MATHEMATICAL ANALYSIS OF RESTRAINT SYSTEM PERFORMANCE WITH THE AID OF A 2 - DIMENSIONAL CAR OCCUPANT MODEL

by

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ABSTRACT

A mathematical model is presented which simulates in 2 dimensions the motion of a restrained car occupant and thereby takes into account the deformations in lumped parameter form which are experienced by the human body as a result of belt loading during a crash event. The human body model has 10 degrees of freedom. In order to allow for a detailed analysis of restraint system performance, independent simplified models of the body regions contacted by a safety belt and of the restraint system itself were developed and combined with the body model. Model validation is performed by comparing the computer calculations with the results of a 50 km/h barrier crash test with sled and dummy.

In view of the pronounced deformation rate dependence of the human mechanical chest characteristics the presently used belt material with its structural damping behaviour, i.e. strain rate independent loading and unloading characteristics, does not seem to offer optimal protection. It is shown that an improved performance within the framework of the mathematical model can be obtained with a restraint system which exhibits a strong viscous, i.e. strain rate dependent mechanical component because such a system would have some capability of adapting its stiffness over a wide range of crash conditions and occupant characteristics.

I. INTRODUCTION

A common method of evaluating the performance of restraint systems for vehicle occupant protection consists in exposing a dummy serving as human surrogate and restrained by the harness to be tested to a prescribed deceleration pattern with the aid of an impact sled. Such a procedure is meaningful if the chosen standard test case or cases of surrogates and decelerations can be regarded as typical and representative of a wide class of possible victims and actual situations. In particular, for a given deceleration pattern the variations in the motions and loads exerted on a body arising from the natural biological variability of crash victims as well as from the normal spread of initial conditions (seating position, etc.) have to lie within certain appropriately prescribed limits with regard to the chosen standard case.

The hypothesis that a chosen set of standard cases indeed approximates sufficiently well a major class of actual accident circumstances is difficult to substantiate because on the one hand the number of tests which would have to be conducted in order to cover a comprehensive selection of accident situations would be unrealistically large and on the other hand our present accident reconstruction techniques do not allow for a sufficiently detailed analysis of actual accidents such that experiments for this purpose would become unnecessary.

In order to alleviate the discrepancy which exists between the limited experimental capabilities and the vast amount of actual accident circumstances and to gain a deeper insight into restraint system performance in general mathematical models for the simulation of mechanical crash victim response have been developed (e.g., McHenry 1963, Young 1970, Huston and Passerello 1971, Danforth and Randall 1973, Robbins et al. 1973, Fleck et al. 1974; for a more complete review see King and Chou 1976). Once a mathematical model is validated extensive parameter studies can be performed at relatively small expenses. Moreover, it should allow to evaluate proposed restraint system improvements prior to experimental realization which sometimes is not readily possible.

As a further step in view of these goals the computer model PSOS (Program for the Simulation and Optimization of Safety Belts) has been developed which allows for a more detailed analysis of harness performance and associated human surrogate response than has previously been possible. It has been developed from MODROS (Danforth and Randall 1973) whereby a main effort has been directed towards the simulation of restraint systems. In particular, PSOS allows the evaluation and optimization of safety belts with respect to

- mechanical characteristics of belt material, anchors, and seat
- mechanical compatibility between belt material and body parts exposed to belt loading
- performance in case of non 50% anthropometric occupants
- deceleration patterns which differ substantially from 50 km/h rigid wall impact

II. MATHEMATICAL FORMULATION

PSOS calculates the motion of a crash victim in two dimensions. The human body model consists of eight rigid segments connected by viscoelastic joints and thus has ten degrees of freedom. This system interacts with a vehicle and restraining safety belts during the course of the motion. The vehicle is composed of ten line segments which can be arranged arbitrarily. It executes a rigid, prescribed motion. The body model and an arrangement of the vehicle segments representing a typical car interior are shown in figure 1. The ten differential equations of motion (in Lagrangian formulation) can be integrated if all the forces acting on the system are known at each integration step. Apart from the gravitation and the nonconservative joint forces there are the contact forces exerted by the vehicle and the restraint system as well as possible contact forces between limbs which are not directly connected.

