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A PRELIMINARY ANALYSIS OF FIFTEEN THORACIC IMPACT TESTS

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At this time fifteen thoracic impacts have been performed at Calspan. These tests were performed at various impact velocities with various impactor masses and configurations. Table 1 summarizes the tests performed in ascending order of injury severity.

Three faces were utilized in these impacts in an effort to evaluate the relationship between size of an impactor and injury. The faces were a 6" diameter circle at 28 $in.^2$, a 6.75 in. x 8 in. rectangle at 54 $in.^2$, and an 8 in. x 10 in. rectangle at 80 $in.^2$. Impactor weight varied from 52.8 lbs. up to 59.0 lbs. and is dependent on the configuration of the impactor face. Velocity of impact was gradually increased from approximately 22 fps up to 36 fps with the intent of causing injuries that would range from mild to severe and life-threatening.

The injuries that were sustained by the subjects along with their resepctive AIS numbers are shown in Table 2. Clearly the vast majority of injuries were fractures of the ribs followed by several fractures of the sternum and clavicle. Only two injuries to internal organs were observed. This injury pattern and the fact that the AIS code rates all injuries separately results in three subjects with an AIS of 1, ten subjects with an AIS of 2, and two subjects with an AIS of 4. The AIS scale is not continuous and does not consider that a subject suffering multiple injuries is more severely damaged, in a mechanical sense, than is a subject suffering only a single injury. The CII (Cumulative Injury Index) is utilized to identify those subjects suffering multiple injuries and to rank them in ascending order of damage. It is felt that this concept of cumulative damage is better suited to examining the data with the intent of defining a relationship between impact parameters and injury. The formula for calculating the CII is shown in Appendix A.

It must be noted that in three of the thoracic impacts the braking cable attached to the impactor interfered with the impact event. Before the subject had attained its final post-impact velocity the cable became tight and slowed down the impactor. The tightened cable put an additional impulse into the system that cannot be quantified and the principles of impulse and momentum and conservation of energy cannot be applied. The injuries sustained by the

Table 1

SUMMARY OF THORACIC IMPACT TESTS

Test No.	Calman No.	Subject Characteristics: Sex	Age	Height (in.)	Weight (lbs.)	Impactor Characteristics: Configuration	Weight (lbs.)	Velocity (fps)
1	31	M	57	67.5	161	8"x10" wood flat	59.0	23.6
2	33	F	70	67.0	131	6.75"x8" wood flat	58.3	24.3
3	29	M	71	67.0	151	8"x10" alum flat	55.8	~32.8
4	30	M	66	69.0	185	8"x10" alum flat	55.8	22.3
5	37	F	57	62.0	103	6.75"x8" wood flat	56.0	33.2
6	39	F	65	66.0	155	6.75"x8" wood flat	56.0	29.5
7	40	M	66	73.0	185	6.75"x8" wood flat	56.0	36.4
8	41	M	62	72.0	180	8"x10" wood flat	59.0	32.7
9	35	M	69	69.0	150	6" dia. wood flat	52.8	25.4
10	34	M	55	71.0	141	6" dia. wood flat	52.8	22.0
11	36	M	61	69.0	160	6.75"x8" wood flat	56.0	33.0
12	25	M	55	72.0	188	8"x10" alum flat	55.8	~23.7
13	42	M	60	68.0	190	8"x10" wood flat	59.0	33.9
14	38	F	49	62.0	97	8"x10" wood flat	59.0	32.7
15	32	F	60	65.5	126	6.75x8" wood flat	58.3	24.1

Table 2

SUMMARY OF THORACIC IMPACT INJURIES

Test No.	Calman No.	AIS #1	#2	#3	#4	#5	CII
1	31	1 - F R (r)					1.00
2	33	1 - F R (r)	1 - F R (l)	1 - F R (r)			1.75
3	29	1 - F R (l)	1 - F R (l)	1 - F R (r)			1.75
4	30	2 - CF R (l)	1 - F R (r)				2.25
5	37	2 - CF R (r)	2 - CF R (l)				2.50
6	39	2 - F CL	2 - CF R (r)				2.50
7	40	2 - F ST	2 - CF R (l)				2.50
8	41	2 - F ST	2 - CF R (r)	1 - F R (l)	1 - F R (l)		2.69
9	35	2 - F ST	2 - CF R (r)	2 - CF R (l)			2.75
10	34	2 - F ST	2 - CF R (r)	2 - CF R (l)	1 - F R (r)		2.81
11	36	2 - CF R (r)	2 - CF R (l)	2 - CF R (l)	1 - F R (r)	1 - F R (l)	2.84
12	25	2 - F ST	2 - CF R (r)	2 - CF R (r)	2 - CF R (l)		2.88
13	42	2 - F ST	2 - F CL	2 - CF R (r)	2 - CF R (l)		2.88
14	38	4 - L LI	1 - F R (r)	1 - F R (l)			4.19
15	32	4 - L SP	2 - F ST	2 - CF R (r)	1 - F R (r)	1 - F R (l)	4.44

F - Fracture
CF - Consecutive Fractures
L - Laceration
R - Rib

ST - Sternum
CL - Clavicle
LI - Liver
SP - Spleen

subjects in those impacts were, therefore, less severe than would be expected for the impact conditions. Tests 32, 33, and 36 were affected in this manner. Precautions are being taken to avoid this problem in the future.

An analysis of this thoracic impact data must consider a large number of variables. A list of those variables considered in this analysis relevant is shown in Table 3. This list is compiled on the basis of several assumptions. It is assumed that the basic material properties of all of the subjects are the same regardless of size, sex, age, etc., with the exception of bone strength which has been measured. It is assumed that the test configuration is identical in all cases with respect to subject position, target point, and subject preparation.

An examination of the thoracic force vs. deflection curves for these tests, shown in Figures 1 through 12, shows a relationship between impactor face size and stiffness of the thorax. All of the force-deflection curves that were generated have a linear slope over the initial portion of the impact. The penetration distance of this linear portion varies from one to two inches, but it is always clearly discernible. The magnitudes of these slopes are shown in Table 4 along with the area of the impactor face. With the exception of subject 36 the 28 $in.^2$ and 54 $in.^2$ impactors generate force-deflection curves with lower initial stiffness than do the 80 $in.^2$ impactors. It may be that the taller, 80 $in.^2$, face impacts an additional set of ribs, or perhaps two sets of ribs. The 54 $in.^2$ face does not show an area effect with respect to the 28 $in.^2$ face, and this 6.75 in. x 8 in. face may not be large enough to impact additional ribs. In future tests the chest of the subject will not be covered, and the impactor outline will be traced on the subject's chest in order to examine the relationship between impactor area and chest anatomy. Finally, this observation of increased thoracic stiffness for larger impactor faces is based on a very small sample and needs to be substantiated with more testing.

Figure 13 is a plot of the CII versus the energy of impact. The injuries observed in these tests were largely skeletal fractures with an AIS of 2. This results in a plot with most of the points grouped around a horizontal line between CII = 2 and CII = 3. No trend relating impact energy and injury is evident.

