Journal of Forensic studies

Research Article

Franck H and Franck D. Forensic Stud: FSTD-109.
DOI: 10.29011/FSTD-109. 100009

Methods to Calculate Stresses Resulting from Whiplash Injuries

Harold Franck*, Darren Franck

Advanced Engineering Associates, Maccorkle Ave Se in Charleston, West Virginia, USA

***Corresponding author:** Harold Franck, Advanced Engineering Associates, Maccorkle Ave Se in Charleston, West Virginia, USA. Tel: +3049258565; Email: harold@aeawv.com

Citation: Franck H and Franck D (2017) Methods to Calculate Stresses Resulting from Whiplash Injuries. Forensic Stud: FSTD-109. DOI: 10.29011/FSTD-109. 100009

Received Date: 26 May, 2017; **Accepted Date:** 06 July, 2017; **Published Date:** 17 July, 2017

Abstract

Rear end vehicular collisions can result in whiplash type injuries to the occupants of the target vehicle. Standard accident reconstruction techniques may be utilized to calculate the respective velocity changes of the bullet and target vehicles. Once the delta-v's are determined, maximum and minimum limits may be placed on the critical stresses that are imparted on the spinal column of the occupants of the target vehicle that may be subjected to whiplash injuries. These stresses can then be compared to the known ultimate compressive, tensional, and torsion ultimate stresses on the soft tissue structures of the spinal column. This treatise develops three methods of analysis for the investigative forensic biomechanical engineer.

Keywords: Injury Mechanism; Ultimate strength; Whiplash

Introduction

There is a significant divergence of opinions on the probability and potential for injury to the spinal column resulting from rear-end vehicular collisions. Some experts claim that injuries may occur as a result of any speed change. We do not agree with such a position because, the principles of material mechanics are well understood and utilized in design and failure analysis irrespective of the material being studied. Therefore, this treatise affords the forensic biomechanical engineer a basis for calculating the potential for failure and injury based on known scientific data.

Generally, these spinal injuries are referred to as whiplash type maladies that are often claimed to result to the cervical, thoracic, and lumbar sections of the spine. It should be noted that the modern vehicle has substantial padding that affects the lumbar and thoracic spine. Consequently, significant speed changes are required to overcome the supportive cushioning effect of the seat back. Furthermore, the seats, especially for the front passengers, are designed to give or collapse beyond a certain limit. Please note that in this analysis we are not concerned with the crashworthiness of the vehicles, seats, and restraint systems.

Similarly, vehicles are equipped with head rests that also offer some degree of protection when the head and the neck of the occupant is thrust rear-ward in the collision. Depending on the seat configuration and the physical structure of the occupant, the head rest may offer little or no protection. As a further caveat for this analysis we note that the supportive structure of the head rest is simply not considered.

(Figure 1) represents a spinal column superimposed on a typical seat. Two important features are noted. One, the spinal column is much more robust in the lower thoracic and lumbar regions. Two, the maximum exposure to whiplash can occur to the cervical and portions of the upper thoracic regions.

Figure 1: Spinal Column and Seat.

Data on Injury to Soft Tissue Spinal Structures

(Tables 1&2) show spinal column dimensions that are necessary for most biomechanical whiplash calculations. From a mechanical standpoint, it is well understood that larger structures, whether biological or not, are more resilient and require greater forces to overcome their failure limits.

Section	20-39 yrs.	40-59 yrs.	60-79 yrs.	Average
Cervical	16.7 ± 0.78	14.6 ± 0.24	11.0 ± 0.11	14.1
Upper Thoracic	18.0 ± 0.31	17.5 ± 0.22	14.2 ± 0.27	16.6
Middle Thoracic	20.2 ± 0.41	20.0 ± 0.31	18.1 ± 0.36	19.4
Lower Thoracic	23.6 ± 0.80	22.3 ± 0.30	21.6 ± 0.22	22.5
Lumbar	27.9 ± 0.43	27.0 ± 0.33	23.6 ± 0.26	26.2

Table 1: Height of Human Vertebrae by Age and Section (mm).

