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EXAMINATION OF THE THEORETICAL BASES OF CURRENT INJURY INDICES AND CONSIDERATIONS FOR THE FUTURE.

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ABSTRACT - A linear, visco-elastic, distributed mass model developed to produce values of local stress, strain, strain energy density, and other traditional material failure indicants as a function of time has been exposed to a wide range of expected impact scenarios. The results of these analytical experiments are then used to determine the ability of several currently popular injury indices, such as TTI and V*C, to predict the extent and severity of structural damage within the model based on each of the traditional failure indicators.

Additional issues, such as (1) effects of geometrical changes on the performance of the current injury indices, (2) temporal relationships between the current indices and the various material failure indicators, and (3) spatial distribution of the predicted failure within the structure, are addressed and evaluated.

Conclusions and recommendations are offered on all of the above subjects.

INTRODUCTION - Current automotive safety evaluation practices subject mechanically based human surrogates, commonly referred to as test dummies, to specified crash circumstances and measure on or within the dummy a variety of engineering parameters, such as forces, accelerations, and displacements. These measurements are then interpreted to predict or limit the degree of human injury severity or risk. The injury interpretations are accomplished through the use of analytical functions that relate the engineering measurements to the various variables classifying the pathophysiological consequences. These relationships are commonly referred to as either "injury criteria," "injury tolerances," or "injury indices."

Because of the difficulty of characterizing in detail both the geometrical and material properties of the human anatomy as well as observing its dynamic response to impact, current impact biomechanics research practice for developing "injury indices" is to conduct a series of impact tests on biological specimens; obtaining characterizations of the structure's impact response by instrumenting and/or observing the structure's motion at a number of locations, determining the extent and severity of the resulting pathophysiology by post test physical examination; and developing indices by using statistical procedures to form empirical relationships between the engineering response parameters and the injury evaluations that characterize the outcome.

Since both accurate injury characterizations and impact response information is desired from each test conducted, the majority of measurement schemes obtain data from instrumentation on the external surface of the intact structure. Invasive instrumentation, while having the prospect of providing a more precise and detailed characterization of local structural response, invariably introduces artifactual trauma either during installation or during the dynamic event itself. Because this artifactual trauma is impossible to differentiate from the true impact induced trauma, internal instrumentation has not seen wide application.

Being limited to surface measurements and readily available measurement technologies has resulted in injury indices using parameters such as local peak accelerations, relative and absolute velocities, and relative deflections. These realities are evidenced by the various injury indices currently being proposed for use with side impact, i.e., the TTI which uses the peak accelerations from two points on the surface, the V*C which uses both relative deflection and velocity between a point on the impact site and a point on the far side of the structure, and relative deflection alone.

In the promotion and debate over the efficacy and technical bases of these various criteria, a variety of claims and counterclaims have become attached to each of them:

<u>TTI</u>

- o While the peak accelerations used do not specifically correspond to the time of occurrence of the actual injury, the TTI correlates well with the occurrence and severity of thoracic/abdominal injury as defined by the AIS, [1]*
- o The TTI has not been associated with any specific local body phenomenon (stress, strain, etc.), [1]
- o TTI lacks biomedical basis, [2]
- o Peak accelerations do not reliably describe injury risk, [2]

<u>V*C</u>

- o V*C is associated with the maximum instantaneous energy dissipated by the viscous elements representing the torso, [3]
- o V*C is not related to the viscosity of the thorax, [4]
- o V*C is found related to the peak (elastic) energy storing rate of the thorax, [4]
- o Viscous response relates to the actual etiology of injury, [5]
- o V*C can successfully indicate the time during the crash when the risk of soft tissue injury is the highest, [6]

It is the intent of this study, through the development and interrogation of a linear, visco-elastic, distributed mass model, to begin to examine the validity and reasonableness of these various claims by examining how well externally derived measurements from the model, such as V*C and TTI, correlate with the magnitude of the model's local, interior, material state variables (that is, stress, strain, and/or strain energy density); that are associated with classical material failure criteria.

<u>DESCRIPTION OF THE MODEL</u> - It was decided that the model should, as a reasonable compromise between complexity for the sake of accuracy and realism, and simplicity for ease of development and execution, be configured as a co-linear, seven-mass, linear visco-elastic system as illustrated in Figure 1. While this model is admittedly not a true representation of the human thorax, either structurally or materially, it was felt that it would be a good test of the basic claims and counterclaims now associated with the various criteria. If these claims could be demonstrated using this simple model, then their extension to the true anatomical structure would at least have the possibility of being true. Likewise, the antithesis would also be applicable. That is, if a concept could not be shown to be viable on such a simple model as the one

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* - Numbers in brackets designate references at end of paper.

proposed, then the probability of a claim being viable on the substantially more complex human structure would be extremely low.

