CAR ACCIDENT MATHEMATICAL MODEL: FEMUR AND PELVIS STRESS ANALYSIS

by

P. M. Calderale

Istituto della Motorizzazione, Politecnico di Torino, Torino

A. Garro

Fiat Auto S.p.A., Torino

and

G. L. Lorenzi

Clinica Ortopedica dell'Università di Torino, Torino, Italy

Introduction

The imposition of increasingly stringent legislative standards and the concept of motor vehicle as working tools have recently generated a research interest in occupant safety problems. This paper approaches the questions of the consequences of a head-on collisio between two vehicles.

A generally applicable mathematical model offering an accurate simulation of both vehicle and occupant and their mutual interactions has been developed to analyse strain and stress in the femur and pelvis during such an accident. As a preliminary approach, the input data have been obtained from a simplified model.

The calculations have been based on the assumption that the occupant is in the driver's seat and free to move to the point where his chest strikes the steering wheel and his knees strike the part of the structure linking the two front pillars. This configuration is relatively typical of head-on collisions. In addition, it is the most serious as far as injury to the driver is concerned.

The model involves discretisation of both the vehicle and the accupant. Discretisation of the vehicle has been descibed elsewhere (1,2). The occupant, on the other hand, has been simulated by an assembly of suitably interconnected finite elements endowed with mechanical properties determined by the nature and geometry of the different parts of the body.

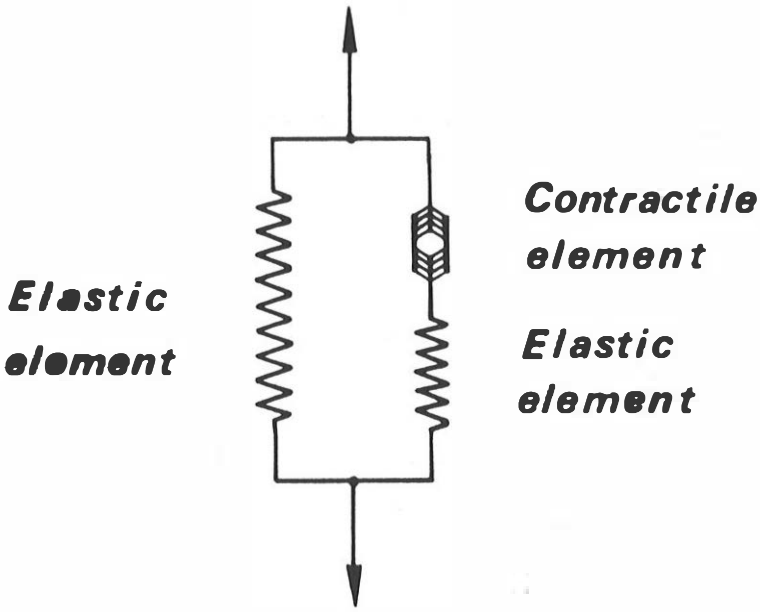


Fig. 1: Hill's muscle model.

The lower extremities are represented by beam elements with carefully defined local cross-sections and characteristics.

The coupling corresponding to the joints was obtained by assuming relative movement with the release of the degrees of freedom associated with the movement allowed. Relative movements were checked by using muscle elements (fig. 1) attached to the bone structure as shown in figs. 2 and 3 showing the outside and inside, anterior and posterior views of the lower extremity respectively.

Movement of the occupant on the seat was represented by instant-by-instant changes in their relative positions. The occupant-seat interaction was simulated by assuming a beam on an elastic foundation (fig. 4).

The pelvis is a sandwich structure composed of both triangular and plate elements. The upper part of the torso consists of beam linked at the vertebral

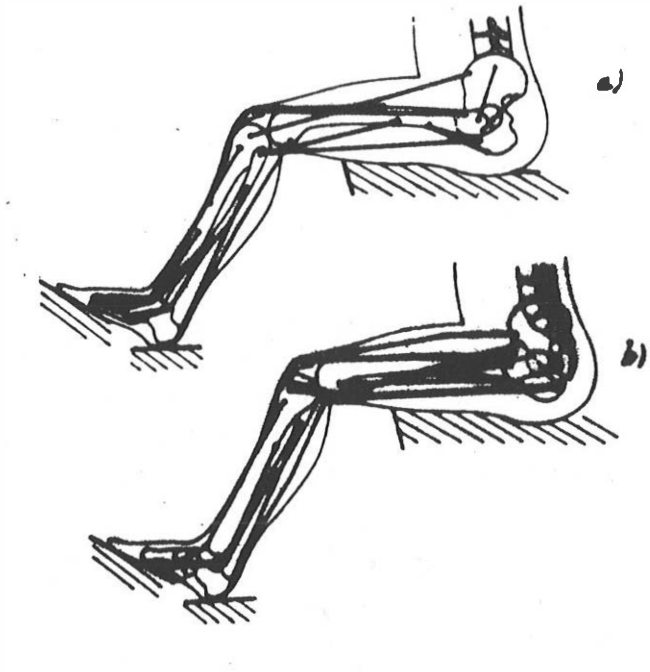


Fig. 2: Lower limb: lateral views.