Table 3

VARIBLES IN THE CALSPAN THORACIC IMPACT TESTS

Impactor Mass Impact Velocity Impactor Face Dimensions
Size of Subject Weight of Subject
Skeletal Quality

Table 4

SLOPE OF THORACIC FORCE DEFLECTION CURVES

Subject	K (slope) (lbs./in.)	A_I ($in.^2$)
25	N/A	80
29	N/A	80
30	1136	80
31	1250	80
32	645	54
33	N/A	54
34	769	28
35	444	28
36	1333	54
37	576	54
38	N/A	80
39	882	54
40	833	54
41	1339	80
42	1316	80

N/A - not available

Figure 1

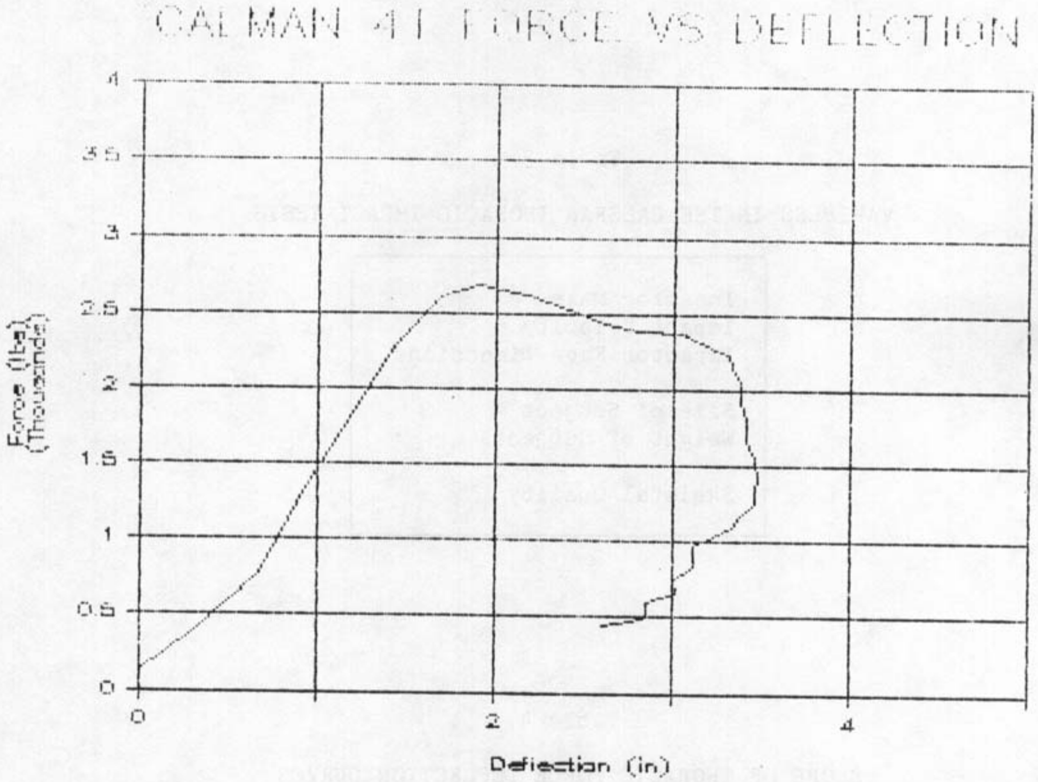


Figure 2

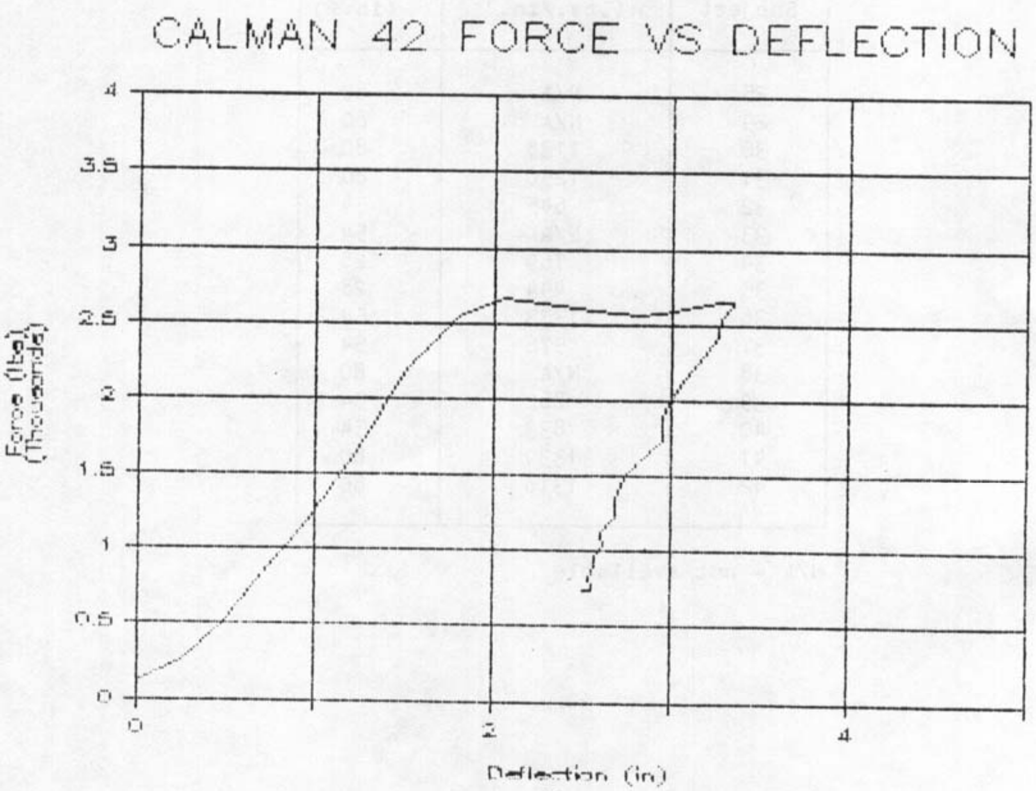


Figure 3

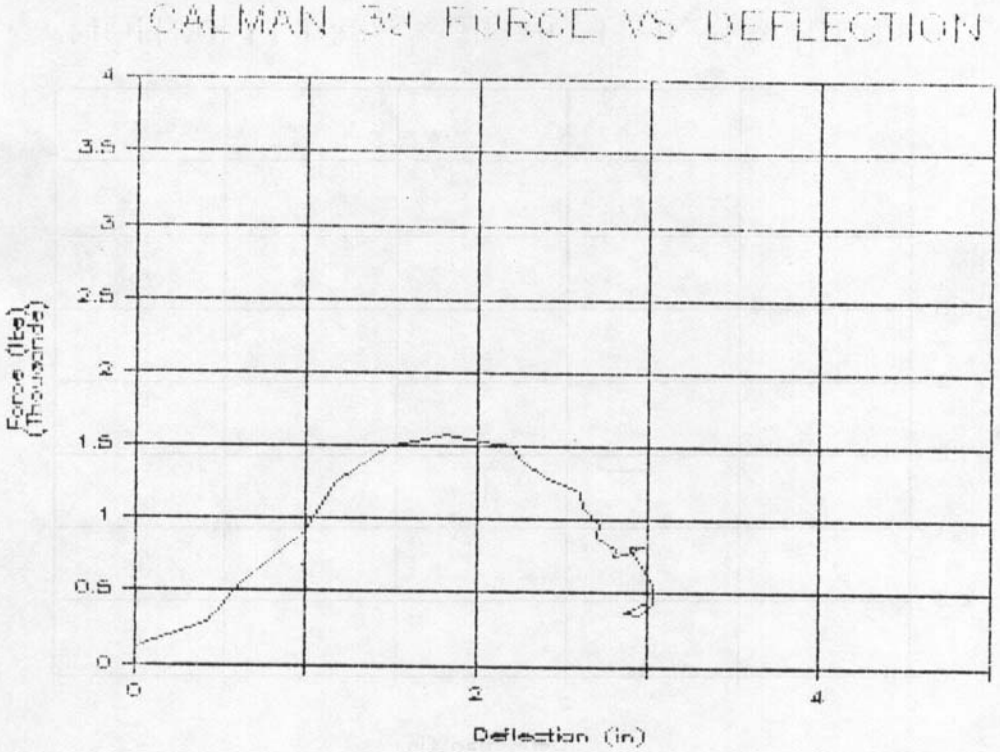


Figure 4

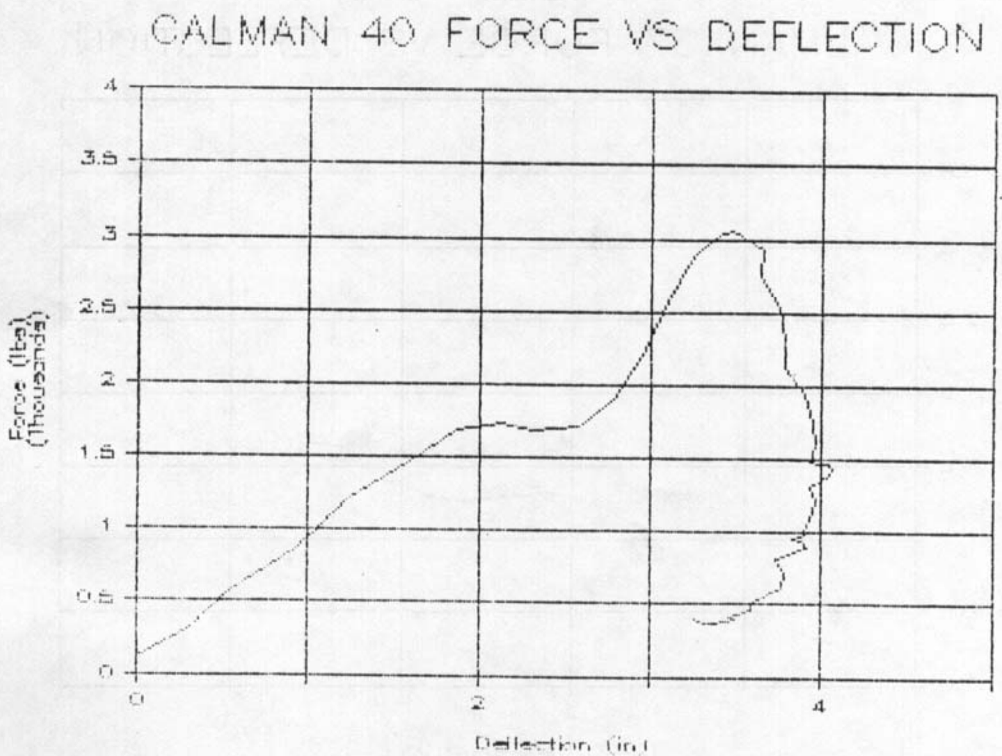
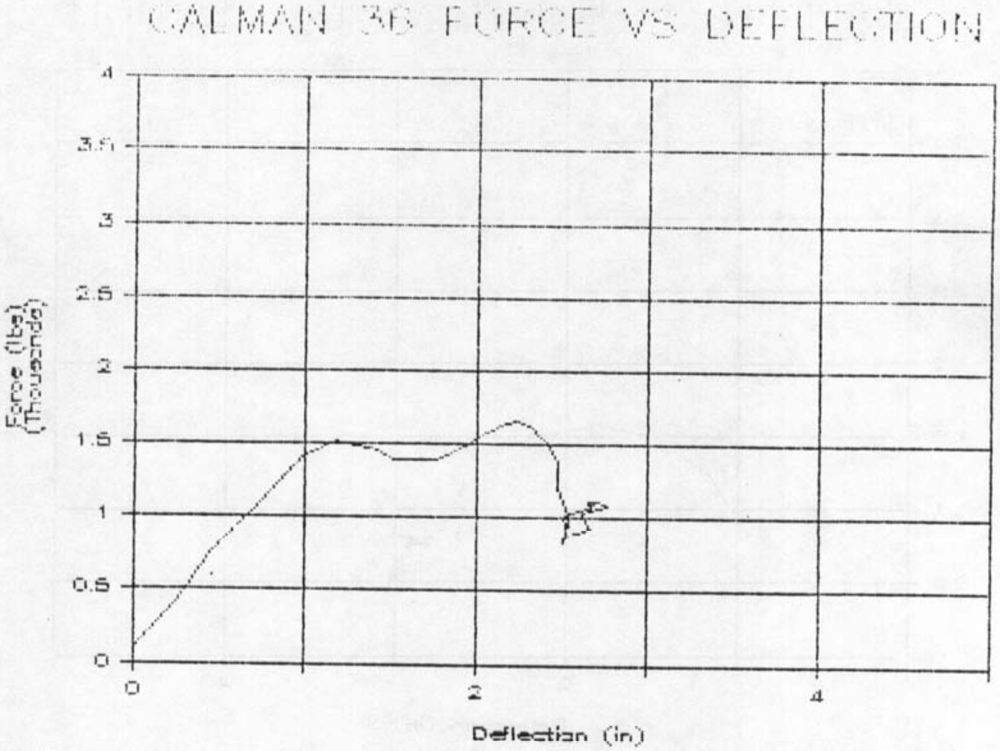


Figure 5



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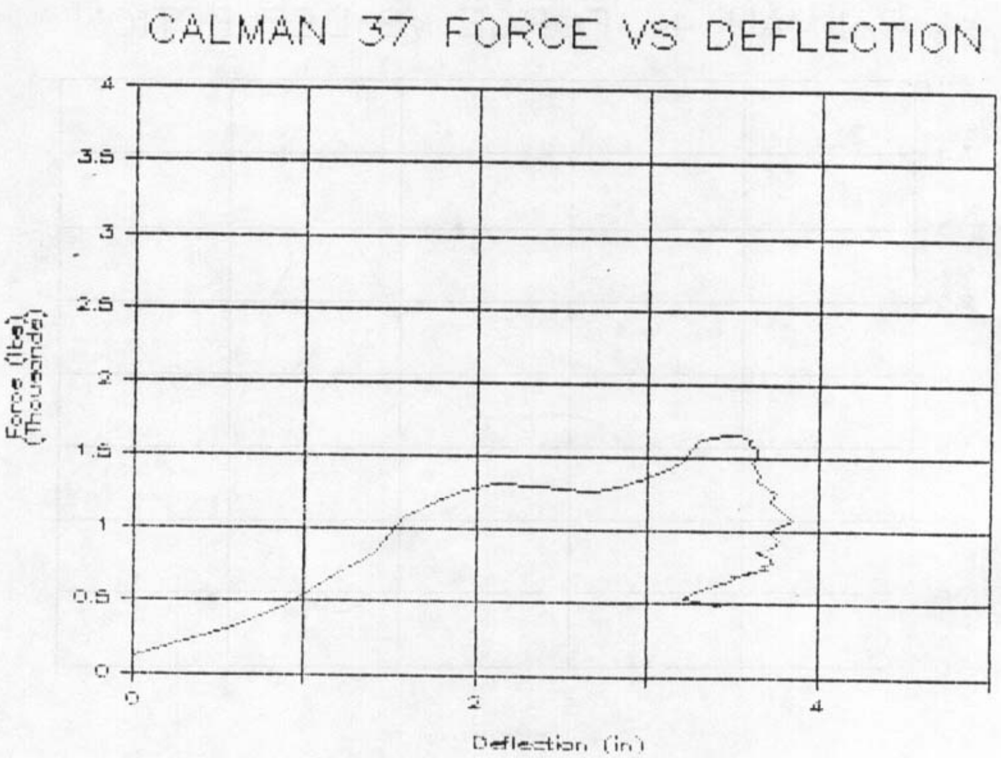

