported PMHS heads. All of the heads were from male subjects. The PMHS height and weight were measured for nearly all of the cases, but details such as head circumference were not reported. The impactor was unpadding and its contact area was circular. (The loading condition will be revisited in the discussion of Step 2, as well.) The applied load was measured via a load cell, and loads were reported subject to CFC 300 filtering. Acoustic emission sensors were also present. They were used to estimate the time of fracture and a corresponding “fracture load [force].” When skull fracture occurred, the fracture loads were lower than the peak loads. The dataset is summarized in Appendix 1.

Figure 1 depicts the data in Appendix 1, where¹ for the no-fracture cases ($n=24$):

“Force” is the peak measured load, *Peak Force*

“Coded Outcome” $\equiv 0$

for the fracture cases ($n=22$):

“Force” is the force at the acoustic emission,

Fracture Force

“Coded Outcome” $\equiv 1$.

Cormier et al. accordingly used those data to develop risk curves via two statistical methods: non-parametric (Kaplan-Meier) and parametric (Weibull curves based on statistical

models with and without censoring), where “censoring” pertains to the assumptions made about the data. (See Kent et al. 2004 for information on censoring.) Age was determined to be statistically insignificant. The resulting three risk curves were cast as a function of force, and they yielded somewhat different results. For example, the forces corresponding to a 15% fracture probability were estimated as follows: 1.3 kN for Kaplan-Meier, 1.9 kN for interval-censored Weibull, and 0.9 kN for non-censored Weibull.

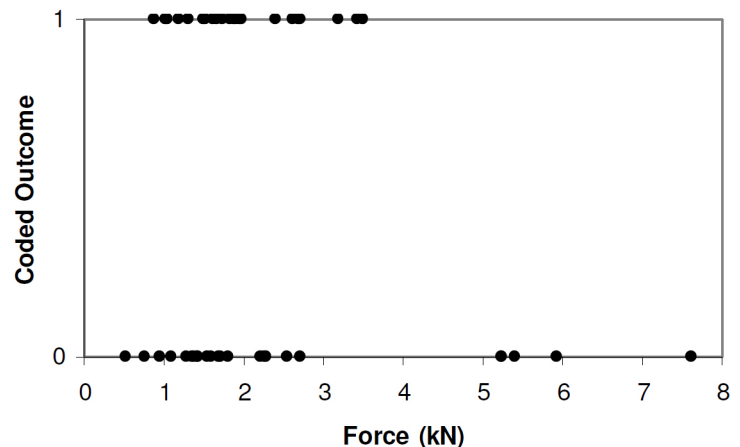


Figure 1. Outcomes of PMHS tests from Cormier et al. (2011a); $n=46$.

Implicit in the three risk curves from Cormier et al. were some highly influential cases (i.e., five non-fracture cases above 5 kN). These data yielded an inconsistent transition zone of outcomes. Ideally, there should be just one transition zone. (For comparison, Cormier et al. (2011b) also reported PMHS test results for the maxilla ($n=38$) subject to a test procedure almost identical to that used for the frontal bone. Those tests results yielded a single, consistent transition zone with fracture force as the predictor variable of maxilla fracture.)

Minitab v14 was used to conduct a binary logistic regression analysis of the data in Figure 1. The resulting risk curve was unacceptable (e.g., there were more discordant pairs than concordant pairs). Appendix 2 contains additional statistical analyses. They showed that, if the five influential no-fracture points were excluded, consideration of just the fracture outcomes roughly approximates consideration of both outcomes.