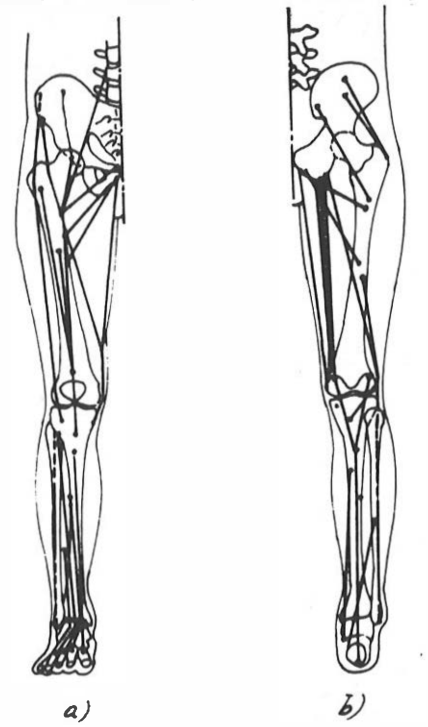


Fig. 3: Lower limb: ant-post views.

joints. The skeleton also carries muscle elements (not shown in the figure) taken from Tennyson (4) and Pontius & Liu (5). The head is represented by a single mass, the scapula by a shell-type structure, and the arms by beams (fig. 5).

The model is of general application. It can, in other words, be used to determine the femur-pelvis, patella-femur, and muscle-structure interacting forces corresponding to any initial hypothesis or input data, together with their stress and strain distribution. Each interaction can be subjected to parametric analysis and a study can be made of the large displacements that occurs in problems of this kind. It should be noted, however, that the results are influenced by the values of elastic parameters of the contractile elements used to represent the muscles. These were obtained from the scanty and, it is submitted, poorly reliable literature data, to ensure compatibility with the results obtained with dummies and cadavers. These, of course, offer no more than a very approximate simulation of the behaviour of the living body. Proper in vivo characterisation of muscle is needed to provide reliable values for the data needed in the mathematical model. Even so, the model is extremely versatile and its receptivity enables the parameters to be varied without altering the simulation philosophy. When the data required are more precisely defined, it will s rve to provide a convergence with true occupant behaviour during an accident at a later stage.

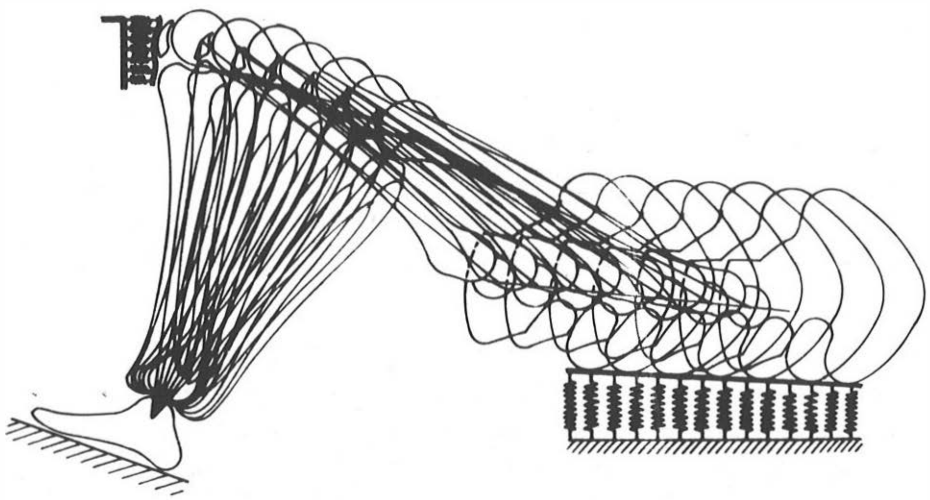


Fig. 4: Occupant-seat interaction model.