The body model and the associated differential equations have been adopted from MODROS (Danforth and Randall 1973). Furthermore, its well validated method of calculating contact forces from the penetration depth of body segments into vehicle elements is also utilized.

In PSOS the exterior body shape is given by ten ellipses which are rigidly connected to the segments and serve as contact sensing elements. The aforementioned penetration depth is derived from the amount of overlapping of these contact ellipses with vehicle elements. In case of an ellipse contacting only partially (edge contact), empirical corrections are introduced in order to prevent unphysical forces and force directions.

The model of the restraint system as implemented in PSOS is seen from figure 2. It includes models for the body parts contacting the belt (elements c_i), the belt itself and the anchors (elements a_i). The anchors a_i are rigidly connected with the vehicle in the anchor points A_1, A_2, A_3. The belt is coupled to the body through c_i which are given properties according to the nonlinear visco-elastic behaviour of the chest, the gut, and the pelvis. The points C_1, C_2, C_3 are rigidly connected to the limbs representing the upper, the middle, and the lower torso, respectively. The belt itself extends in a single strap from B_1 to B_6; it can glide in B_2, ..., B_5.

In order to be able to perform an integration step, one has to know the forces in and perpendicular to the elements c_1, c_2, c_3. The locations and the velocities of the points A_1, A_2, A_3, C_1, C_2, C_3 and the angles β_1, ..., β_6 are known at the beginning of a step. The forces in question can be calculated if the deformations δa_1, δa_2, δa_3, δc_1, δc_2, δc_3 of the anchors and the body elements as well as the gliding distances δb_{12}, δb_{23}, δb_{34}, δb_{45} of the belt in the points B_2, ..., B_5 are determined because then the deformations of the five connected belt segments B_1B_2, B_2B_3, B_3B_4, B_4B_5, B_5B_6 are also known as the whole system is geometrically uniquely determined. Therefore, we have the ten unknowns $d\delta a_1$, $d\delta a_2$, $d\delta a_3$, $d\delta c_1$, $d\delta c_2$, $d\delta c_3$, $d\delta b_{12}$, $d\delta b_{23}$, $d\delta b_{34}$, $d\delta b_{45}$, where d ... indicates the increment of the quantitiy to be calculated for this time step. They are determined from the following ten equations:

$$
\begin{aligned}
F_{a1} - F_{b1} &= 0 \\
F_{c1} - F_{b1}\cos\alpha_1 - F_{b2}\cos\alpha_2 &= 0 \\
F_{c2} - F_{b2}\cos\alpha_3 - F_{b3}\cos\alpha_4 &= 0 \\
F_{a2} - F_{b3}\cos\alpha_5 - F_{b4}\cos\alpha_6 &= 0 \\
F_{c3} - F_{b4}\cos\alpha_7 - F_{b5}\cos\alpha_8 &= 0 \qquad (1)
\end{aligned}
$$