The model was designed to simulate conditions representative of the variety of conditions that have been used in side impact testing, i.e., wall impacts at specified initial velocities and pendulum tests into the free standing body structure. In the model, M_0,(the left most mass of Figure 1), represents the wall or the pendulum, is assigned an initial velocity, V_0, and allowed to interact with the other masses representing the body which are initially at rest. When interaction with a constant velocity wall was desired, the mass of M_0 was set arbitrarily high (6300 lbm.) while when a pendulum simulation was desired, M_0 was set at 63 lbm. To simulate a variety of interface conditions between the striking surface and the simulated body, a variable elastic interface, (k_0 in Figure 1), was used. Its stiffness characteristic was varied between an extremely stiff setting representing a rigid wall and a soft setting representing a surface with a considerable amount of padding on it.

The model's representation of the body was accomplished by distributing 63 pounds of mass over the remaining six masses. The first five masses were assigned a value of 9 lbm. while the sixth, or the far side mass, held a value of 18 lbm. The elastic stiffness between each of the simulated body masses was set at 1500 pounds-force per inch (this represents an overall stiffness of the total body of 300 lbf/in) and each inter-mass linear damper characteristic was set at 10 lbf-sec/in. Throughout all subsequent simulations, all parameters defining the body were held invariant and only the initial velocity and mass of the impactor and the stiffness of the interface were varied.

The local material state variables were defined and calculated by the following methods:

Strain - the relative displacement between any two adjacent body masses divided by a gage length (2 in.) at any time "t" during the simulation.

Stress - the total force (the instantaneous sum of the elastic and viscous force) transmitted between any two adjacent body masses at any time "t" during the simulation.

Elastic Stress -
The force transmitted by the elastic component between any two adjacent body masses, (directly proportional to strain).

Viscous Stress -
The force transmitted by the viscous element between and two adjacent body masses.

Local Strain Energy Density -
The work expended in compressing both the elastic and viscous elements from time zero until time "t" between any two adjacent body masses.

Local Viscous Strain Energy Density -
The energy dissipated by the viscous element between any two adjacent body masses from time zero to time "t".

Total Absorbed Energy -
The sum of all five Local Strain Energy Densities at time "t".

Total Viscous Absorbed Energy -
The sum of all five local Viscous Strain Energy Densities at time "t".

The values of the various injury indices for each simulation were calculated using only data derivable or available from masses "1" or "6". That is, TTI was calculated as the average of the maximum accelerations observed on mass "1" and "6", V*C was calculated, as prescribed by the originators, as the maximum instantaneous product of the relative velocity and normalized deflection between mass "1" and "6." Total exterior deflection was calculated as the relative displacement between masses "1" and "6."

<u>DEFINITION OF FAILURE</u> - All major anatomical structures -- because they are structures that must be provided with a variety of physical materials for nourishment, cleansing, protection, etc. via an intimate, closed loop circulatory system, must be provided innervation for functional input or output, must maintain a specific and unique cellular configuration to achieve their unique life function for the body -- are not homogeneous or isotropic in any stretch of the imagination. Rather they are intimate intermingling of many different structural entities that all contribute a structure's architecture and function. Therefore, as mechanical disturbances from impact propagate through such structures, their effects, whether dysfunctional or destructive, effect each of the sub-anatomical entities at different times and with different severity. However, when these individual effects are viewed as a whole and graded by a coarse severity grading scheme such as the AIS, the overall rating of injury severity appears to increase gradually with increasing mechanical intensity of the impact event rather than having a distinct threshold below which nothing occurs and above which total catastrophic destruction and/or disfunction occurs.

Since the model being interrogated in this study is extremely simple and does not represent any specific anatomical reality, the degree of failure or injury severity, for the sake of this study, will be considered to be proportional to the magnitude of the material state variables defined and no specific threshold failure levels will be assigned to any state variable. The characteristics of the model will remain linear and invariant regardless of the intensity of the simulated event.

<u>TEST MATRIX</u> - The model described above was exercised using a full factorial test matrix with the following variable ranges:

- Impactor Mass, (M_O)
  - 6300 lbm (to represent wall test) or
  - 63 lbm (to represent pendulum)
- Interface Stiffness, (k_O)
  - 400, 800, 1600, 3200, or 6400 lbf/in
- Initial Velocity, (V_O)
  - 10, 15, or 20 miles per hour

For each of the 30 simulations, all described material state variables and associated injury indices were calculated and recorded.

DISCUSSION OF ANALYTICAL TEST RESULTS

<u>Temporal Relationships</u>: Details of the time response of various state variables at each of the five sections that constitute the total length of the body are illustrated in Figures 2 through 4. This set of figures represents only the model's response from one test condition, (15 mph wall

impact with a padding stiffness of 1600 lbf/in) for the sake of clarity. The sequential propagation of the various state variables along the length of the model was evident in all impact conditions modeled, only the shape and magnitudes obviously varied somewhat.