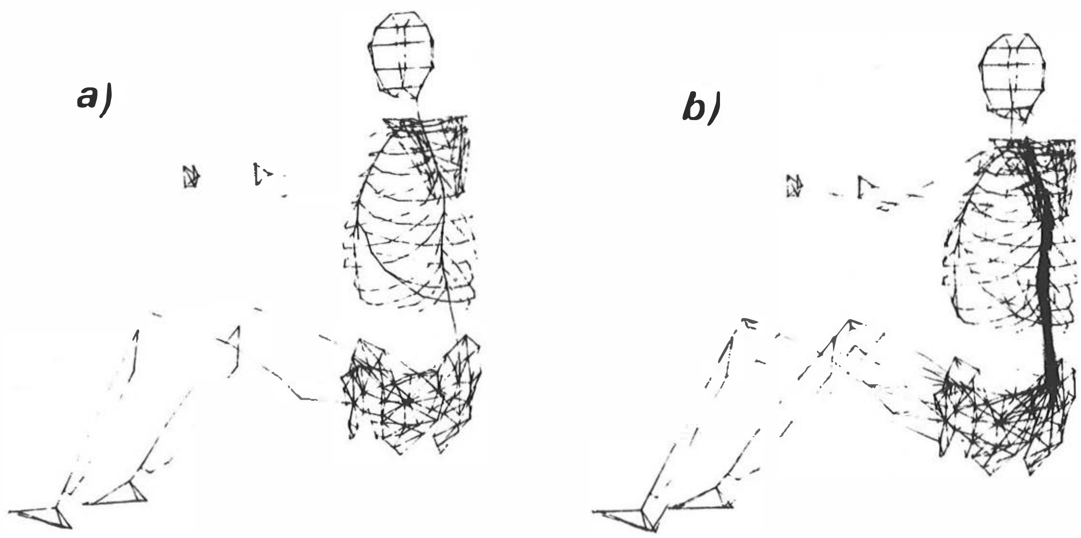


Fig. 5: Finite element model of the driver: a) bony structure; b) bony structure and muscles.

Dynamic analysis

The flow chart in fig. 7 shows that two sub-structures (the vehicle and the driver) and their interaction must be analysed.

The driver is not held to the seat or any part of the structure of the vehicle by restraining belts. His permitted motion is thus that arising out of the dynamics of the impact; its boundaries are those of the compartment itself.

The mathematical process representing this phenomenon is Newmark's direct integration of differential equations method (9). This is one of two methods used to correct the stiffness and damping matrixes for each integration step, so as to allow for the changes brought about by the large displacements and the constitutive laws associated with the local plasticisation of the structural components.

This analysis leads to a typical case of discontinuity, which arises when the driver strikes one of the inside parts of the compartment, and the steering wheel and its supporting cross-member in particular. This impact phenomenon is dealt with by including the conservation of momentum in the collision. Account is taken of the stiffness of the knee hitting the cross-member, and the stiffness of the latter, plus the flexibility of any covering it may have.

Evaluation of the stiffness of such covering, and its effects on the magnitude of the forces exchanged between the structures involved in possible injuries to the femur and pelvis, has been carried out by means of a parametric analysis linking the stiffness of the covering to its thickness.

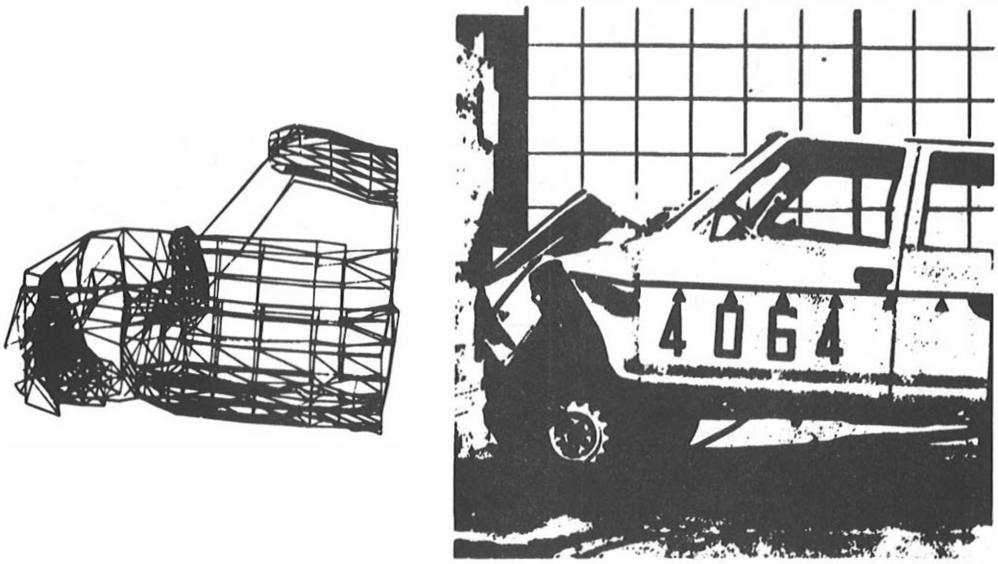


Fig. 6: Finite element model of the car. Experimental and calculated deformation.

As shown by the flow chart, the values of the forces exchanged constitutes input data for the analysis of femur and pelvis deformation and stress.