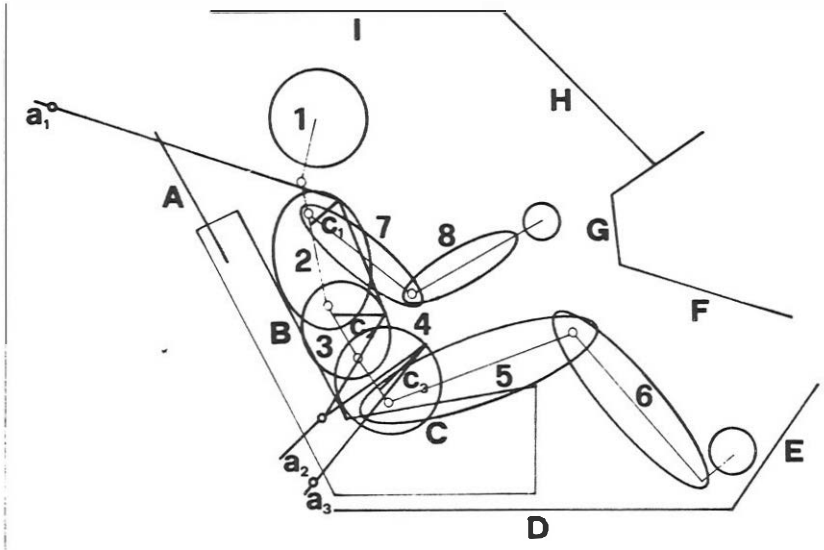

Fig. 1: 2-dimensional computer model PSOS

1 - 8:	body segments
A - I:	vehicle contour elements
$a_1,\ldots,a_3$:	belt anchors
$c_1,\ldots c_3$:	chest, gut, and pelvis element, connecting respective body segment with belt (see fig. 2)

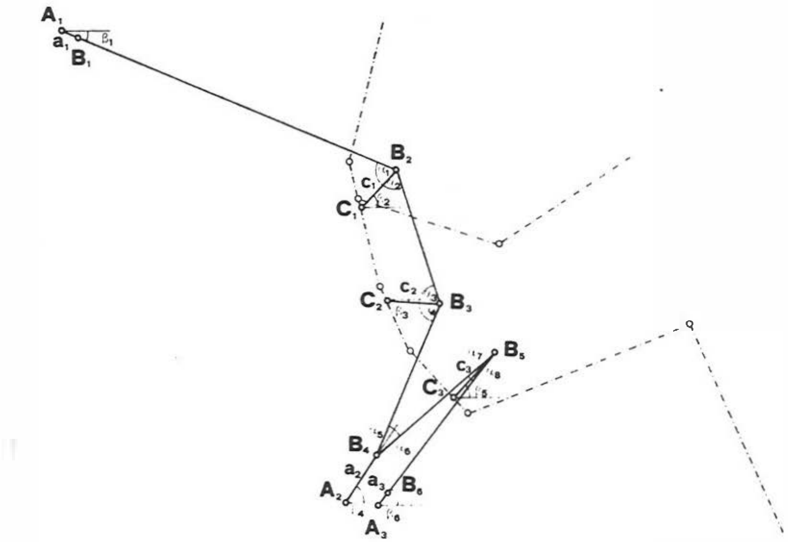

Fig. 2: Model of restraint system

broken line:	body model
solid line:	restraint system
A_1,A_2,A_3 :	anchor points with anchors a_1,a_2,a_3
$B_1,\ldots,B_6$:	belt consisting of five connected segments $B_1B_2=b_1,B_2B_3=b_2,B_3B_4=b_3,B_4B_5=b_4,B_5B_6=b_5$. It may glide in $B_2,\ldots,B_5$; the associated gliding distances are denoted by $\delta b_{12},\delta b_{23},\delta b_{34},\delta b_{45}$, respectively.
C_1,C_2,C_3 :	points rigidly connected to the upper, middle, and lower torso segments, serving as connecting points for the body support elements c_1,c_2,c_3
$\beta_1,\ldots,\beta_6$:	angles defining direction of body support and anchor elements, to be determined during integration such that $\alpha_1=\alpha_2$, etc.

$$F_{a3} - F_{b5} = 0$$
$$F_{b2} - F_{b1}\, e^{\pm \mu_1 (\pi - \alpha_1 - \alpha_2)} = 0$$
$$F_{b3} - F_{b2}\, e^{\pm \mu_2 (\pi - \alpha_3 - \alpha_4)} = 0$$
$$F_{b4} - F_{b3}\, e^{\pm \mu_3 \pi} = 0$$
$$F_{b5} - F_{b4}\, e^{\pm \mu_4 \pi} = 0$$

In these equations F_{ai} and F_{ci} are the forces in the anchors and the body elements, and F_{bi} are those in the five belt segments. The angles α_i are defined in figure 2. The first six equations follow from the equilibrium conditions for the points B_1, ... B_6 in the direction of the elements a_i and c_i, respectively. The equilibrium conditions perpendicular to these elements are fulfilled automatically if the forces F_{ci} are such that their directions coincide with c_i. This is achieved by calculating the angles β_2, ..., β_5 accordingly. The angles β_1 and β_6 are chosen such that the anchor and the belt segment fall into a straight line. The last four equations in *(1)* follow from the relations describing the gliding friction of a belt which slides over a cylinder with the friction coefficient μ_i and which is in touch with it over the angle appearing in the exponent. The signs follow from the direction of gliding.