It is easily recognized from examination of these local state variables verses time plots that the effects of the simulated mechanical impact, whether local stresses or strains, propagate through the length of the body with some velocity that is determined by the model's defining parameters. Therefore, if one were to associate failure with a specific threshold level associated with a particular state variable, it is obvious that this threshold level is exceeded at different times at different locations in the body. This would suggest that there is no unique time after the initiation of the impact at which the total body is at greatest risk because each local body region reaches the prescribed risk level at a different time. As a result, the assertion that "V*C can successfully indicate the time during the crash event when the risk of soft tissue injury [read internal lesion] is the highest" [6] is not supported by this analysis.

<u>Injury Criteria verses State Variables</u>: To examine the predictive capabilities of the various injury indices in the most vehicle like side impact simulation, the constant velocity wall, all three injury indices were cross-plotted against each of the material state variables over the range of interface stiffness (400 to 6400 lbf/in) for the three initial velocities (10, 15, and 20 mph). The results are presented in Figures 5 through 11. Nine curves are presented on each plot. A set of three curves for each injury measure corresponding to the three initial velocities and each curve representing the range of interface stiffness from the softest (usually the left most point) to the stiffest (on the right).

The predictive capabilities of each of the injury indices for the wall simulations are easily observed in the figures. It is obvious that no one index predicts all material state variables perfectly. That is, the indices do not possess linear or non-linear, single valued, monotonic relationships with a state variable. It is equally obvious that all three indices have some predictive capability. In general, it can also be stated, that the predictive capabilities are least in the simulations associated with the stiffer interface conditions.

Examining Figure 5, which depicts Peak Local Stress, indicates that all three indices are poor performers. If the two stiffest test conditions are ignored, both Deflection and V*C would have tighter bands of points (with Deflection being the best) and appear to be better predictors than TTI. Figure 6, which depicts Maximum Local Strain, illustrates that total defection is the best and most linear predictor of local strain. If the two stiffest conditions were ignored, the capabilities of the other two predictors would improve slightly. Considering Peak Local Viscous Stress, Figure 7, illustrates the almost perfect linearity of TTI with this measure while the other indices perform poorly. Again, removing the two stiffest interface conditions improves the V*C's performance substantially but with only a small improvement in the predictive capability of Deflection.

Examining the performance of the injury indices with respect to the various strain energy density functions again shows that they possess varying predictive capabilities. Specifically, considering Maximum Local Absorbed Energy (elastic and viscous combined) in Figure 8, it can be seen that all criteria diverge from the performance of an ideal function, i.e., single valued and monotonic. Again, neglecting some of the stiffest interfaces improves the performance of all criteria with none having a substantially better performance than any other. In the specific case of Maximum Local Viscous Absorbed Energy (Figure 9), TTI appears to be the best performer over the entire range of simulations. As elimination of the stiffer interface conditions is made, TTI improves most readily, followed by V*C, and deflection really never becoming a good performer. Since Maximum Local Strain Energy is proportional to the square of the local strain, evaluation of the performance of the indices on Local Strain Energy will be the same as those give on strain above, i.e., Deflection the best, followed by TTI and then V*C.

If injury were related to the total absorbed energy of the body regardless where or when it was absorbed, examination of Maximum absorbed energy would be most appropriate. Figure 10 illustrates Maximum Total Absorbed Energy. Here V*C performs the best with Deflection close behind. TTI's performance does not improve until the two stiffest interface conditions are eliminated. The ability of the various criteria to predict the maximum total absorbed viscous energy (which has been suggested as the true etiological factor by Lau, [5]) is shown in Figure 11. Here, all indices are poor performers when all interface conditions are considered. Elimination of the two stiffest conditions appears to improve TTI and V*C substantially, but deflection never obtains a reasonable functional relationship.

<u>Effects of Mechanical Configuration on Response</u>: To assess the effects of changing the stimulation environment from a constant velocity wall to the substantially lighter pendulum type test, individual cross-plots of each injury measure verses the various state variables for the entire range of initial velocities and interface stiffnesses for both the wall and pendulum were made.

Figure 12, which shows the peak local viscous stress verses TTI for both wall and pendulum illustrates that for the same TTI values, the same level of viscous stress is generated. This performance suggests several things: that TTI is a fairly robust measure when used to predict this specific state variable and that pendulum tests would be as appropriate to use in developing an experimental data base as would the wall tests.

Figure 13 illustrates V*C's relationship to peak local stress for both pendulum and wall type impacts. What is obvious is that for a given level of peak local stress in a wall test, a higher value of V*C is produced than in a pendulum test. This performance also suggests several things: (a) V*C is not a robust predictor of this specific state variable, (b) that pendulum tests are substantially different from wall tests to produce two different values of V*C for the same level of peak local viscous stress, (c) and using pendulum tests as an experimental environment to develop a data base for predicting injury in wall type tests may be misleading.