Stress analysis demands the construction of mathematical models capable of taking in all the consequences from the injury standpoint. It was therefore necessary to build a structure formed of 20-node, hexahedric three-dimensional elements. This was sub-divided in such a way as to permit the local variation of the physical properties of the spongy bone, and hence obtain a response in keeping with the questions posed in an investigation of this kind.

<u>The femur and pelvis models.</u>

The femur model correctly follows the structural geometry. It shows considerable thickening of the mesh near the neck and distal epiphysis.
These parts are formed of a thin layer of cortical bone and contain the internal spongy bone. The trabecular architecture of the spongy mass follows the lines of force of the structure subjected to stress under ordinary conditions. This feature gives rise to an anisotropic characteristic of the interior mass, whose local features are accompanied by directional properties that vary from one point to another.

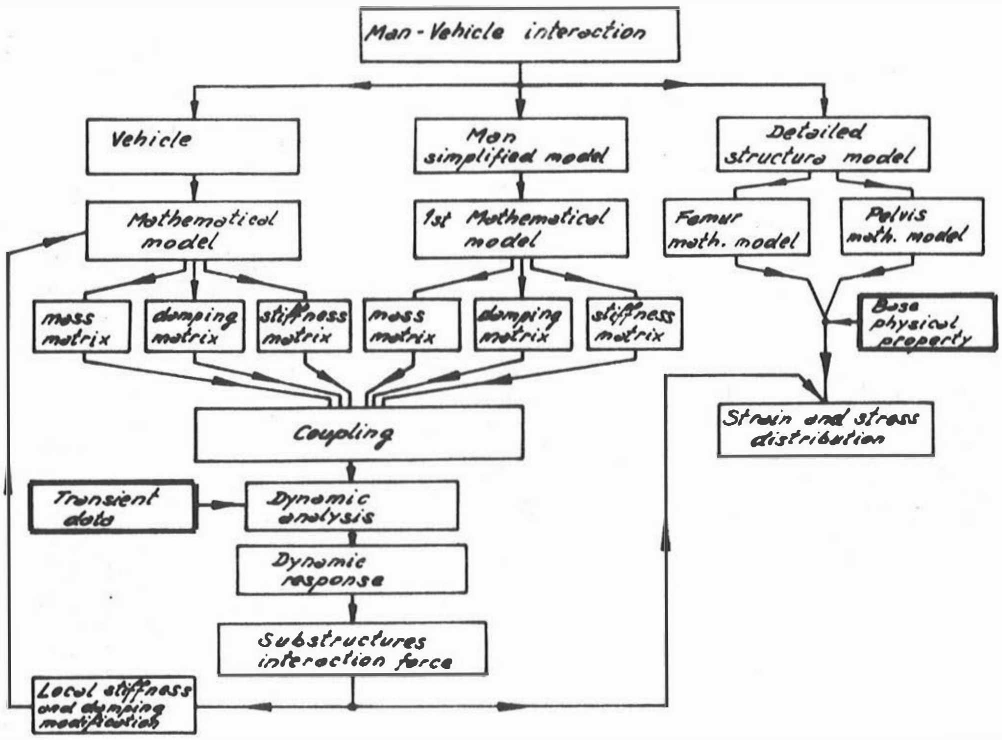
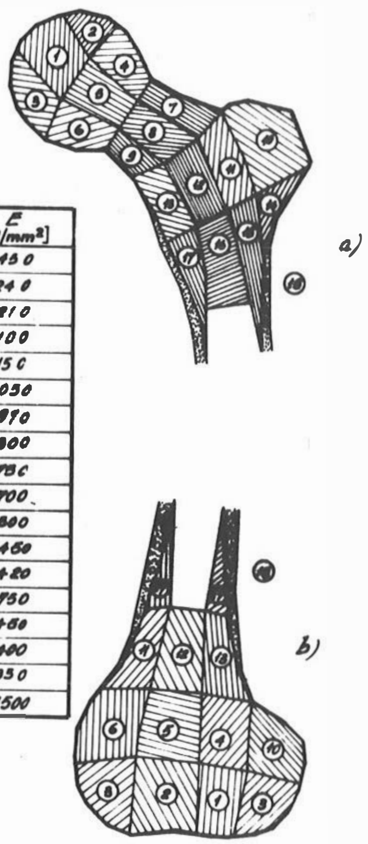


Fig. 7: Flow chart of the dynamic and stress analysis.