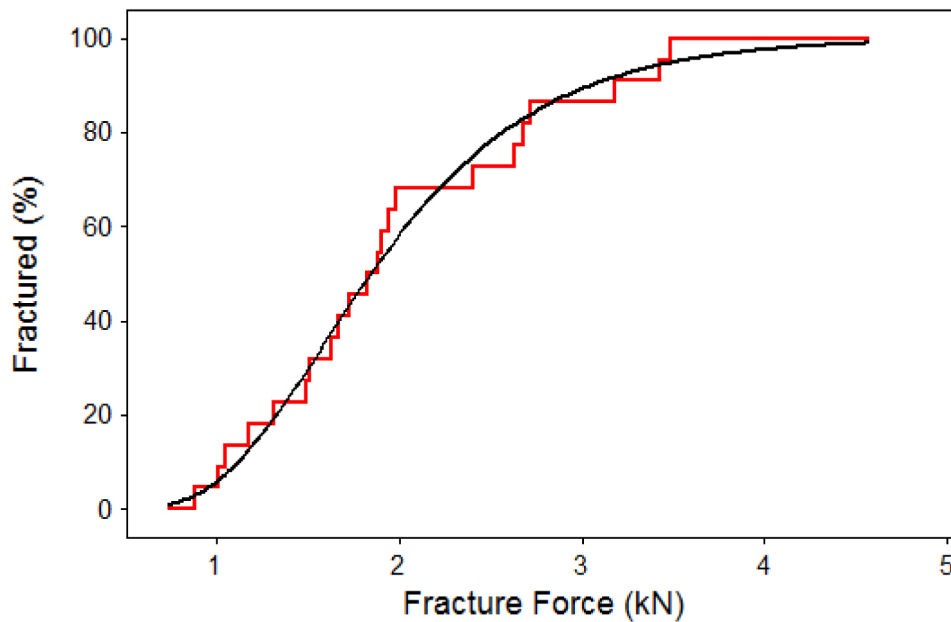
Therefore, for the present study, we chose to consider only the fracture cases of the Cormier dataset. Minitab was accordingly used to assess various parametric functions for fitting the cumulative density function of *Fracture Force*, and the lognormal function yielded the best results.² Table 1 contains the resulting fit details, and Figure 2 shows the corresponding cumulative density functions. Therein, the stair-step curve is the empirical (non-parametric) form, and

¹ Italics will be used to identify the name of a variable used in the subsequent statistical modeling.

² A lognormal function is a probability distribution of a continuous variable, $\tilde{x}$, whose log-transformation yields a normal distribution. The mean of $\ln(\tilde{x})$ is called the “location,” and the standard deviation of $\ln(\tilde{x})$ is called the “scale.” The cumulative density function for a lognormal function can be evaluated in Excel as follows: Cumulative Probability, =LOGNORM.DIST(x_i , location, scale), where x_i is the evaluated level of the studied variable.

Table 1. Statistical analysis of dataset in terms of Fracture Force (kN).

Dataset	Category	Number of Fractured Specimens	Minitab Results (lognormal function)		
			Pearson Goodness of Fit	Location	Scale
Fracture cases from Cormier et al. (2011a)	PMHS tests (Reference)	22	0.805	0.6127	0.3908

**Figure 2. Cumulative density functions for fracture cases of Cormier et al. (2011a), n=22.**

the smooth curve is the lognormal (parametric) form, evaluated in Excel as follows:

$$P_{\text{fracture}} = \text{LOGNORMDIST}(\text{Fracture Force}, 0.6127, 0.3908) \quad (1)$$

where *Fracture Force* is in kN.

Equation 1 will be the “reference risk curve” to which the FE-based results will be compared. Because only fracture cases were used to derive Equation 1, we also deemed it to be a “conditional” risk curve. Moreover, note that it was derived by considering fracture forces that ranged from 0.891 to 3.490 kN - a fact that will be revisited. Finally, Equation 1 was assumed to pertain to a mid-sized male. This assumption

was supported by the results in Appendix 3, wherein the sensitivity of reference risk curve to the PMHS size was assessed.

STEP 2: DEVELOPMENT OF BASE MODELS

Ruan et al. (1993) initially validated the head model relative to eight cadaveric head impact tests from Nahum, Smith, and Ward (1977). That model was the basis for head in the FHBM, and it included representations of the skull³, dura mater, brain, cerebral spinal fluid, falx cerebri, scalp, and skin.