The above example of the TTI's good and the V*C's poor performance illustrated above on the combined set of wall and pendulum tests was not meant to suggest that this was their behavior for all state variables examined. Rather, it was given as an example of good and poor performance of an index as test conditions are varied. The overall performance of each of the various indices varied and depended on with which state variable it was being compared.

Several comments are appropriate at this juncture. First, there are substantial relative differences between the mechanical environment that pendulum tests present to an invariant mechanical system and the environment presented by wall tests. That is, it is not possible to create an event totally equivalent to a wall impact with a pendulum. Only certain characterizing parameters can be equivalent while others must be different. For example, if relative impact velocity is to be the same, total energy managed cannot be the same, nor can the distribution of maximum viscous induced stress within the body be the same. Second, because of these differences, development of empirical injury indices, such as TTI and V*C, using data generated in a mechanical environment substantially different from the one where the index will be applied, may lead, depending on which fundamental state variables actually relate to injury severity, to the use of an erroneous and inappropriate injury index.

The antithesis to this last statement is also true. That is, the inappropriateness of an injury index may not be demonstrated by the fact that it cannot perform well in an environment for which it was not designed. If the performance of the index has, by whatever evaluation criteria used, been judged adequate for use in a specific environment, the fact that it does not perform well in another environment has no relevance.

<u>SUMMARY</u> - Comparing the results of this analytical investigation with the various claims and counterclaims attributed toward the three injury criteria studied, the following, within the context of the modelling assumptions, can be stated.

1. If relating to the actual etiology of injury can be construed to mean that an injury index exhibits a strictly linear or non-linear, single valued, monotonic relationship with a state variable over the entire range of compliances, all initial velocities, and both test environments, then, of the three indices studied, TTI (because of its linear, single valued relationship with peak viscous stress) and Deflection (because of its linear, single valued relationship with strain) may be considered possible etiological variables. Because V*C did not demonstrate such a single valued relationship with any of the examined state variables, its possible status as an etiological variable has not been established by this study.
2. Because the effects of impacting a viscoelastic, distributed mass system propagate through the length of the body and occur at various instants in time, any claim that V*C can identify an unique instant in time when total body injury risk is the highest is unsupportable by this study.
3. The claim that any of the externally derived indices is a good correlate of injury cannot be refuted by this study. That is, without making a prejudgment on which state variable, or combination of variables, are the etiological parameter(s) related to injury, every externally derivable parameter examined did correlate, with a varying degree of rigor, with at least some of the state variables examined.
4. While V*C does correlate with the various state variables associated with the viscous components of the model, the TTI generally had a better correlative ability with these particular state variables. Therefore, the claim that V*C is associated with the viscous absorbed energy is supported by this study. The

claims that TTI lacks biomechanical basis and that peak accelerations do not reliably describe injury risk are not supportable in the context of this study.

5. While the originators of the TTI indicated that they had not associated the index with any specific local body phenomenon (stress, strain, etc.), this study indicates that TTI does correlate well with several local and overall state variables.

<u>CONCLUSIONS</u> - Current experimental biomechanical practice limits practicable instrumentation to the surface of test specimens to avoid artifactual trauma interfering with injury assessment techniques. This has resulted in currently proposed injury indices utilizing measurements derivable from the surface of the the specimen. Since the true etiology of failure is most likely associated with local material state variables and a strict functional relationship between these local phenomenon and the surface responses has not been demonstrated, the determination of the efficacy of any empirical injury index can only be based upon the goodness of its correlative power with a specific injury measure and determined from a data set which encompasses the conditions of anticipated use. The use of data generated in a mechanical environment that is substantially different from the one of intended use, to either provide creditability to a given index or to discredit another, is highly speculative, not scientifically rigorous, and fraught with danger.

Within the limited complexity and reality of the model utilized, the claims critical of TTI appear unfounded. Also, without additional evidence to suggest that one particular local state variable is the only one associated with injury, this analysis cannot rule out any of the proposed criteria from being viable injury indices. It appears, therefore, that the only true method currently available to assess the efficacy of an injury index is to evaluate and judge its performance on a data base derived from experimental tests that encompass the expected range of its operation.

<u>REFERENCES</u>

1. Eppinger, R.H., "A Discussion of: "Evaluation of the SID Dummy and TTI Injury Criterion for Side Impact Testing" by D.C. Viano, SAE#872208" NHTSA Docket 88-06; Side Impact Protection, Washington, D.C.
2. Page 2 of Summary, General Motors submission USG 2665 to NHTSA Docket 88-06; Notice 1 and 2, October 24, 1988.
3. Lau, I.V. and Viano, D.C., "The Viscous Criterion-Bases and Applications of an Injury Severity Index for Soft Tissues," 30th Stapp Car Crash Conference Proceedings, #861882, SAE, Warrendale, PA, 1986.
4. Wang, J.T., "Analytical Studies of Injury Criteria for the Thorax," Research Publication GMR-6475, General Motors Research Laboratories, Warren, Michigan, 48090, November 4, 1988.
5. Lau, I.V., Viano, D.C., "How and When Blunt Injury Occurs-Implications to Frontal and Side Impact Protection," 32nd Stapp Car Crash Conference Proceedings, #881714, SAE, Warrendale, PA, 1988.
6. Page 8 of Summary, General Motors submission USG 2665 to NHTSA Docket 88-06; Notice 1 and 2, October 24, 1988.