Zone	E [N/mm²]
1	1450
2	1240
3	1210
4	1100
5	1150
6	1050
7	970
8	800
9	730
10	700
11	600
12	460
13	420
14	750
15	450
16	400
17	930
18	14500

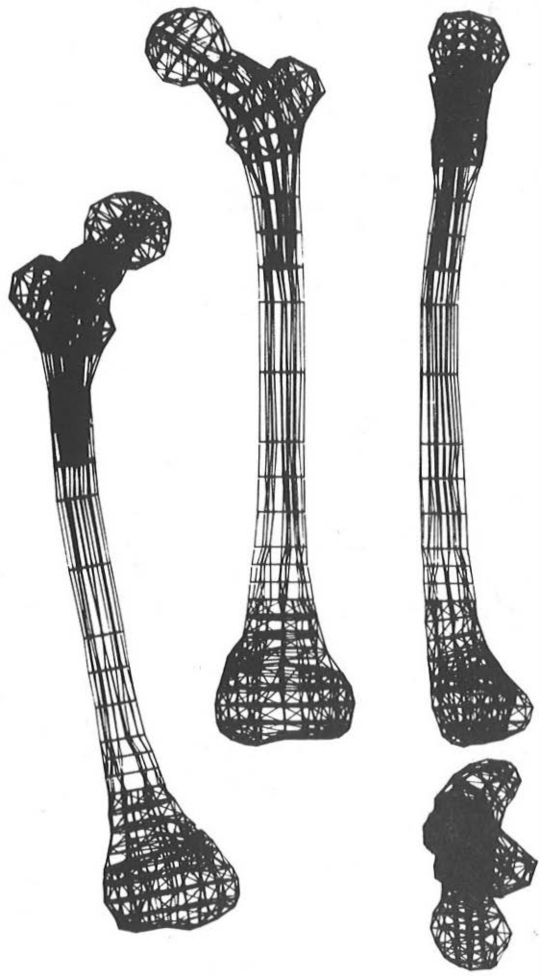
Fig. 8: Elastic moduli of the femur cortical and spongy bone.

The ability to take account of the material constitutive laws is a feature of the discretization methods employed. The understanding of these properties, however, constitutes a considerable obstacle.

Reference has been made to the vast literature on the subject to obtain the properties associated with each of the 17 regions into which the interior of the proximal and distal epiphyses is divided (fig. 8).

The mesh shown in fig. 9 will serve to clarify the criteria used in the division.

Similar considerations were taken into account in the construction of the pelvis model. As already stated, this is a typical sandwich



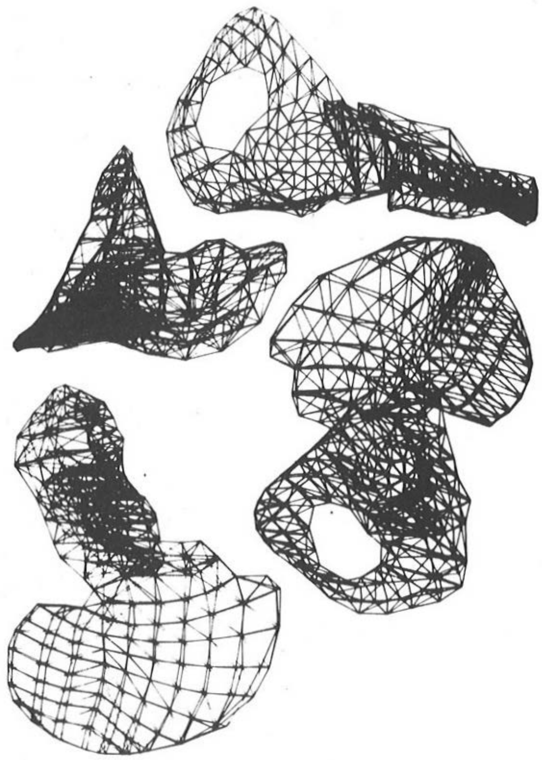


Fig. 9: Femur mesh Fig. 10: Pelvis mesh

structure whose perfect stiffness distribution makes it a wonderful concrete example of lightness allied with considerable strength.

The mesh of the pelvis is illustrated in fig.10. The criteria used to analyse the stresses in the acetabulum are readily apparent. One of the difficulties encountered in this simulation arises from the lack of data concerning the properties of the part formed by the core of the sandwich, i.e. the trabecular structure. In the model shown, the entire cortical bone was built with triangular plate elements, whereas the inside was simulated with 20-node solid elements. The physical features of these elements are shown as type 1 and type 2 in fig.8.

Results

The described mathematical models have been used for the dynamic analysis of frontal impact with an obstacle, and that of the stress distribution in the pelvis and femur.

The values for the mechenical properties of the muscle bundles brought into the calculations were progressively corrected until dynamic responses comparable with those observed on dummies and cadavers were obtained.