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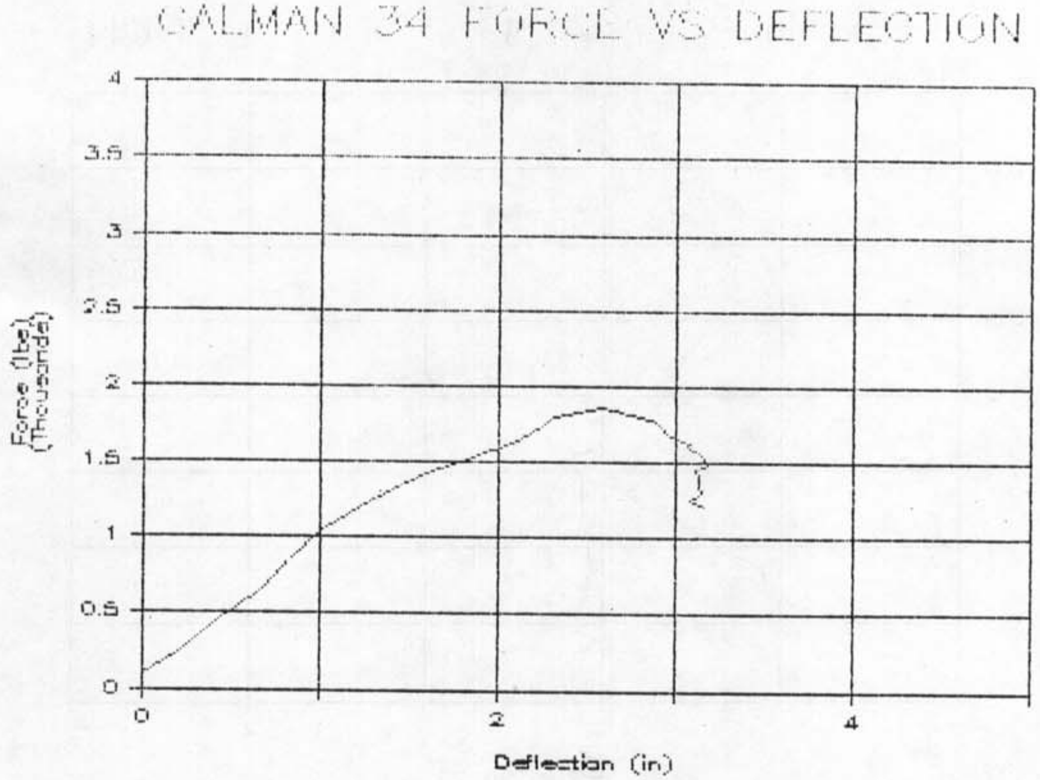

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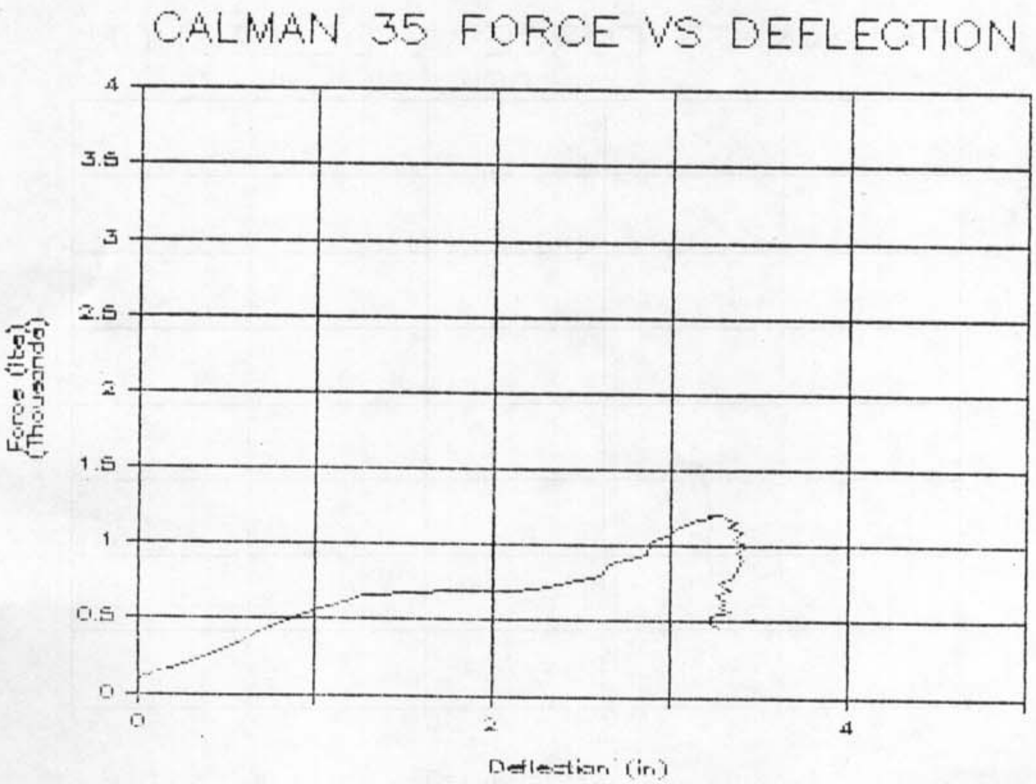

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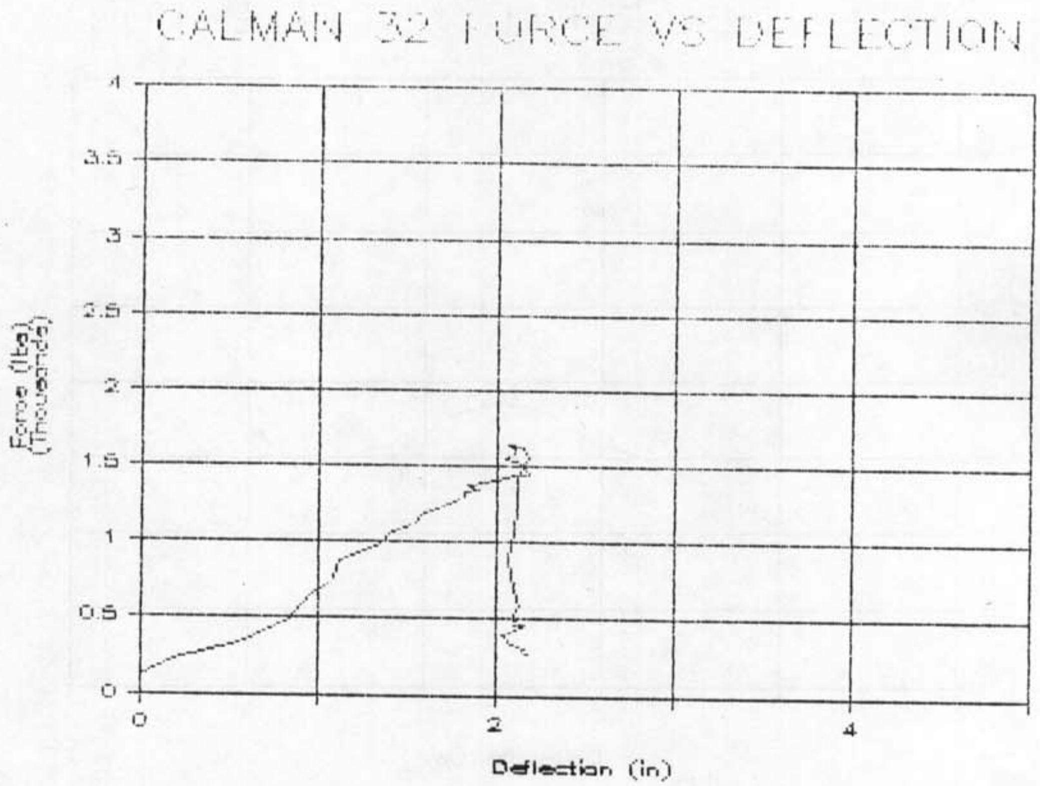