Section	20-59 yrs.	60-79 yrs.	Average
Cervical	326 ± 7	264 ± 10	305
Upper Thoracic	432 ± 13	380 ± 12	415
Middle Thoracic	556 ± 18	525 ± 14	546
Lower Thoracic	870 ± 34	749 ± 22	830
Lumbar	1088 ± 18	990 ± 21	1055

Table 2: Cross Sectional Area of Human Vertebrae by Age and Section (mm2).

(Tables 3,4&5) relate the ultimate strengths in tension, torsion, and compression for various sections of the spine and for various age groups.

Section	20-39 yrs.	40- 79 yrs.	Average
Cervical	0.33 ± 0.02	0,29 ± 0.03	0.30
Upper Thoracic	0.24 ± 0.01	0.20 ± 0.03	0.21
Lower Thoracic	0.26 ± 0.02	0.22 ± 0.01	0.21
Lumbar	0.30 ± 0.01	0.24 ± 0.01	0.26

Table 3: Ultimate Tensile Strength of Human Intervertebral Discs (Kg/mm^2).

Section	20-39 yrs.	40-79 yrs.	Average
Cervical	0.52 ± 0.07	0.46 ± 0.05	0.48
Upper thoracic	0.46 ± 0.03	0.38 ± 0.04	0.41
Middle Thoracic	0.47 ± 0.02	0.42 ± 0.03	0.44
Lower Thoracic	0.48 ± 0.02	0.44 ± 0.04	0.45
Lumbar	0.51 ± 0.03	0.46 ± 0.03	0.48

Table 4: Ultimate Torsional Strength of Human Intervertebral Discs (Kg/mm^2).

Section	40-59 yrs.
Cervical	1.08
Upper Thoracic	1.02
Lower Thoracic	1.08
Lumbar	1.12
Average	1.08

Table 5: Ultimate Compressive Strength of Human Intervertebral Discs (Kg/mm^2).

The data above was taken from H Yamada, and H Franck and D Franck. (Figure 2) shows the stress-strain curves for wet intervertebral discs in tension for various portions of the spine for individuals between the ages of 20 and 39 years of age corresponding to the data on (Table 3). Note that the cervical discs exhibit the greatest stress capability simply because they must allow for the greatest movement in the neck and head area. I fact the cervical discs allow up to a 40-degree angle of twist while the lumbar and thoracic vertebrae restrict the angle of twist to about 20 degrees.

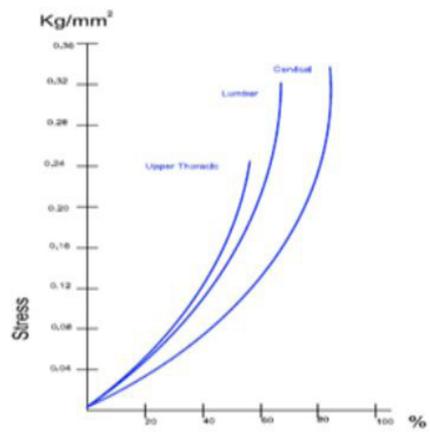


Figure 2: Elongation Tensile Properties of Discs.

Hooke's Law

(Figure 2) requires some explanation and review. Analysis of structural elements, in this case the stresses on the spinal disc structures, requires a determination of the forces acting on the structure. The forces that affect the structure and the resistance of the particular structure to separation of movement within the structure are considered internal. The forces that transmit the loads are considered external and are dependent on the motion produced on the entire body by an event such as a rear-end collision. Generally, the force acting on the body is proportional to the stress times the cross-sectional area or

$$F = \sigma A$$

The stress $\sigma\sigma$ can also be referred to as the intensity of forces distributed over the cross section. Stresses imparted on the body induce deformations which may change the shape, length and cross-section of the body. The deformation $\delta\ \delta$ of the body per unit length L is known as the strain $\varepsilon\varepsilon$ and is given by,

$$\varepsilon = \frac{\delta}{L}$$

The relationship between the stress and the strain is known as Hooke's Law, or

$$\sigma = E\,\varepsilon$$

This relationship is linear for the elastic phase of the stress-strain diagram as represented in Figure 2. Note that the end points of the curves in Figure 2 represent the ultimate values before failure of these discs occur. Additionally, E is known as Young's Modulus.