From the system *(1)* the ten unknowns are to be determined. For this purpose, the forces are expressed in these quantities by assuming that F_{ai}, F_{bi}, F_{ci} can be represented as polynomials in the deflection and the deflection rates of the respective elements. This procedure is straightforward for F_{ai} and F_{ci}, but for F_{bi} the deformation and their time derivatives have to be eliminated using the geometrical relationships governing the displacements of B_1, ..., B_6 and the gliding distances δb_{12}, ..., δb_{45}. If materials with strain-rate independent characteristics are to be modelled, force-deflection characteristics can also be prescribed in tabular form. The resulting system of equations is nonlinear and therefore solved by iteration.

III. RESULTS

1. Standard Case

A standard test case for the evaluation of restraint system performance consists in a 50 km/h rigid barrier impact of a sled with dummy. It was therefore attempted to simulate first such a sample case with PSOS for validation purposes. Input parameters were taken from the MODROS baseline conditions (Danforth and Randall 1973), whenever applicable. The deformability of the chest element c_1 is chosen according to the measurements of Kroell et al. (1971)

while those of the gut and pelvis (c_2 and c_3) are hypothetical. Belt material characteristics are entered in tabular form in order to simulate the typical mechanical properties of present harnesses with strain-rate independent loading and unloading characteristics.

Representative results for the standardcase are documented in figures 3a (shoulder belt force F_{b1}), 3b (lap belt force F_{b4} as function of time), and 3c resultant (head acceleration as function of time). The solid lines show the calculated response, while the dotted lines indicate the typical resultsof a sled test (Klarhoefer, Volkswagen AG, private communication). In general, in view of the approximations and simplifications used in the model the results can be considered acceptable. However, the details of the head acceleration curve show considerable differences in comparison to the experimental curve, which can be attributed to the relatively unsophisticated neck and shoulder model of the mathematical surrogate. It can be expected that the implementation of an extensible neck and shoulder element could lead to more reliable head acceleration results. The differences found in the shoulder and lap belt curves may be explained by differences which exist in the mechanical seat characteristics of the mathematical model and the sled seat as well as by differences in the mechanical responses of the body elements c_i and the dummy.

In order to demonstrate the sensitivity of the computed sample results with respect to some of the crucial input parameters the influence of varying these parameters within the following ranges is shown in figures 3:

- joint stop angles of the two spine joints (see figure 1) between 15 and 45 degrees
- friction coefficients of the spine and neck joints within one order of magnitude
- friction coefficients μ_i (see eqs. (*1*)) between 0.01 and 0.1.

The spread of the resulting curves is depicted in figures 3 by shaded areas. As can be expected, the head acceleration curve exhibits the strongest sensitivity. The calculated HIC values range between 460 and 890. Furthermore, it was found that the friction coefficients μ_i have a significant influence on the simulation results. Due to this friction, the computed lap belt force is sometimes considerably lower than the one in the shoulder strap which is not confirmed by experiments. It can therefore be concluded that the friction model applied in eqs. (*1*) overestimates the influence of belt-body friction.

2. Improved belt system

Present restraint systems are optimized for a 50 km/h rigid barrier impact and have, as mentioned above, strain-rate independent loading and unloading characteristics. One might hypothesize that a restraint system with mechanical properties which exhibit a strong viscous, i.e. strain-rate dependent component would be