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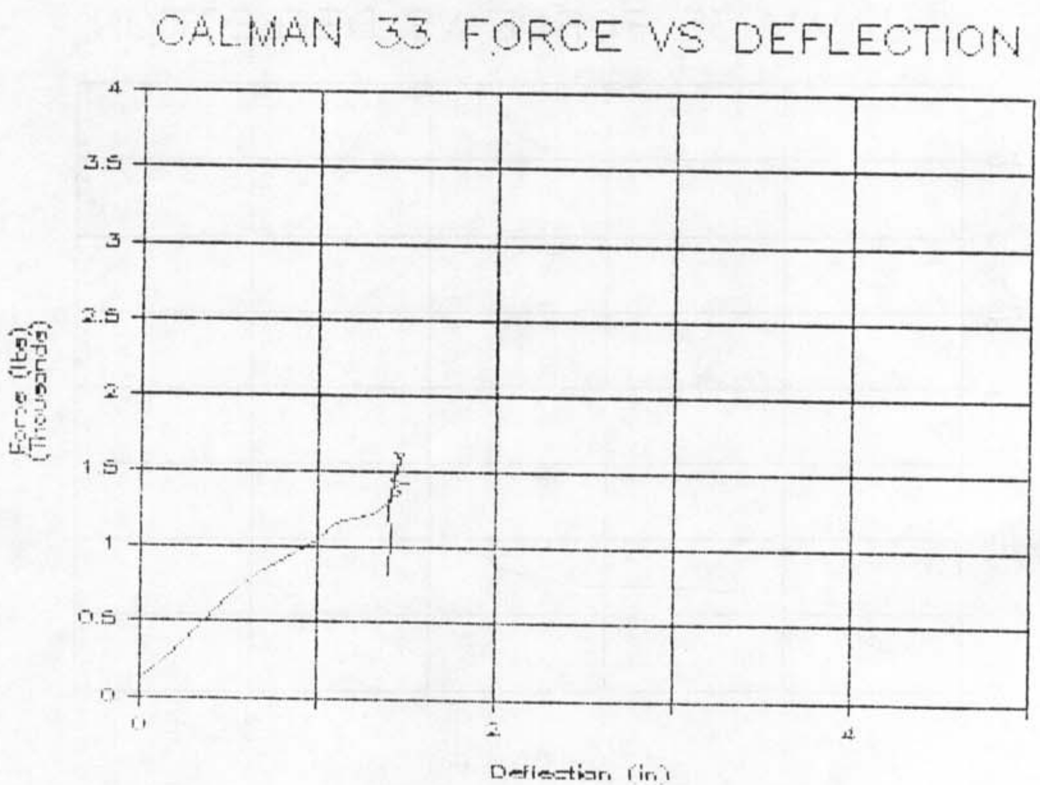


Figure 11

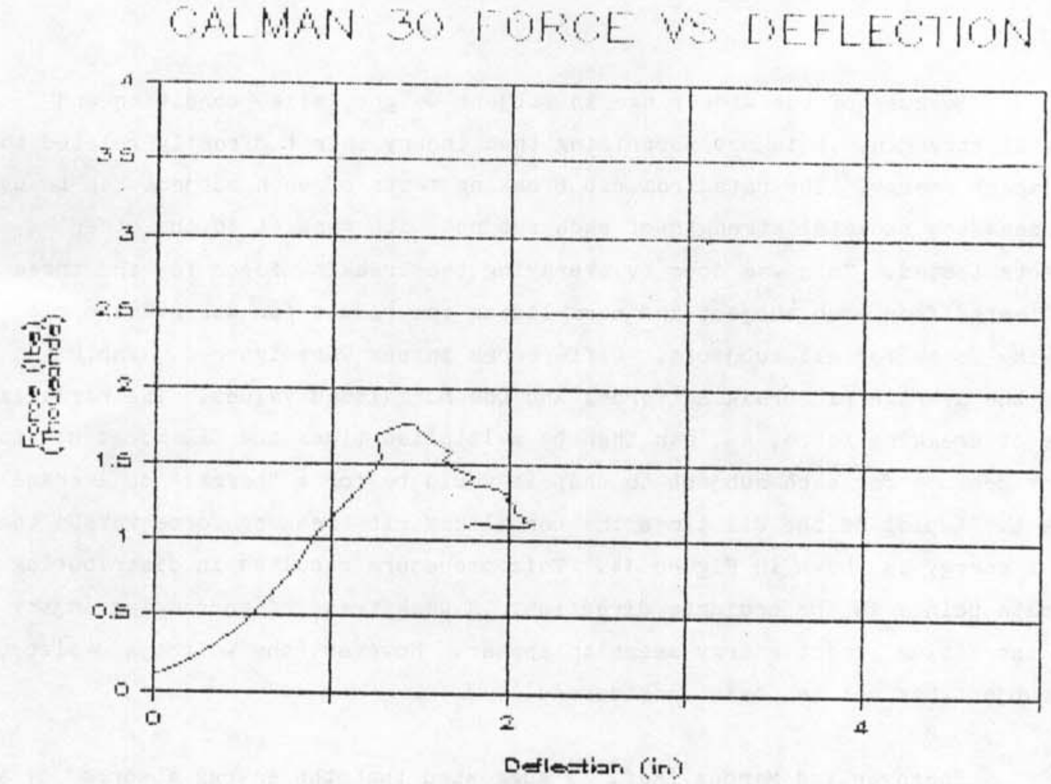
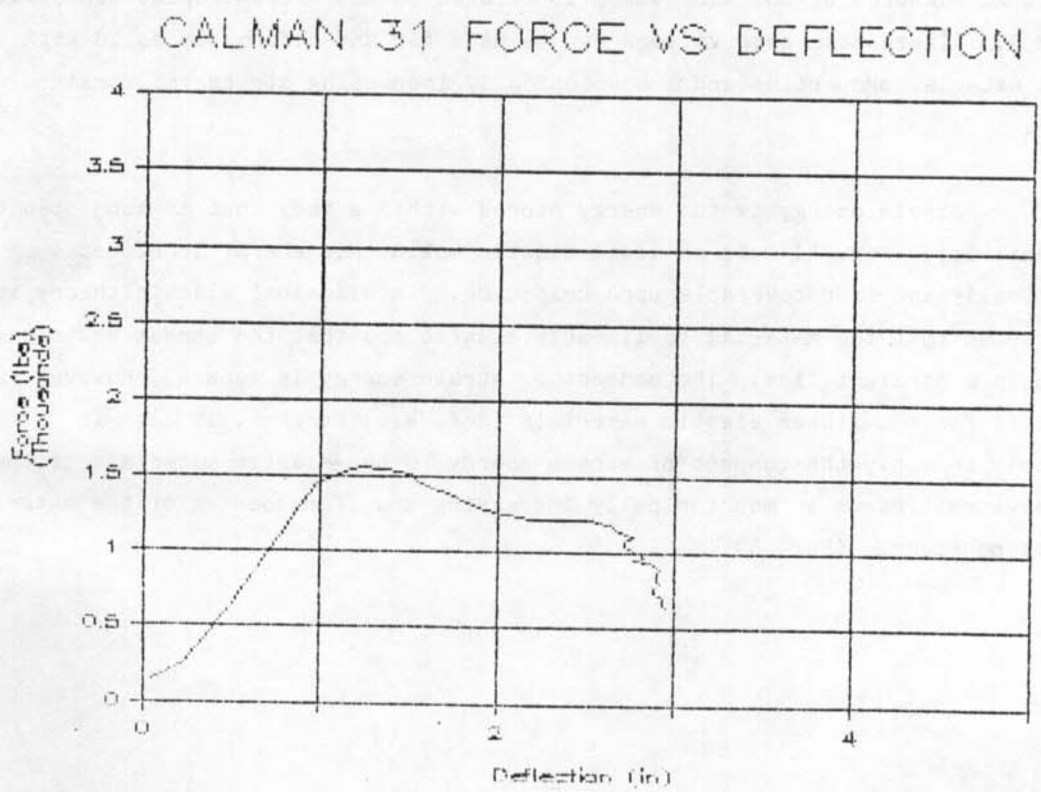


Figure 12



Because of the wide range in subject weight, size, condition and skeletal strength, it is not surprising that injury is not directly related to the impact energy. The data from rib breaking tests of each subject can be used to assess the skeletal strength of each subject with respect to the other subjects tested. This was done by averaging the breaking force for the three ribs tested from each subject and normalizing the result for the average rib breaking force for all subjects. Differences in sex were ignored. Table 5 gives the average rib breaking forces and the normalized values. The normalized value of breaking force, R_B, can then be multiplied times the CII to adjust the injury measure for each subject to what it would be for a "normal" or average subject. A plot of the CII times the normalized rib breaking force versus the impact energy is shown in Figure 14. This procedure resulted in distributing the data points in the ordinate direction. A weak trend of increasing injury with increasing impact energy seems to appear. However, the weight and size of the subject has not yet been considered.