Methods of Analysis

In this section, we introduce three methods of analysis in order to compare and contrast these methods to instrument rear-end crash tests performed by the authors on a sled test jig. The subjects of these tests were a 66-year-old man and a 40-year-old woman in order to represent a cross section of the population.

The **First Method** is attributed to Damask and is constructed as follows. The differential distance between the lower spine and the rest of the spine is approximately = 0.2 feet. Consequently, the acceleration produced resulting from a velocity change is,

$$a = \frac{v^2}{2x}$$

The mass of the individual for this model is determined from the weight w of the individual divided by two in order to consider only the torso weight and then multiplied by 5/6 of the torso weight. The mass is then,

$$m = \frac{w}{2}\left[\frac{5}{6}\right]m = \frac{w}{2}\left[\frac{5}{6}\right] = \frac{5w\,5w}{12\;12}$$

The force is then.

$$F = ma$$

In this model, the shearing force is assumed to be evenly distributed over 15 discs, seven cervical and 8 thoracic. The force in kilograms is,

$$F_k = \frac{F}{15(2.2)}$$

The tensile stress on any disc is then divided by the average cross section of the all the discs which is approximately 660mm^2 mm^2.

$$\sigma = \frac{F_k}{660}$$

The **Second Method** is that of a couple which is produced by the movement of the head resulting from the collision. This is a two-dimensional problem. Consider Figure 3 below.

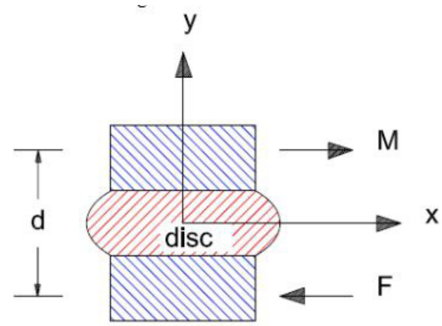


Figure 3: Couple Model.

In the Couple Model FF is the force produced by the collision which produces a moment M on the adjoining vertebra and damages the disc. Standard equations are,

$$F = F_c = ma$$

$$M = Fd = mad = \frac{1}{2}\,m\,v^2$$

$$a = \frac{dv}{dt} = \frac{1}{2d}v^2$$

$$\frac{dx}{dt} = v = \frac{-1}{\left[\frac{t}{2d} + c_1\right]}$$

$$x = \frac{-\mathrm{Log}\left[\frac{t}{2d} + c_1\right]}{\left[\frac{1}{2d}\right]} + c_2$$

$$a = \frac{1}{2d\left[\frac{t}{2d} + c_1\right]^2}$$

In the above equations, the force F_cF_c or moment is produced by the weight of the head and the acceleration a. the parameter t is the pulse width and the distance 2d is approximately 0.131 ft. which represents the leverage produced on the disc by the movement of the head. This distance may be shorter for a particular individual. The tensile stress is then computed as,

$$\sigma = \frac{F_c}{A}$$

The cross section of the disc for this model is not the average of all the discs but the value for the average of the cervical and thoracic discs which is approximately 350mm^2mm^2.

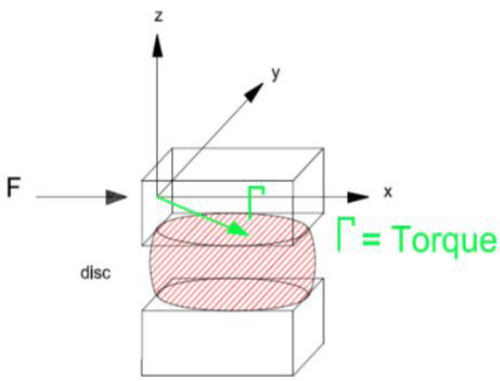


Figure 4: Torque Model.