³The diploe layer of the skull is modeled with solid elements, whereas the inner and outer table layers are modeled with shell elements. The inner table layer shares the nodes on the inside surface of the diploe; the outer table layer shares the nodes on the outer surface of the diploe.

More recently, [El-Jawahri et al. \(2011\)](#) reported additional validations for the FHBM head. Specifically, more test speeds and test modes of PMHS were considered (i.e., rigid bar impact to the forehead, zygoma, and maxilla, lateral pendulum impact, and front pendulum impact to the frontal bone, nasal bone, and maxilla). The authors reported that the model-based responses were within the available published cadaveric response corridors. El-Jawahri et al. reported the model parameters and material-model details, and those parameters were within the spread of other human body models. For example, the modulus of elasticity of the present FHBM skull is 6.5 GPa; other published human models have used 6.0 GPa, 7.3 GPa, and 11.0 GPa from [Zhang et al. \(2001\)](#), [Haug et al. \(2004\)](#), and [Shigeta, Kitagawa, and Yasuki \(2009\)](#), respectively.

In a different but pertinent study, [El-Jawahri et al. \(2010a\)](#) reported that the FHBM approximately represents a 55-year old male. Subject to age-based approximations, those authors generated two additional models representing 35 and 75-year old males. Therefore, three models resulted, and they were designated as follows: “35 YO,” “55 YO,” and the “75 YO.”

In the present study, the skull in these models was modified subject to the following assumptions:

1. The cortical bone, trabecular bone, skin, and flesh (frontalis muscle) material parameters were assumed to follow the aging functions applied in [El-Jawahri et al. \(2010a\)](#).
2. The cortical bone thickness was assumed to follow the 0.35% annual decrease used for long bones discussed in [El-Jawahri et al. \(2010a\)](#).
3. The density of the trabecular bone was assumed to follow the rate of decline in the bone mineral density reported by [Yamada et al. \(1982\)](#).⁴
4. As a first approximation, fracture was considered for only the cortical bone of the skull. (Fracture data for the skull trabecular bone were not readily available.) More details on the fracture modeling and related assumptions follow.

FRACTURE MODEL

The cortical bone was modeled subject to the elastic-plastic Johnson-Cook model for isotropic materials without temperature dependence:

$$\sigma = (a + b\varepsilon_p^n)(1 + c \ln(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0})) \quad (2)$$

where σ is the flow stress which includes both elastic and plastic components, a is the yield stress, b is the strain

hardening coefficient, ε_p is the plastic strain, n is the strain hardening index, c is the strain-rate coefficient, $\dot{\varepsilon}$ is the strain rate, and $\dot{\varepsilon}_0$ is the reference strain rate.

The assigned values for these parameters were reported in [El-Jawahri et al. \(2010b\)](#) as follows: $a \approx 48$ MPa, $b \approx 300$ MPa, $n \approx 0.3$, $c \approx 0.04$, and $\dot{\varepsilon}_0 \approx 0.001 \text{ ms}^{-1}$. The strain rate parameters were estimated from models of tests of cadaveric femurs undergoing compression at different rates. These strain-rate parameters were assumed to apply for the head.

Fracture can be modeled in Radioss - the finite element simulation code applied herein for the FHMB - subject to a set of fracture criteria consisting of two parameters: the failure stress, σ_{ult} , and the failure strain, ε_{ult} . Specifically, when the failure stress is reached during the computation, the stress remains constant and the material deforms until the failure strain is reached, and when both criteria are met in an element, that element is eliminated and load is no longer transmitted ([Mecalog, 2005](#)).