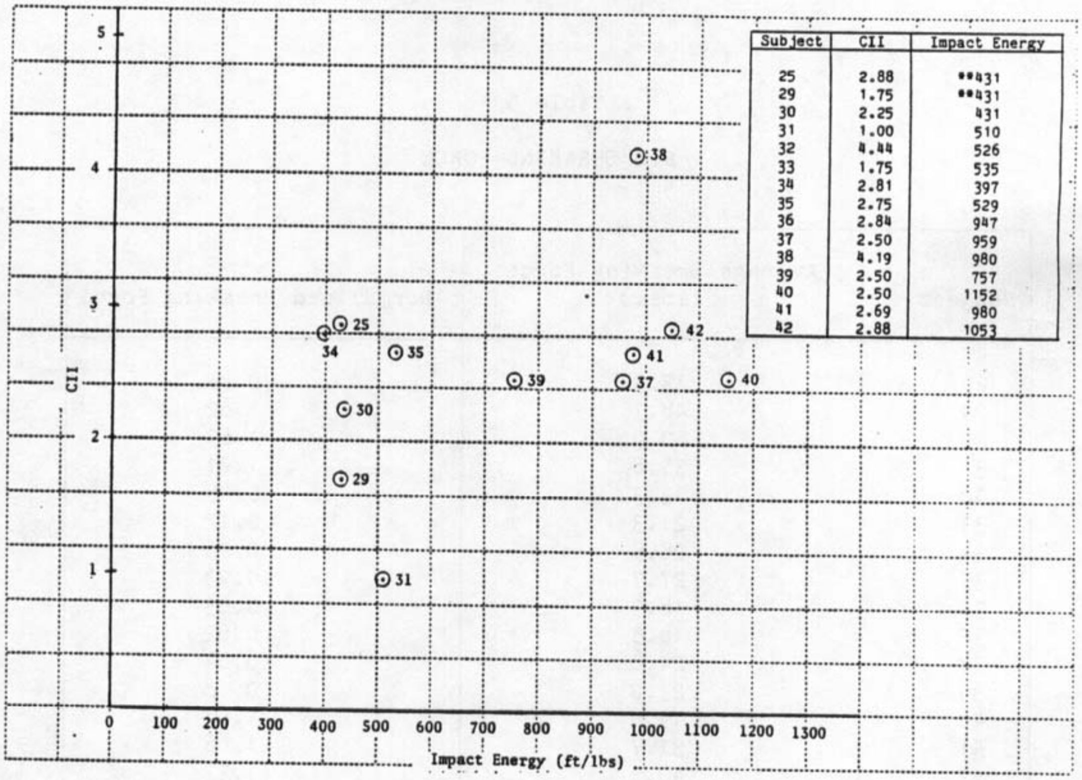
Eppinger and Marcus (Ref. 1) suggested that the energy absorbed by a subject in a blunt frontal thoracic impact is related to injury as measured by the AIS number. It is also generally accepted that thoracic injury from a blunt impact as measured by the AIS number is related to the chest displacement (Ref. 2 and 3). These same observations can be made for any deformable solid with known material properties and a monotonically increasing stress vs. strain curve.

Strain energy is the energy stored within a body that is subjected to external load (Ref. 4). In an ideal elastic solid this energy is stored elastically and is recoverable upon unloading. In classical elastic theory it is assumed that the material is linearly elastic and that the stress vs. strain curve is a straight line. The concept of strain energy is general, however, and is valid for non-linear elastic materials (Ref. 4). Further, it also is possible to apply the concept of strain energy to non-elastic materials if the stress-strain curve is monotonically increasing and if unloading of the material is not considered (Ref. 5).

Table 5

RIB BREAKING FORCE

Subject	Average Breaking Force (lbs.)	Normalized Breaking Force
25	13.3	0.45
29	48.1	1.62
30	50.0	1.69
31	35.8	1.21
32	13.3	0.45
33	21.3	0.72
34	28.5	0.96
35	27.7	0.93
36	18.9	0.63
37	18.5	0.62
38	24.8	0.84
39	23.0	0.78
40	49.6	1.67
41	31.7	1.06
42	40.5	1.37
	AVG. 29.7	



Subject	CII	Impact Energy
25	2.88	**431
29	1.75	**431
30	2.25	431
31	1.00	510
32	4.44	526
33	1.75	535
34	2.81	397
35	2.75	529
36	2.84	947
37	2.50	959
38	4.19	980
39	2.50	757
40	2.50	1152
41	2.69	980
42	2.88	1053

Figure 13 CII VS. ENERGY OF IMPACT

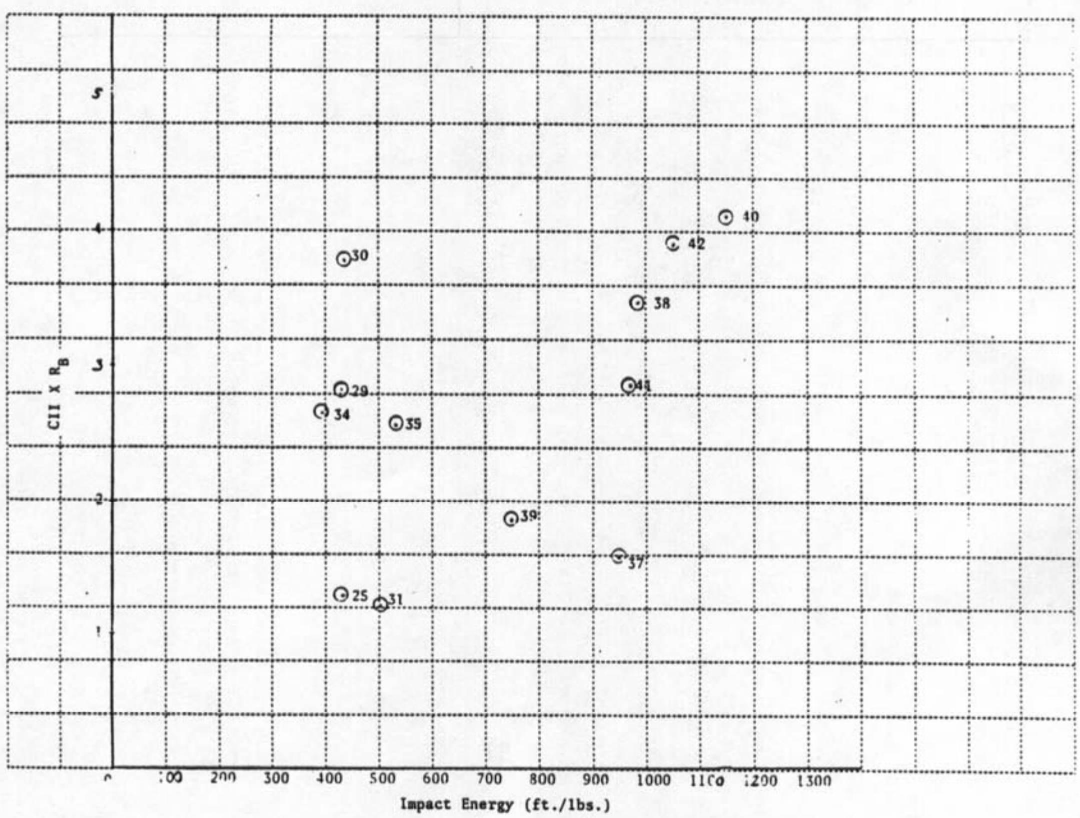


Figure 1: CII X RIB BREAKING FORCE VS. IMPACT ENERGY

Strain energy density for a unidirectional loading is:

$$U^* = \int_0^{\epsilon_{MAX}} \sigma \, d\epsilon$$

Figure 15 is an example of a non-linear monotonically increasing stress-strain relationship that may or may not be elastic. Clearly strain energy density, U*, is the area beneath the stress-strain curve. The total strain energy, U, for a given body is the strain energy density function integrated over the volume of the body.