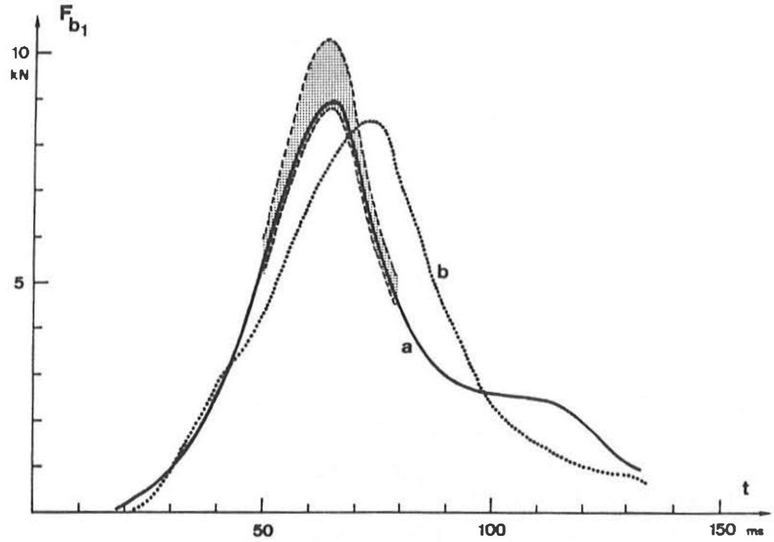

Fig. 3a: Force F_{b_1} in shoulder belt segment b_1 as function of time; standard case.

a: simulated results
b: typical test result

shaded area: see text

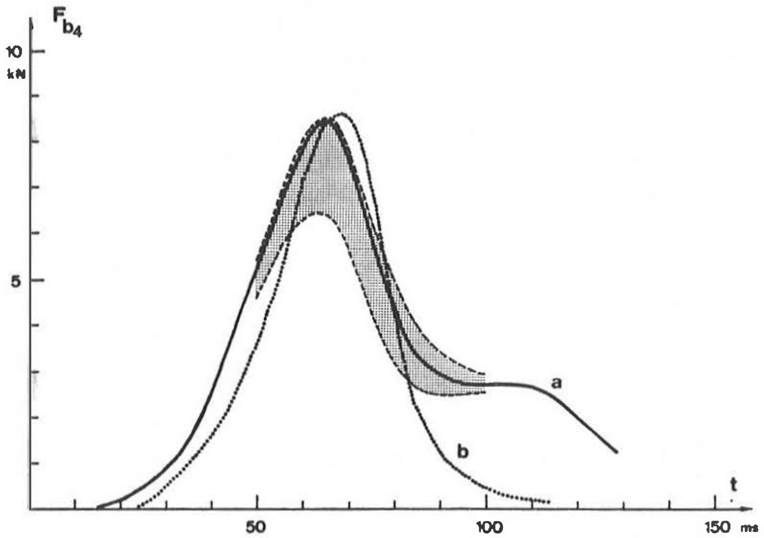

Fig. 3b: Force F_{b_4} in lap belt segment, same notation as fig. 3a.

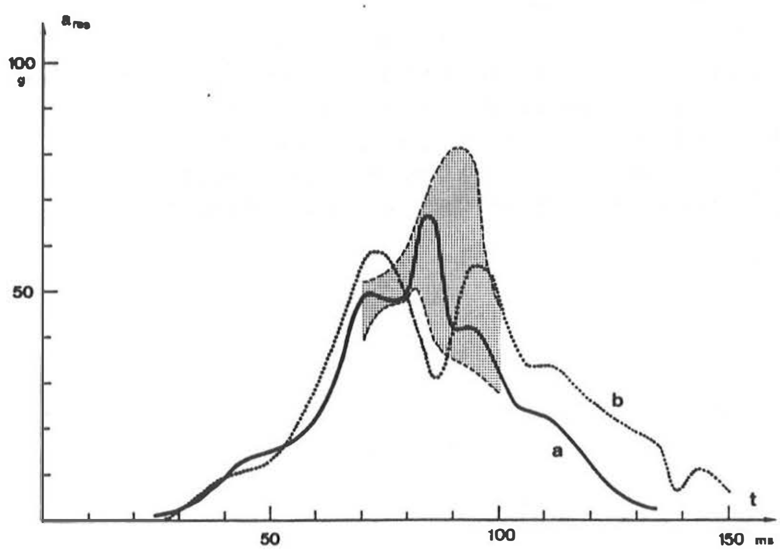

Fig. 3c: Resultant head acceleration, same notation as 3a.