The **Third Method** is produced by a torque on the discs. One argument that is proposed states that the rotation of the head relative to the direction of the force makes a difference whether injury might occur. (Figure 4) represents the torque produced by such motion. The pertinent equations follow,

$$\text{Work} = \int \bar{F} \cdot d\bar{s}$$

$$\text{Torque} = \Gamma = \bar{r} \times \bar{F}$$

$$\bar{F} = F_x \bar{a}_x$$

$$\bar{r} = r_x \bar{a}_x + r_y \bar{a}_y + r_z \bar{a}_z$$

$$\Gamma = F_x \left[r_z \bar{a}_y - r_y \bar{a}_z \right] = F\, r\, \bar{a}_s$$

From the Work Energy Principle

$$\frac{dv}{dt} r = \frac{1}{2} v^2$$

$$v = \frac{-2r}{[t + 2 r c_1]}$$

$$a = \frac{2r}{[t + 2 r c_1]^2}$$

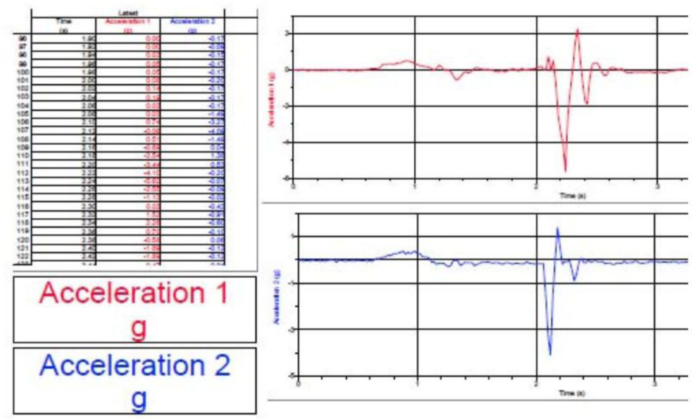
For the torque equations t is the pulse width but the 2r term is different as follows. The separation between the vertebrae at mid line is approximately 20 mm and the area of the cervical discs is about 350 mm^2 with a diameter of approximately 18 mm. Consequently, the 2r term is about 0.176 ft.

Summary of Whiplash Tests

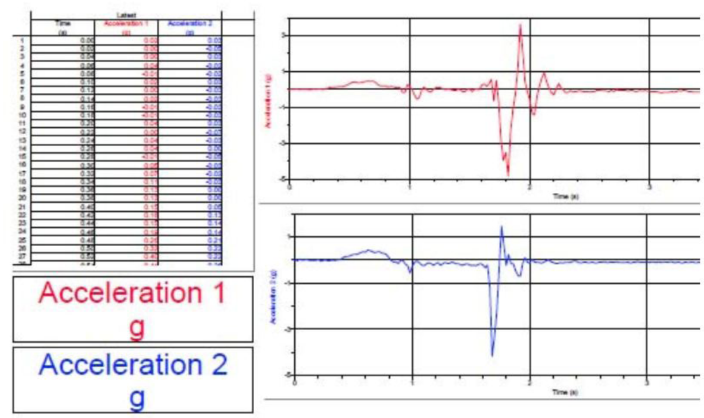
Test	Time (sec)	Accel (g)	Area (g-s)	Del V (ft./s)	Del V (mph)
10A	0.14	5.62	0.3929	12.62	8.63
11A	0.16	4.84	0.3850	12.40	8.46
12A	0.14	3.62	0.2862	9.22	6.29
13A	0.18	5.14	0.3661	11.79	8.04
14A	0.14	5.46	0.3373	10.86	7.41
15A	0.16	9.28	0.6746	21.72	14.82
Averages	0.15	5.66	0.4070	13.11	8.94

Table 6: Whiplash Tests and Head Accelerations 40-year-old Female.