$$U = \int_V U^* \, dV$$

or

$$U = \int_V \int_0^{\epsilon_{MAX}} \sigma \, d\epsilon \, dV$$

For the Calspan impacts the stress could be the force developed by the impactor at any time divided by the area of the impactor face. The strain, at any time, could be the penetration of the impactor face into the subject divided by the depth of the thorax. Using these assumptions the equation for strain energy would be written:

$$U = \int_V \int_0^{\epsilon_{MAX}} \frac{F_I}{A_I} \, d\left(\frac{P}{D}\right) dV$$

where F_I = impactor force
A_I = impactor face area
P = penetration
D = chest depth

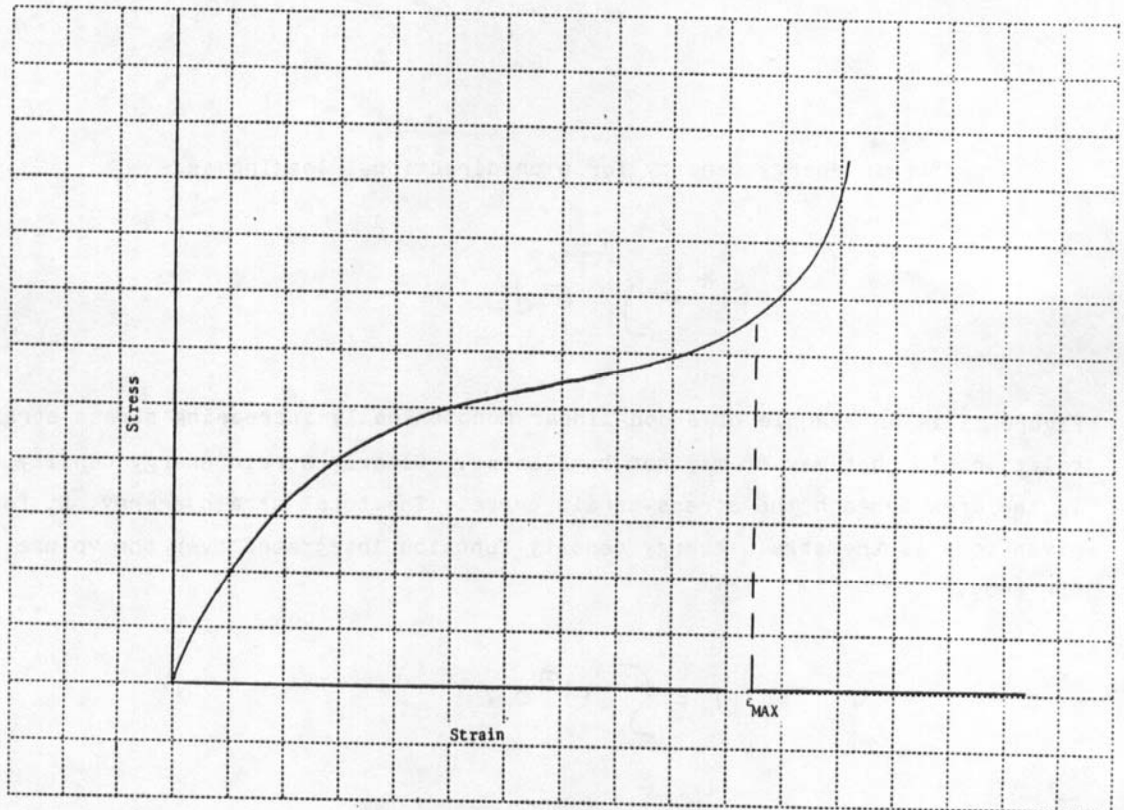
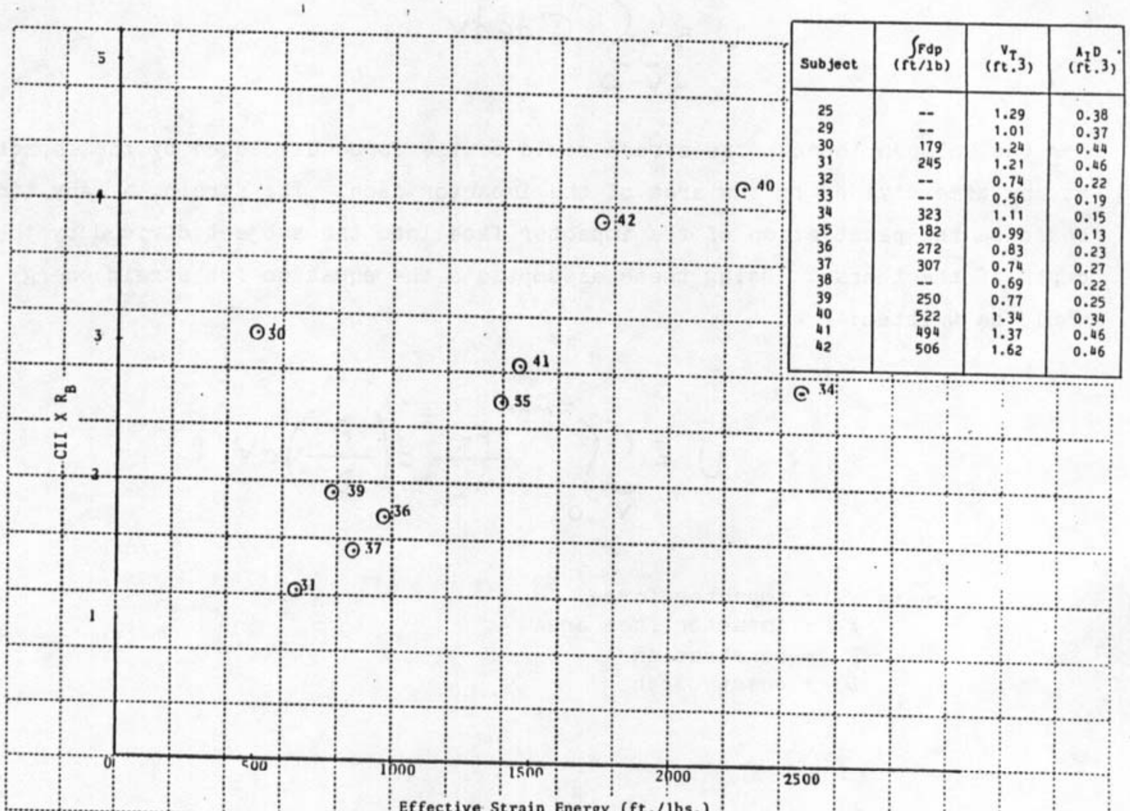