Our initial estimates for the fracture criteria were based on the test results of [McElhaney et al. \(1970\)](#). In that study, human samples of the cranial bone were tested in tension, compression, simple shear and torsion. All tests were quasi-static. [McElhaney et al.](#) reported that the failure stress for the skull bone ranged from 56 MPa to 95 MPa for tension and compression, respectively; the failure strain ranged from 2.4% to 2.9% for tangential and radial compression, respectively. We assumed that some dynamic amplification would be involved (dynamic vs. quasi-static). Therefore, for the present study, two iterations on the fracture criteria for the skull were considered:

- Initial Fracture Criteria: $\sigma_{\text{ult}} \approx 150$ MPa and $\varepsilon_{\text{ult}} \approx 3.0\%$, and
- Final Fracture Criteria: $\sigma_{\text{ult}} \approx 125$ MPa and $\varepsilon_{\text{ult}} \approx 2.2\%$.

However, for ease of presentation, only the results of Final Fracture Criteria will be presented in the main portion of the paper; the results for Initial Fracture Criteria will be reported in an [appendix](#) as a sensitivity study.

ADDITIONAL MODEL VALIDATIONS

Additional model validations were conducted subject to the test setup of [Cormier et al. \(2011a\)](#) depicted in [Figure 3](#).

The test setup of [Cormier et al. \(2010, 2011a\)](#) involved a rigidly-supported PMHS head. This boundary condition was modeled by rigidly fixing six nodes on the posterior aspect of the skull. This approximation was confirmed via personal communication ([Cormier, 2011](#)).

First, the model-based stiffness of the skull was assessed relative to PMHS test data from [Cormier et al. \(2010\)](#). Specific force-displacement data were kindly provided in a

⁴[Yamada et al. \(1982\)](#) studied age-related changes in cranial bone mineral density in 495 cases. They reported a decline in the bone mineral density, from a value of 1164 ± 143 Hounsfield Units (HU) for 20-30 year olds to a value of 629 ± 119 HU for 70+ year olds. The annual percentage decline in the bone mineral density was calculated to be 0.92%. By assuming that the trabecular bone density of the original FHBM pertained to that of a 55 YO male, the densities for the different ages could accordingly be calculated subject to the aforementioned annual percentage decline.



Figure 3. Frontal bone impact test simulation of Cormier test setup.