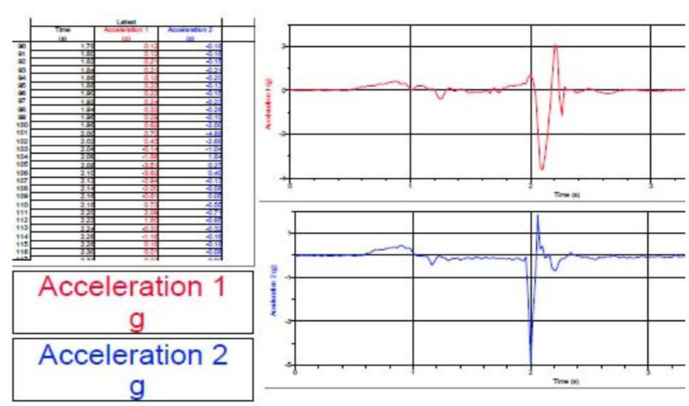
The Graphs for the Previous Tests are Shown Below



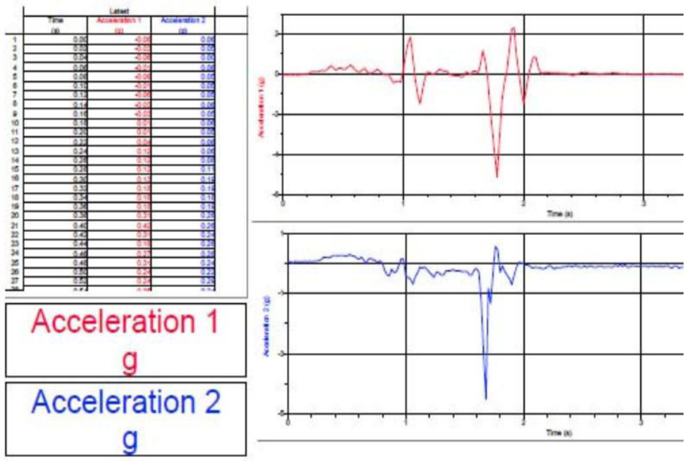
10A Graph.



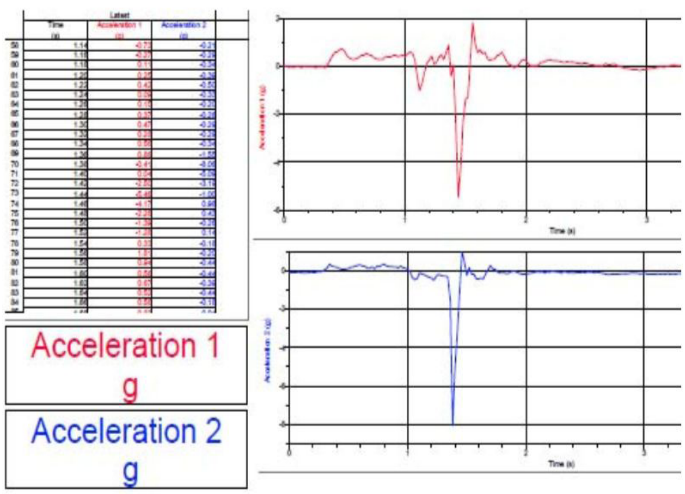
Test 11A Graph.



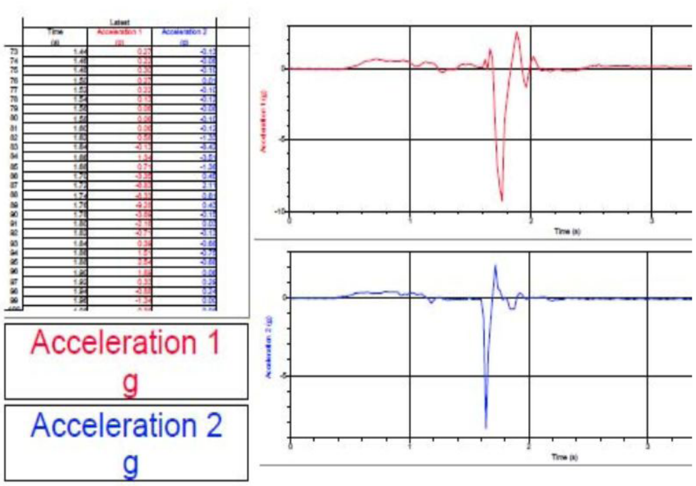
Test 12A Graph.