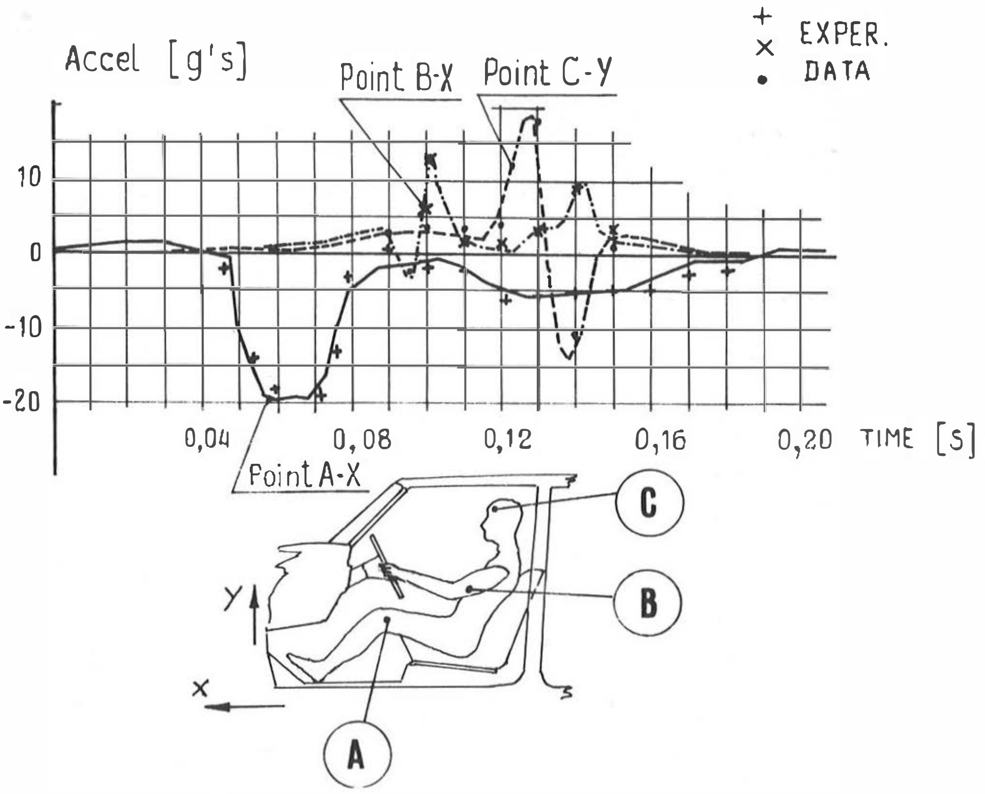


Fig. 11 : Knee, chest and head acceleration : model results and experim. data.

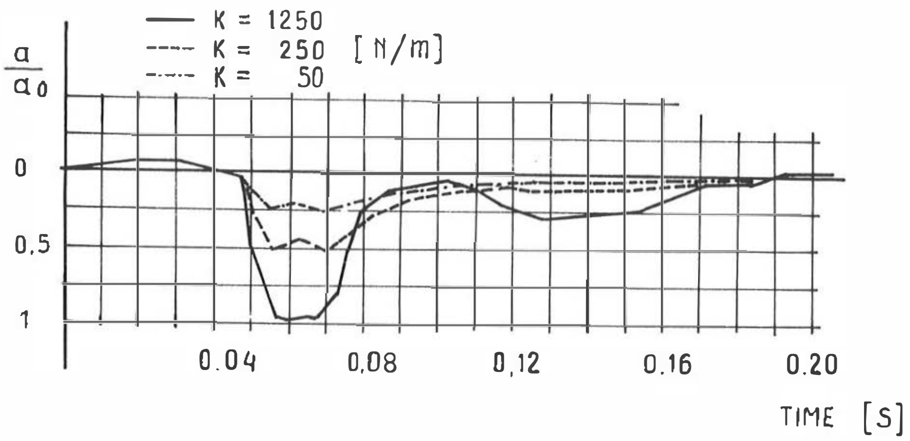


Fig. 12 : Knee acceleration as function of the dashboard covering stiffness.

Fig. 11 shows the acceleration response at certain significant points of the model, together with the corresponding experimental values used in the calibration. Fig. 12 illustrates the knee acceleration A versus time for 3 different stiffness values of the dashboard covering struck by the knee. The curves are normalised with respect to the calibration curve whose peak value is 20 g. The considerable influence exerted by the stiffness of the covering on acceleration and hence on the impact forces sustained by the femur is clear.