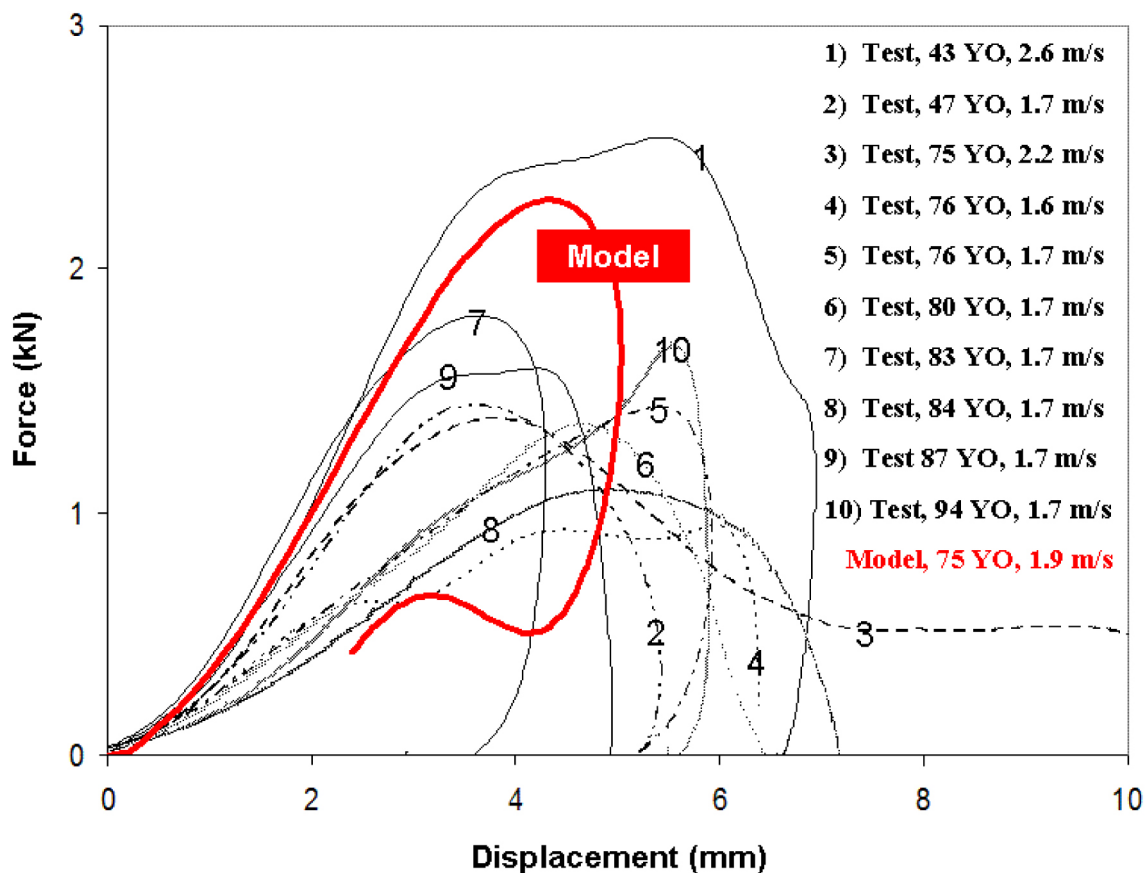


Figure 4. Force-displacement comparisons for lower-speed/non-fracture cases.

personal communication (Cormier, 2011). We binned those tests into two categories:

Lower-Speed/Non-Fracture Cases (n=10)

The average age of those cases was 74.5 years old (std dev=16.6) and the average speed was 1.9 m/s (std dev=0.3). The aforementioned 75 YO head model was accordingly run for that average speed. That “average model” yielded no

fracture. Figure 4 shows stiffness results for the model and the ten tests.⁵

When the ten cases were individually modeled (i.e., the specific PMHS age and the specific impactor speed were introduced into representative models), the majority of the cases (8 of 10) yielded no fracture. (Those ten models are not shown in the figure.)

⁵All model-based forces were based on CFC 600 filtering. CFC 300 was not available for our processing.