preferable because such mechanical properties would allow a restraint system to become increasingly stiffer with increasing crash severity where in general higher deformation rates are to be expected. It would therefore have some capability of adapting its stiffness over a wide range of crash conditions and occupant characteristics and thereby retain reasonably small elongations. Moreover, in view of the viscoelastic properties of the chest which are also strongly deformation rate dependent, the mechanical compatibility between chest and harness could also be improved for situations which deviate substantially from the standard case considered above.

To substantiate this hypothesis, simulation results are shown in the following which were obtained with hypothetical restraint system characteristics having the desired viscous properties. Figure 4 shows the calculated maximal shoulder belt force as a function of impact speed for the standard (curve a) and the improved system (curve b). As expected, for the conditions of the standard case (13.4 m/sec impact speed) the differences are relatively small, while the improvements become progressively more important with increasing deviation from this case. Furthermore, in figure 4 the maximal relative extensions (%) of the shoulder belt segment for the standard (curve c) and the improved system (curve d) are seen indicating that an improved performance is obtained in spite of the substantially lower elongation of the hypothetical system. HIC values and head accelerations which however were seen to scatter considerably for the computer model and which therefore should not be assigned a decisive significance, are in all cases lower for the improved system.

In figure 5, the results are depicted for variations of the crash victim dimensions. Similar improvements are obtained as in case of the variations of the crash severity.

A further aspect of improved system performance is finally seen in figure 6 where the mechanical hysteresis loops for the standard belt (a) and the viscous system (b) are shown for the standard case. In spite of the lower maximal elongation, energy dissipation capabilities of the viscous system are superior. Moreover, the belt forces reach high levels already relatively early during the course of the crash because then the deflection rates are also high. This fact explains the lower head accelerations occuring with the improved system.

IV CONCLUSIONS

The computer model PSQS has been described and representative results have been demonstrated which show an acceptable agreement with experimental findings. As a next step of model improvement, an extensible neck and shoulder element could be of benefit.

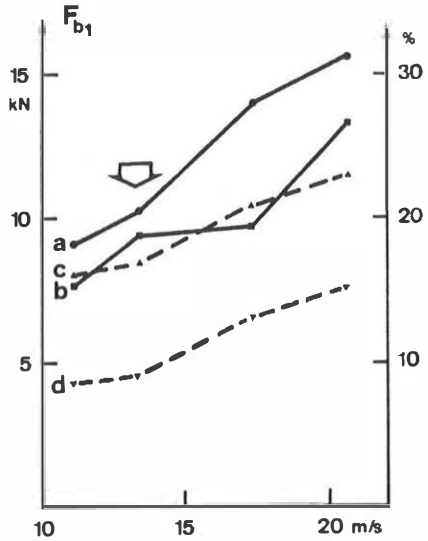

Fig. 4:
Maximal shoulder belt force F_{b_1} for standard belt (a) and improved belt (b) and maximal elongation of shoulder belt segment of standard belt (c) and improved belt (b) as function of impact speed. Standard case is indicated by arrow.

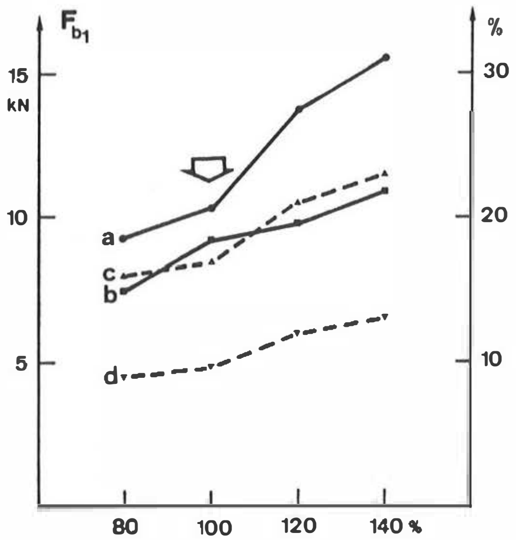

Fig. 5:
Same as fig. 4 for variation of crash victim characteristics, whereby 100% represents the standard case surrogate. Impact speed = 13.4 m/sec.