Figure 1 - Configuration of Analytical Model

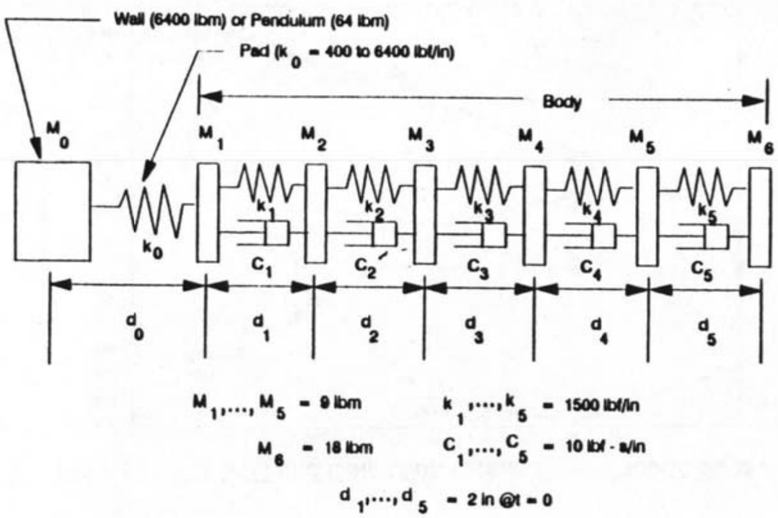


Figure 2 - Local Strain versus Time

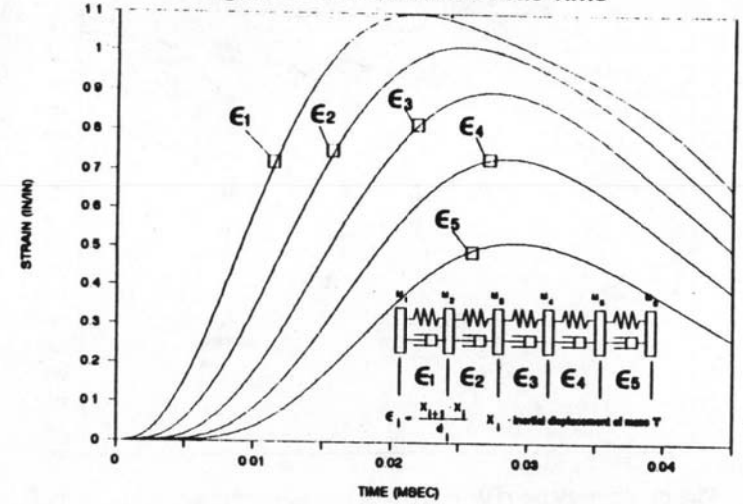


Figure 3 - Local Stress versus Time

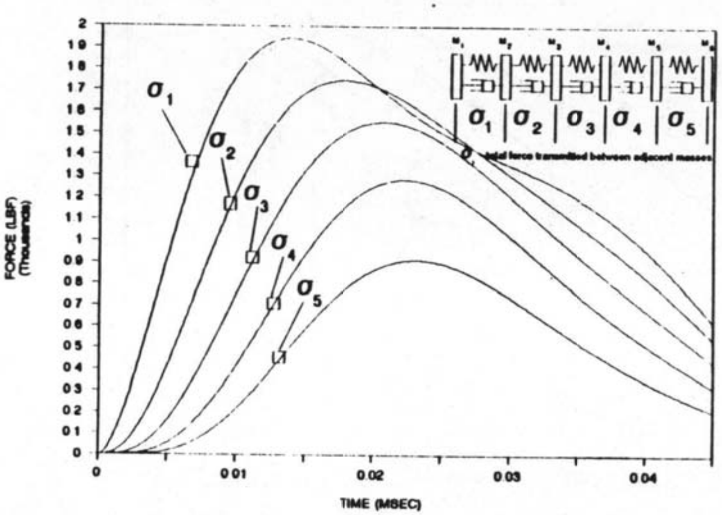


Figure 4 - Local Viscous Stress versus Time

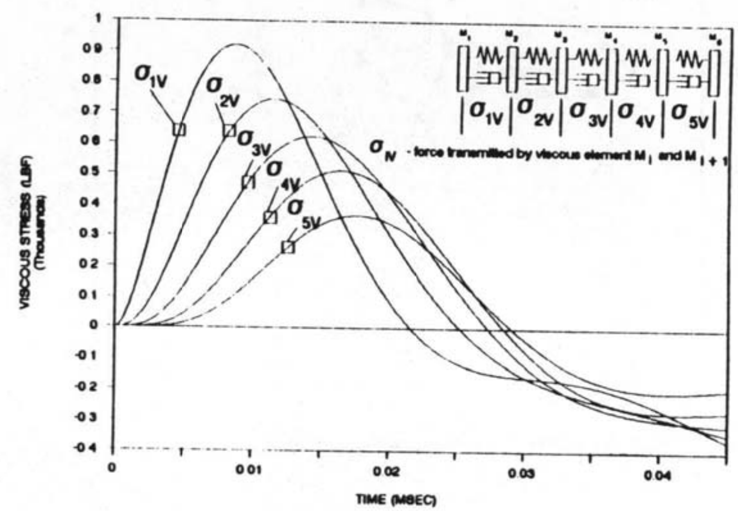