Figure 15 TYPICAL STRESS VS. STRAIN CURVE



Subject	$\int Fdp$ (ft/lb)	V_T (ft.3)	$A_I D$ (ft.3)
25	--	1.29	0.38
29	--	1.01	0.37
30	179	1.24	0.44
31	245	1.21	0.46
32	--	0.74	0.22
33	--	0.56	0.19
34	323	1.11	0.15
35	182	0.99	0.13
36	272	0.83	0.23
37	307	0.74	0.27
38	--	0.69	0.22
39	250	0.77	0.25
40	522	1.34	0.34
41	494	1.37	0.46
42	506	1.62	0.46

Figure 16 EFFECTIVE STRAIN ENERGY (ft./lbs.) $\left(U_\epsilon = \frac{V_T}{A_I D} \int_0^{P_{max}} F_I \, dP \right)$

or,

$$U = \frac{1}{A_I D} \iint_{V\,0}^{P_{MAX}} F_I \, dP \, dV$$

$$U = \frac{V_T}{A_I D} \int_0^{P_{MAX}} F_I \, dP$$

where V_T = volume of the thorax

This could also be written

$$U = \frac{A_T D}{A_I D} \int_0^{P_{MAX}} F_I \, dP$$

where A_T = the equivalent rectangular chest area

or,

$$U = \frac{A_T}{A_I} \int_0^{P_{MAX}} F_I \, dP$$

The integral is the work done by the impactor upon the subject that does not result in motion, i.e., the strain energy.

The ratio of areas, A_T/A_I, serves to increase the effective strain energy for large subjects. This term compensates for the fact that penetration is dependent on size of the impactor face with respect to the subject size.

This equation represents an equivalent strain energy for a human subject undergoing a blunt thoracic impact. It is based on the strain energy developed in a rectangular volume loaded along a single axis. This is, at best, an approximation. However, this approach does consider the energy of impact, the mass of the subject, the area of the impactor face, and the penetration. Further, if we plot the value of U calculated from this equation versus the CII times the rib breaking force the strength of the subject is also included. Figure 16 shows this plot. The force-displacement values for the integral were obtained from the curves presented in Figures 1 through 12. The value for A_T is not known so the volume of the thorax was calculated assuming it is an ellipse with the depth as a minor axis, the width as the major axis and the dimension from waist to shoulder as the height, and this volume was divided by depth D. A trend is clearly evident although there is some scatter.

The value of the integral in the strain energy equation cannot be found until after a test is performed. The approach for calculating absorbed energy as presented by Eppinger and Marcus (Ref. 1), however, can be applied before a test, since it is dependent on subject mass, if the planned impact velocity is used. Figure 17 is a plot of strain energy versus CII times rib breaking force using absorbed energy as calculated instead of the integral discussed earlier. The trend is again evident.

The rib breaking strength of a subject also cannot be known until post-test bending tests are performed. It may be possible to estimate this parameter from long bone percent cortical area measurements from X-rays or from Cameron bone mineral content density measurements. If this is true, then this effective absorbed energy relationship can be used to predict injury for a given subject and test conditions.

At this time this effective strain energy relationship must be considered to be very preliminary. The tests performed at Calspan have generated primarily skeletal injuries, and no information is available for more serious internal injuries. The data available for 6 inch diameter impacts performed at other laboratories must also be examined. Further testing with other size faces should also be performed. This effective absorbed energy relationship may, however, permit the systematic selection of test conditions for future tests.

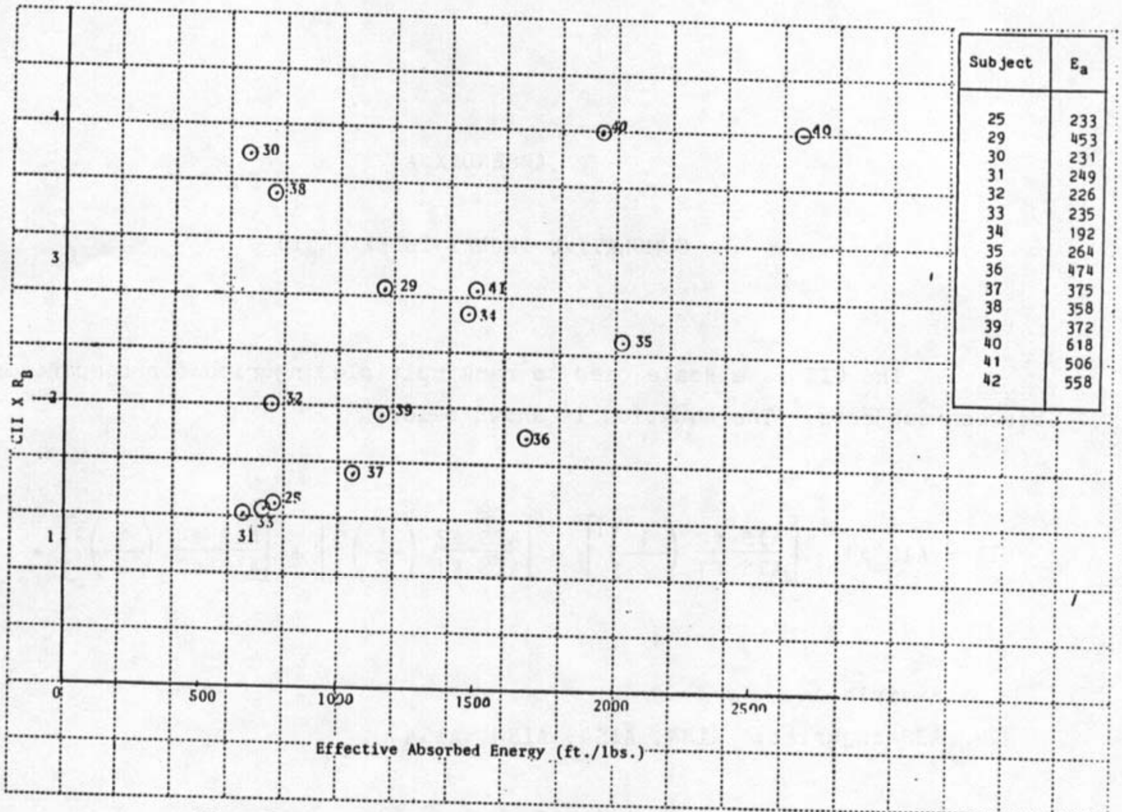


Figure 17 CII X RIB BREAKING STRENGTH VS. EFFECTIVE ABSORBED ENERGY $\left(U_A = \frac{V_r}{A_I D} E_a \right)$

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APPENDIX A

CUMULATIVE INJURY INDEX (CII)

The CII is a scale used to rank multiple injuries for comparison between subjects. The equation is shown below.

$$CII = AIS\ \#1 + \left[\frac{AIS\ \#2}{AIS\ \#1}\left(\frac{1}{2}\right)^1\right] + \left[\frac{AIS\ \#3}{AIS\ \#1}\left(\frac{1}{2}\right)^2\right] + \left[\frac{AIS\ \#4}{AIS\ \#1}\left(\frac{1}{2}\right)^3\right] + \ldots$$

Example 1

AIS injuries: AIS4, AIS4, AIS4, AIS4

$$4 + \left[\frac{4}{4}\left(\frac{1}{2}\right)^1\right] + \left[\frac{4}{4}\left(\frac{1}{2}\right)^2\right] + \left[\frac{4}{4}\left(\frac{1}{2}\right)^3\right] = 4.875$$

Example 2

AIS injuries: AIS2, AIS2, AIS2, AIS2

$$2 + \left[\frac{2}{2}\left(\frac{1}{2}\right)^1\right] + \left[\frac{2}{2}\left(\frac{1}{2}\right)^2\right] + \left[\frac{2}{2}\left(\frac{1}{2}\right)^3\right] = 2.875$$

From these examples it can be seen that the CII weights the AIS values in a similar manner regardless of the AIS level.