Test 13A Graph.



Test 14A Graph.

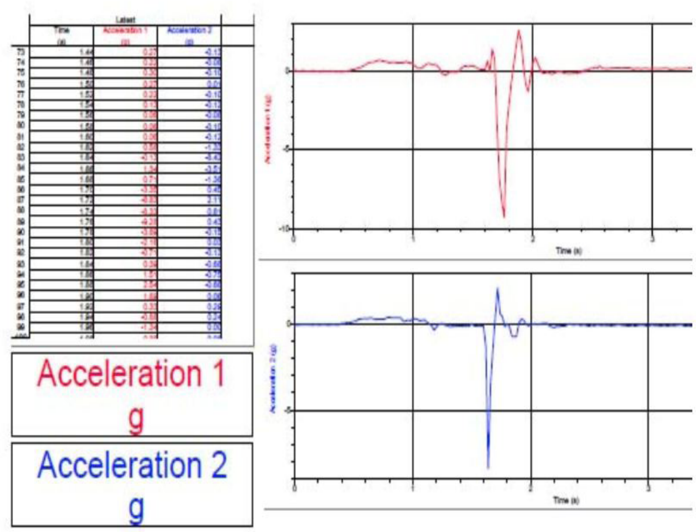


Test 15A Graph.

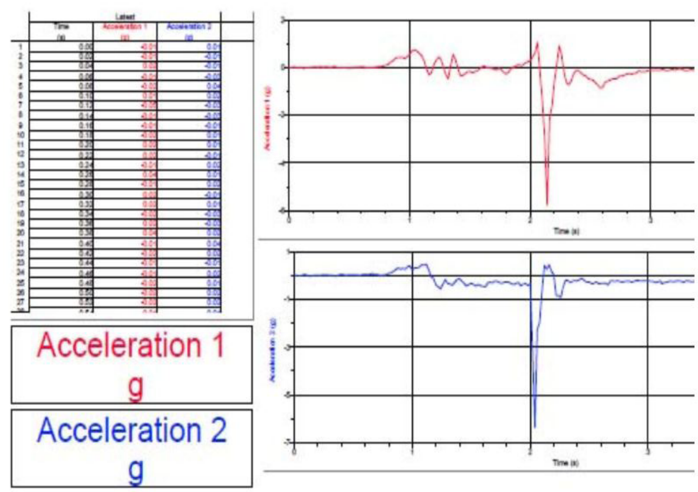
Test	Time (sec)	Accel (g)	Area (g-s)	Del V (ft/s)	Del V (mph)
16H	0.14	3.91	0.2487	8.01	5.46
17H	0.14	5.75	0.2827	9.10	6.21
18H	0.10	9.34	0.4467	14.38	9.81
19H	0.14	4.31	0.2675	8.61	5.88
20H	0.14	4.34	0.2678	8.62	5.88
21H	0.14	2.86	0.2614	8.42	5.74
Averages	0.13	5.09	0.2958	9.52	6.50

Table 7: Whiplash Tests and Head Accelerations 66-year-old Male.