(140%: occupant of approx. 110 kg weight)

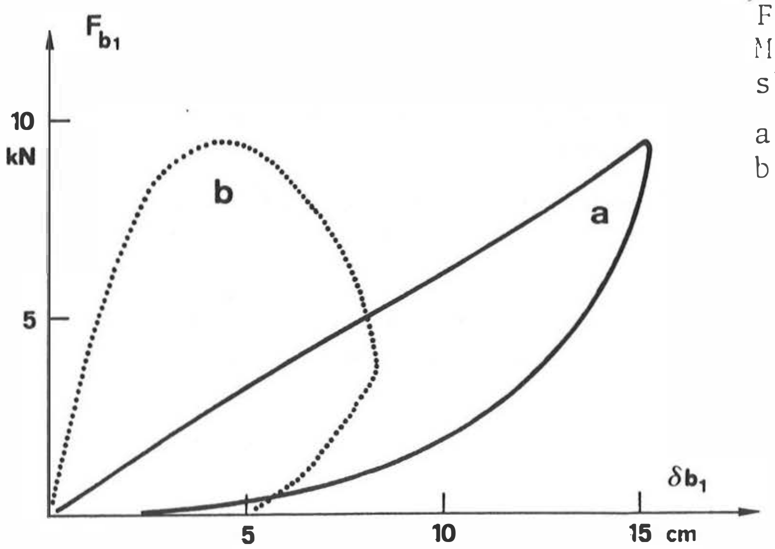

Fig. 6:
Mechanical hysteresis of shoulder belt strap

a: standard belt
b: belt with strain-rate dependent properties

Simulation results with a hypothetical viscous system seem to indicate that substantial improvements of present belt systems are possible for crash situations deviating significantly from a 50 km/h rigid barrier impact. The possibility of systems with mechanical properties directed towards the strain rate dependence proposed here have previously been analysed by Adomeit (1976). Such systems may represent some alternative or addition to other proposed improvements such as force limiters and preloading devices (e.g., Hoffmann et al. 1978). However, extensive experimental verification of the results presented in this paper remains to be conducted.

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REFERENCES

Adomeit, D.: A Force Limiting System on a Three-Point-Belt System Depending on Crash Velocity. Proc. 3rd Conf. Occ. Prot., SAE, New York 1974, p. 274.

Danforth, J.P., Randall, C.D.: Modified ROS Occupant Dynamics Simulation User Manual. General Motors Research Laboratories, Warren, MI., GMR Research Publication 1254, 1973.

Fleck, J.T., Butler, F.E., Vogel, S.: An Improved Three-Dimensional Computer Simulation of Motor Vehicle Crash Victims. CALSPAN Corporation, 1974.

Hoffmann, G., Köpke, W., Weissner, R.: The Influence of Preloading on the Efficiency of Belt Systems. Proc. ISATA, Wolfsburg 1978, p. 236.

Huston, R.L., Passerello, C.E.: On the Dynamics of a Human Body Model. J. of Biomech., 4(1971), p. 369-378.

King, A.I., Chou, C.C.: Mathematical Modelling Simulation and Experimental Testing of Biomechanical System Crash Response. J. of Biomech., 9(1976), p. 301.

Kroell, C.K., Schneider, D.C., Nahum, A.M.: Impact Tolerance and Response of the Human Thorax. GM Res. Labs, Warren, MI., GMR Research Publication 1167, 1971.

Robbins, D.H., Bennett, R.O., Bowman, B.M.: MVMA 2D Crash Victim Simulation Version 1. HSRI, University of Michigan, Ann Arbor, UM-HSRI-BI-73-5.

Young, R.D.: A Three-Dimensional Mathematical Model of an Automobile Passenger. Research Report 140-2, Texas Transportation Institute, A & M University, Texas, 1970.