Figure 5 - TTI, V*C & Deflection versus Peak Local Stress

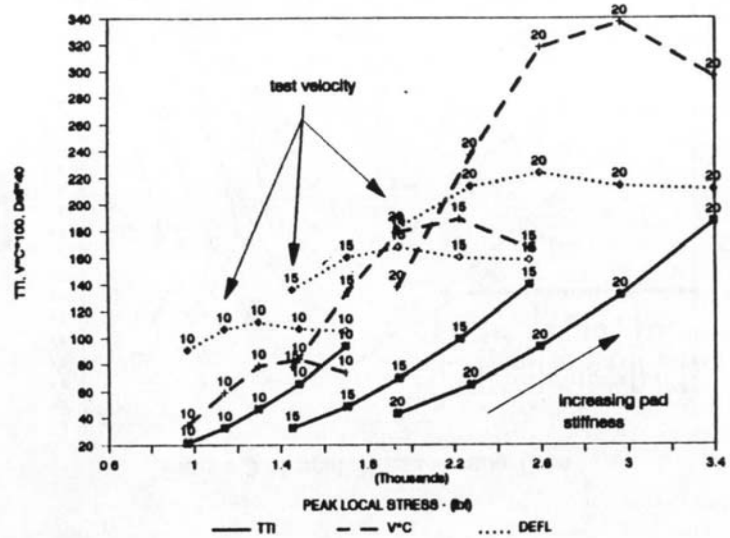


Figure 6 - TTI, V*C and Deflection versus Peak Local Strain

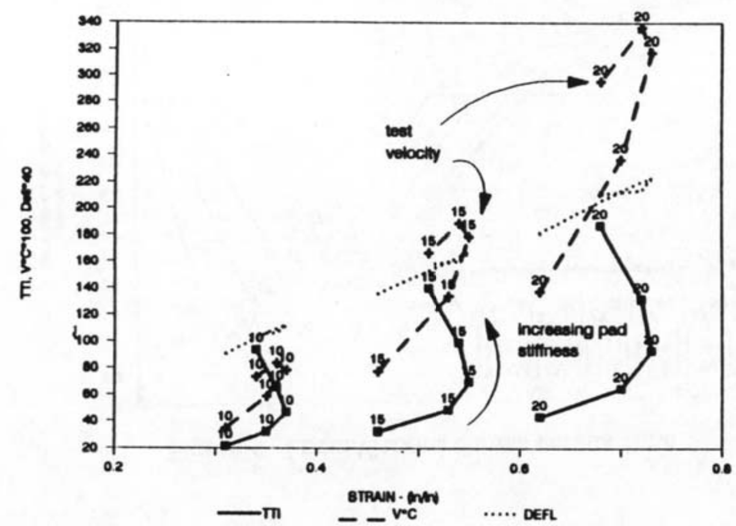


Figure 7 - TTI, V*C and Deflection versus Peak Viscous Stress

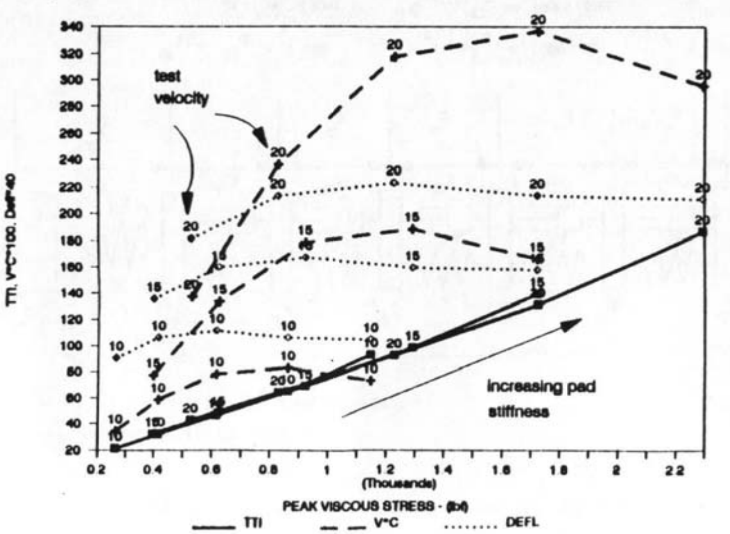


Figure 8 - TTI, V*C and Deflection versus Maximun Local Absorbed Energy