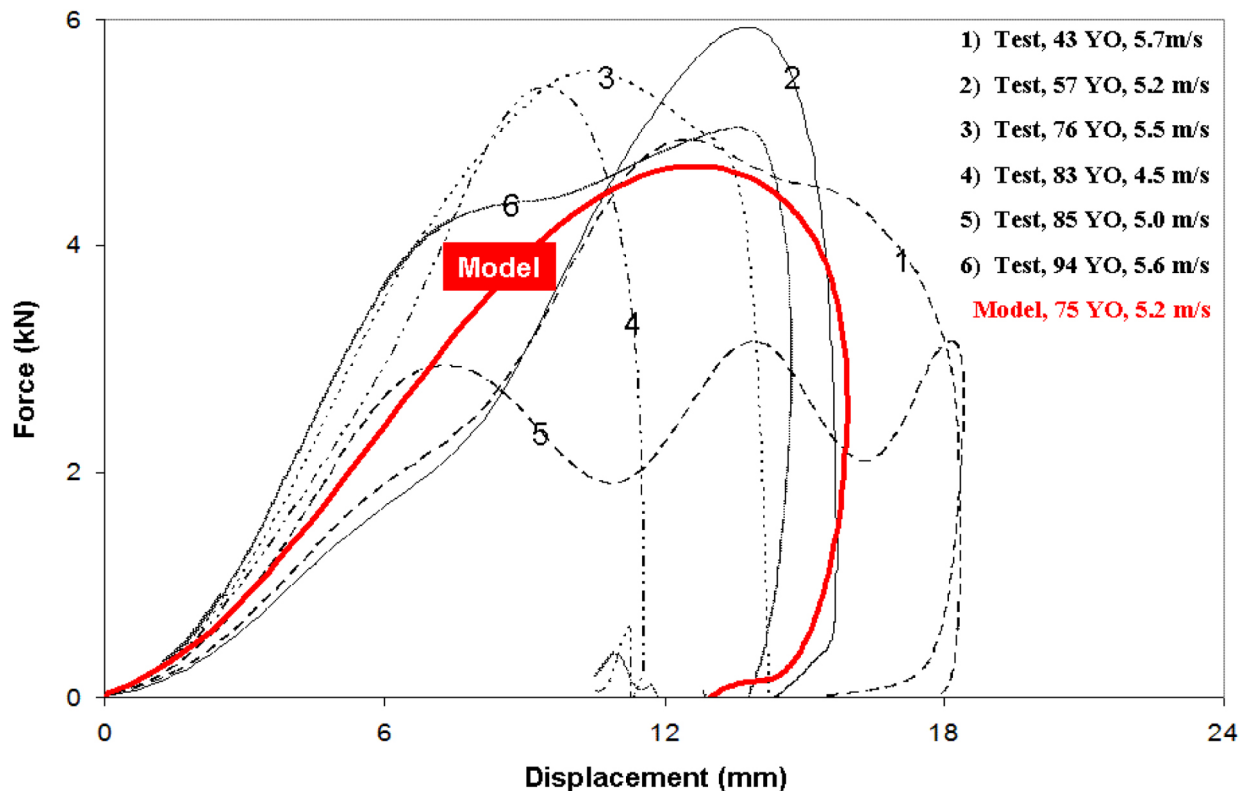


Figure 5. Force-displacement comparisons for higher-speed/fracture cases.

Higher-Speed/Fracture Cases (n=4)

The average age of those cases was 74.5 years old (std dev=22.4) and the average speed was 5.4 m/s (std dev=0.3). As with the lower-speed/non-fracture cases, the 75 YO head model was run for that average speed. That “average model” yielded fracture. Figure 5 shows stiffness results for the model and the four tests. (Note that the axes in Figures 4 and 5 have different scales.)

When the four cases were individually modeled, all of the cases (4 of 4) yielded fracture. (Those four models are not shown in the figure.)

Figures 4 and 5 collectively show that the model-based initial stiffness, peak force, and peak displacement were within the test spread. Also note that the tests demonstrated considerable variability. This fact will be considered later. (Because the fracture model made no difference in the shapes of the force-deflection responses, the two distinct settings for the fracture model were not shown in these figures. The same conclusion pertained to the PMHS tests, as the filtering mitigated the slight force drop at time/displacement of fracture.)

Next, the 22 fracture cases in the dataset of Cormier et al. (2011a) were considered. The average age of those fracture cases was 74.2 years old (std dev=13.2), and the average speed was 5.35 m/s (std dev=0.25). Therefore, the aforementioned 75 YO head model was run for that 5.35 m/s test condition. The model-based results were then compared to these test averages. The results are shown in Table 2. The

Force-at-Peak Stress was deemed a better estimate of the test-based Fracture Force than was Peak Force or Force-at-Peak Strain.

STEP 3: ASSESSMENT OF MODEL-BASED FRACTURE CRITERIA

Head models were constructed for each of the individual cases involving fracture in the dataset of Cormier et al. (2011a), that is, 22 models involving specific PMHS age and specific impactor speed. For easy reference, this set of simulations was designated “Model Set 1.” The resulting model-based response data are found in Appendix 4. Supplemental data such as the time at peak force, time at peak stress, HIC, and location of peak stress are also reported in this appendix (and others) as well.

By inspecting these results of Model Set 1, we observed that the model-based fracture forces demonstrated less range than those of the tests. (The same observation applied to the peak forces.) We assumed that this was most likely due to variability in the tests and the test subjects, or conversely, a lack of variability in the models. Inspection of Cormier's PMHS dataset supports this assumption. For example, therein, responses were reported for two male subjects (#17 and #31) of the same age (67 yrs), the same impact energy (47 J), and indeterminate size difference (i.e., the height of #31 was not known). The only known difference between the two was the tested aspect (left vs. right). The finite element