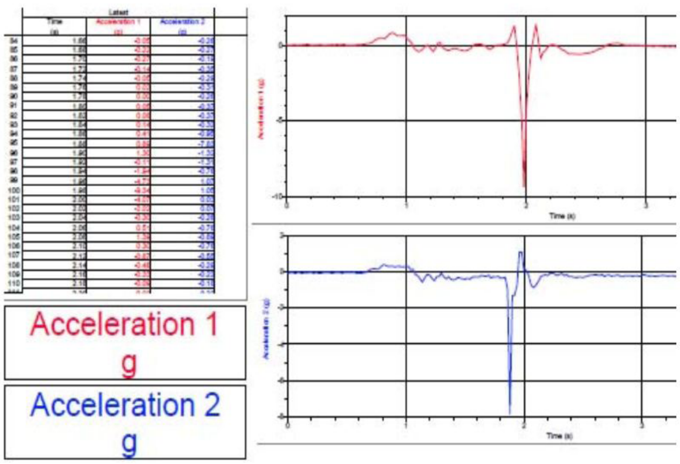
The Graphs for the Tests on Table 7 are Shown below



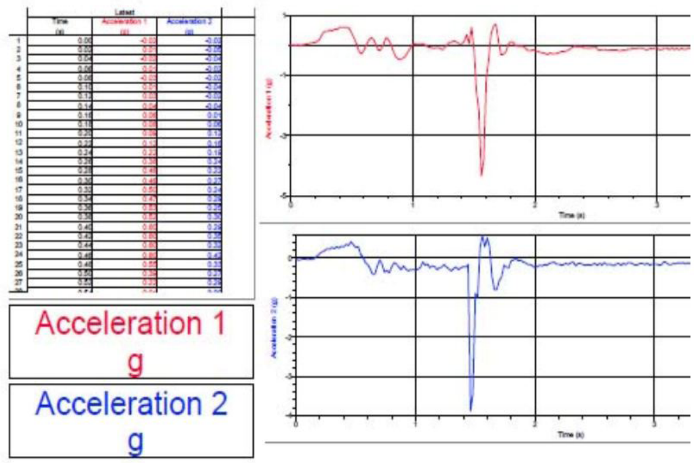
Test 16H Graph.



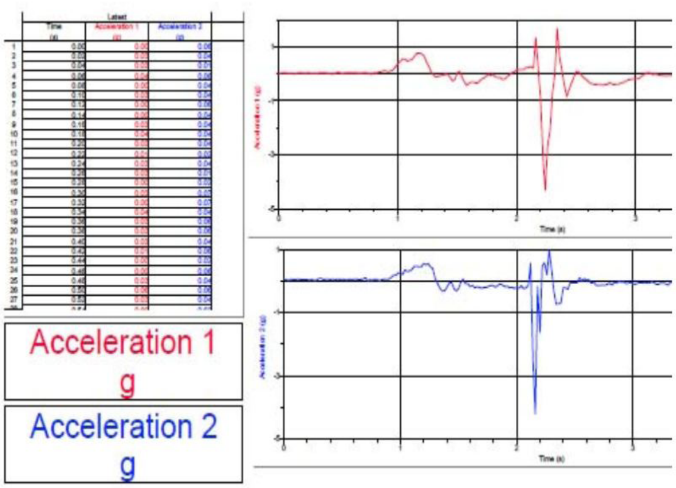
Test 17H Graph.



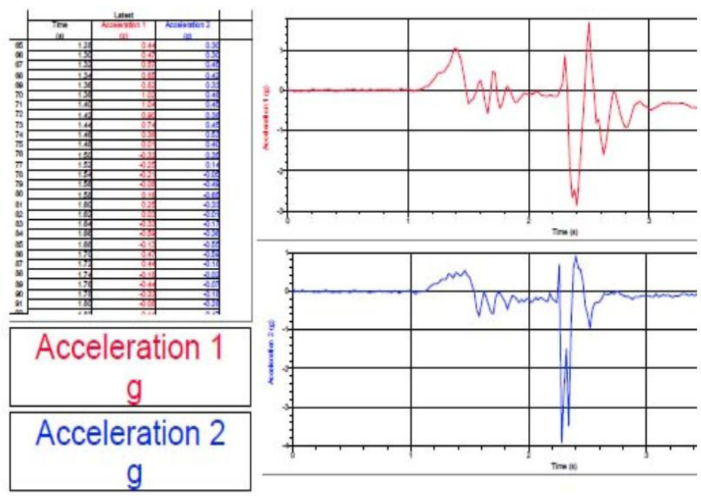
Test 18H Graph.