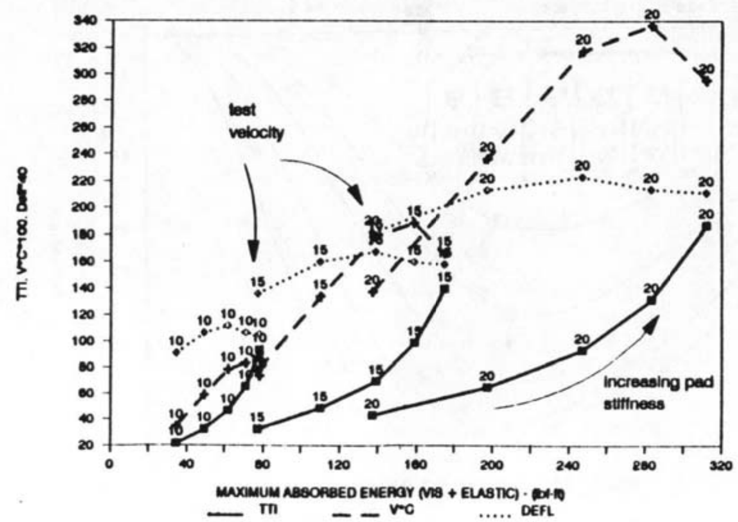


Figure 9 - TTI, V*C and Deflection versus Max Local Absorbed Viscous Energy

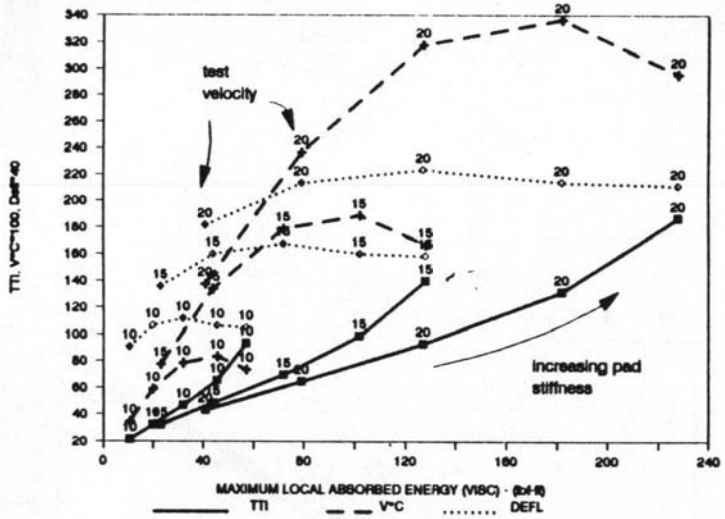


Figure 10 - TTI, V*C, & Deflection versus Maximum Total Absorbed Energy

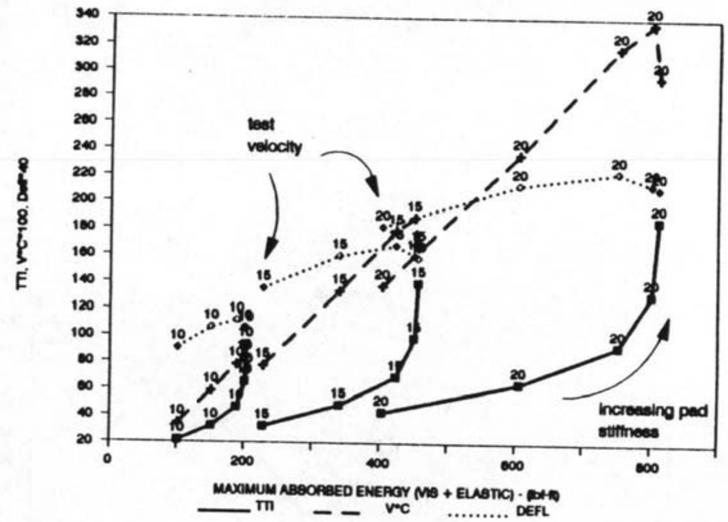
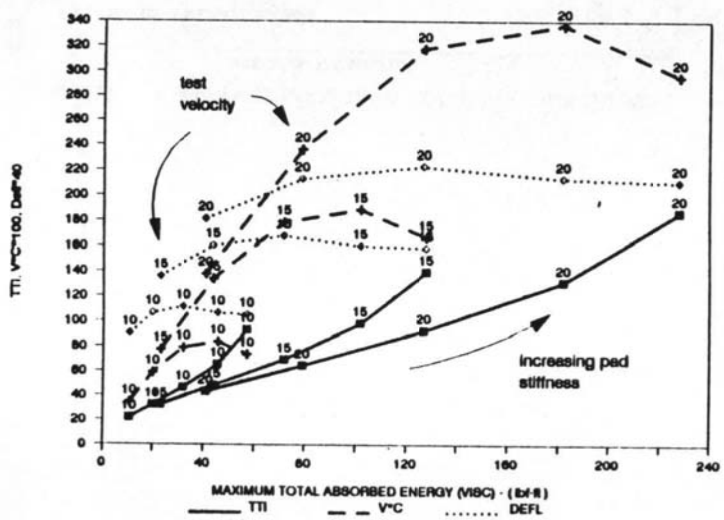