Test 20 H Graph.



Test 19H Graph.



Test 21H Graph.

For each of the test graphs, the top graph in red corresponds to the head acceleration and the bottom graph represents the measurement of the chest acceleration

test	weight	v(mea)	a(mea)	pulse (t)	A(da)	A(co)	A(to)	sig(da)	sig(co)	sig(to)
10A	130	12.65	5.62	0.14	12.424	37.869	28.237	0.032	0.040	0.030
11A	130	12.4	4.84	0.16	11.938	36.387	27.132	0.030	0.039	0.029
12A	130	9.22	3.62	0.14	6.600	20.117	15.000	0.017	0.021	0.016
13A	130	11.79	5.14	0.18	10.792	32.895	24.528	0.028	0.035	0.026
14A	130	10.86	5.46	0.14	9.157	27.910	20.811	0.023	0.030	0.022
15A	130	21.72	9.28	0.16	36.627	111.639	83.244	0.093	0.118	0.088
Av(A)	130	13.11	5.66	0.15	13.344	40.673	30.328	0.034	0.043	0.032
16H	155	8.01	3.91	0.14	4.981	15.183	11.321	0.015	0.019	0.014
17H	155	9.1	5.75	0.14	6.429	19.597	14.612	0.020	0.025	0.018
18H	155	14.38	9.34	0.1	16.055	48.935	36.488	0.049	0.062	0.046
19H	155	8.61	4.31	0.14	5.756	17.543	13.081	0.017	0.022	0.017
20H	155	8.62	4.34	0.14	5.769	17.584	13.111	0.018	0.022	0.017

21H	155	8.42	2.86	0.14	5.504	16.777	12.510	0.017	0.021	0.016
Av(H)	155	9.52	5.09	0.13	7.037	21.447	15.992	0.021	0.027	0.020

Table 8: Comparison of Methods.

The data from Table 8 is plotted below. The Couple Model yields the greatest stress shown in yellow. The Damask and Torque Models yield essentially the same results.

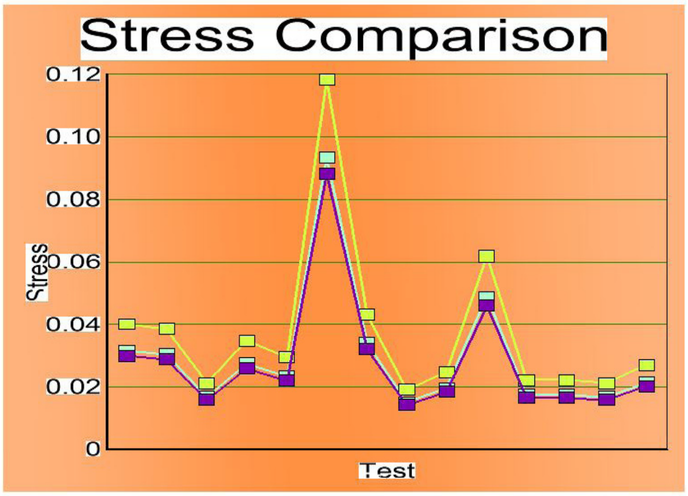


Figure 5: Stress Comparison.

Conclusions

In order to assess the potential for injury to the upper spinal column, calculations are required in scientifically correct terms.

References

1. Damask AC, Damask J (1990) Injury Causation Analysis: Case Studies and Data Sources. The Michie Company, Charlottesville, VA.
2. H. Franck, D Franck (2016) Forensic Biomechanics and Human Injury – Criminal and Civil Applications-An Engineering Approach. Boca Raton FL: 262.
3. Yamada H (1970) The Strength of Biological Materials. Williams and Wilkins, Philadelphia, PA.