Figure 11 - TTI, V*C and Deflection versus Max Total Absorbed Viscous Energy



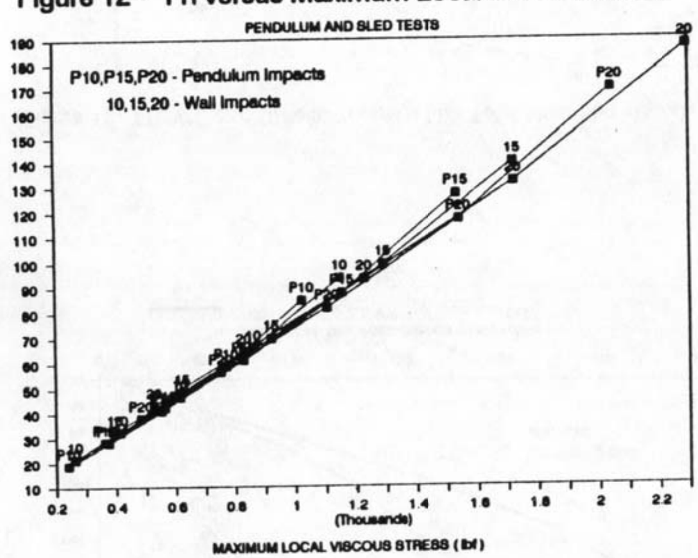


Figure 12 - TTI versus Maximum Local Viscous Stress

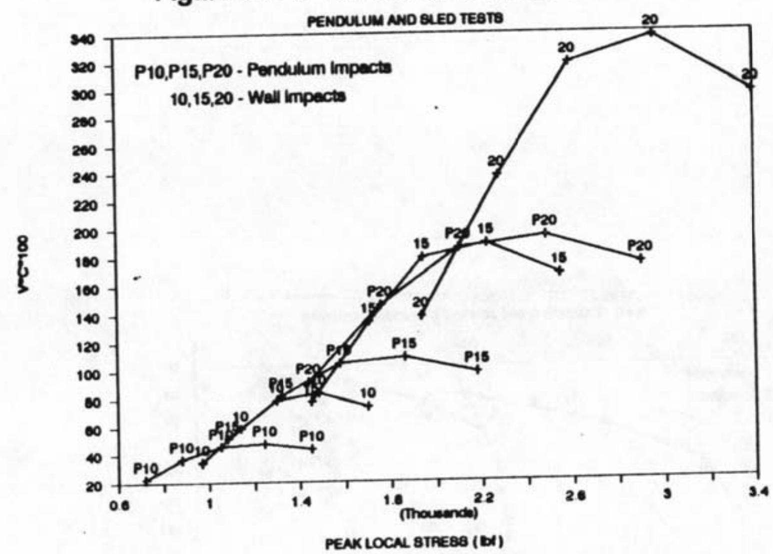


Figure 13 - V*C versus Peak Local Stress

PAPER: Examination of the Theoretical Bases of Current Injury Indices and Considerations for the Future

SPEAKER: Rolf H. Eppinger, DOT/NHTSA

Question: Walter Pilkey, University of Virginia

What is viscous stress?

Answer: It's the force that's transmitted through the damper, in this very simple system. This is discrete, obviously.

Q. Would you get a different result if you used a continuous model, but still get a consistent mass?

A. I would expect it would be. We've had some experience with some finite modelling of the thoracic chest. Again, we made a gross assumption of a uniform viscous material but in the finite element sense. We also see this wave propagation effect. There are several people in England, the names escape me, but, they also gave a paper, doing a lot of lung modelling. They saw this very progessive wave phenomenon going through the lung and that's how they explained the contusions that are arrived at in the lung. In fact, the criteria that they've come up with now is that the maximum dp/dt in the lung can be anytime during the event of the impact. Therefore, they're saying that nothing happens at a particular time when entire anatomical structures are at maximal risk but it's sort of a propagation process and that a certain part of a structure could be at risk at one moment in time and this wave continues propagating on and later another part of the structure is at maximum risk. So they go back through with a temporal free criteria and just accumulate all structures that exceeded a certain threshold dp/dt or dp/px.

Pilkey: I was asking about a lumped mass model as a continuous mass model you still have to "discretize" what you do with the finite elements.