The complete array of results obtained from the dynamic analysis was utilised as the input for evaluation of the stress distribution in individual structures,

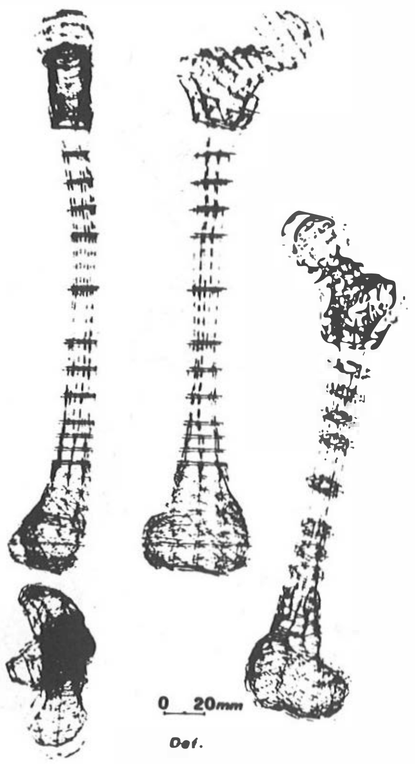


Fig. 13: Femur elastic deformation

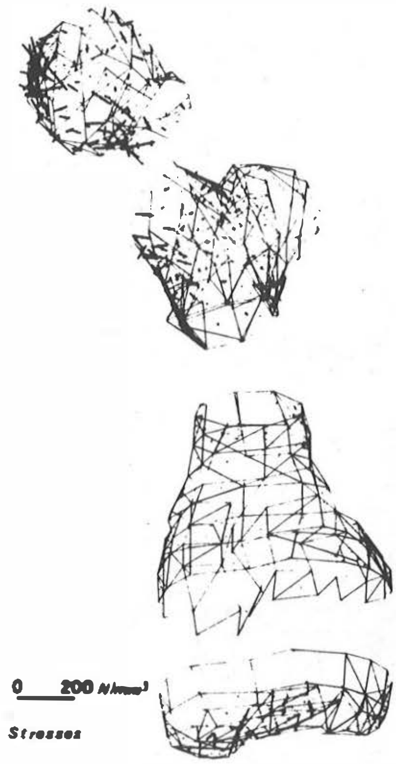


Fig. 14: Stresses in the cortical bone

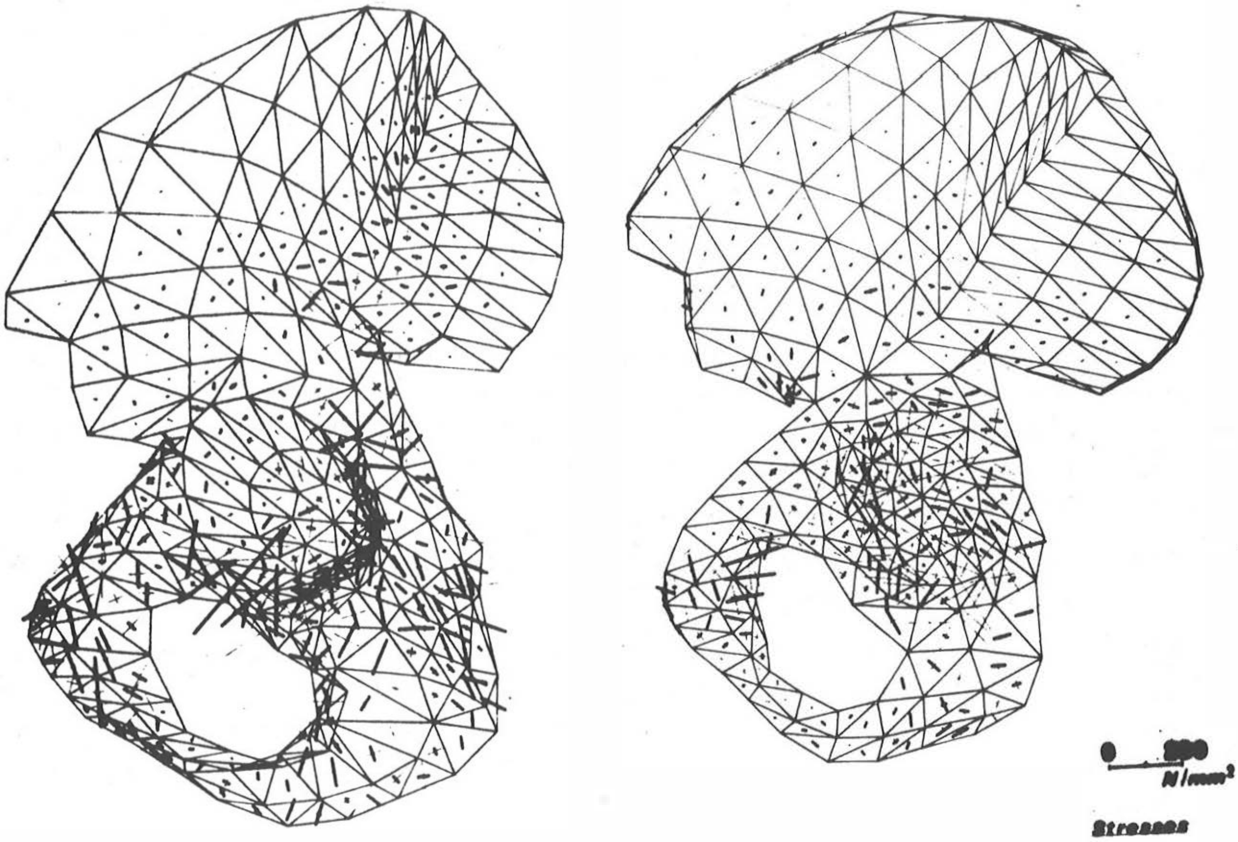


Fig. 15: Stress distribution on the cortical shells of the pelvis

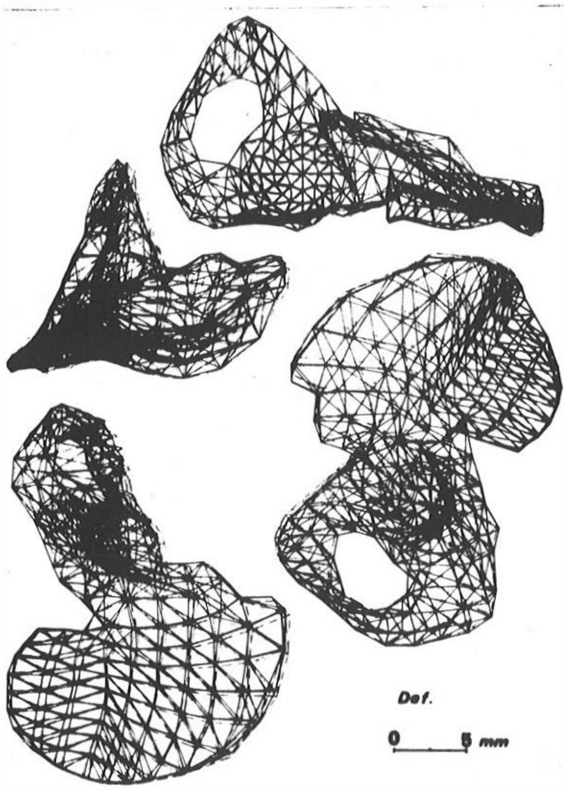


Fig. 16: Pelvis elastic deformation

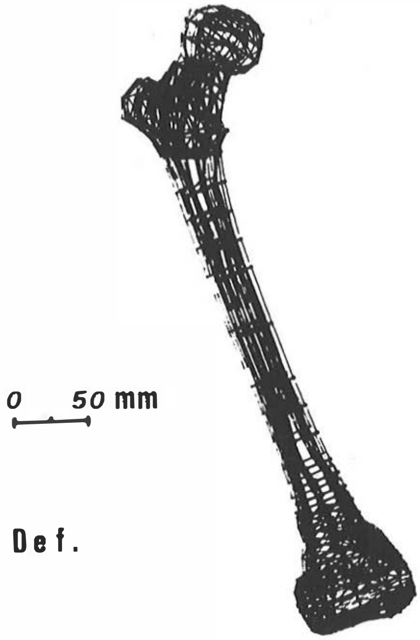


Fig. 17: Femur elastic deform. initial angle of his axis $\alpha = 20°$

and in the femur and pelvis in particular. Various initial positions were adopted for the driver's legs. The results are far too extensive to be summarised in this note. The most significant findings are therefore shown in figs.13/17. These illustrate the stresses and the elastic deformations of the femur and pelvis in the case of a frontal impact at 5.6 m/s , with the axis of the femur at right angles to the vehicle cross-member.

The principal stresses on the pelvic cortical bone and some key parts of the femur are represented by oriented vectors whose length is proportional to their value. Fig.14 indicates that, in the case of the femur, the neck and the contact areas with the patella and acetabulum are the parts most subjected to stress.

In the pelvis, stresses are primarily concentrated on the two cortical shells housing the spongy bone.

Figure 15 shows the areas of major stress and the stress area inside the acetabulum. The case where the axis of the femur is at 20° to the direction of travel is of particular interest. It will be seen from the deformation pattern in fig. 17 that dislocation of the hip is the probable outcome in this situation.

Conolusions

Dynamic and stress analysis in complex, interacting structures, as examined in this note, demanded the employment of finite element methods. The results offer a reasonably exhaustive picture of the dynamic behaviour of the femur and pelvis and the stresses to which they are subjected in a simulated frontal impact.

The numeric values, however, must be regarded as first approximations, not so much because the mathematical model is defective or subject to limitations, as because of the lack of sufficiently reliable data, especially with regard to the elastic properties of the contractile elements. By contrast, the model itself is sufficiently general to enable it to be applied for both the dynamic and the stress analysis of structures involved in an impact under any hypothetical conditions. Its particular composition makes it a versatile tool in the parametric analysis of occupant-vehicle interactions.

Research now being conducted on various fronts should lead to the establishment of more reliable values for the elastic features of muscle in vivo.

When the hoped for results are available, further refinement of the investigation by applying more accurate values and exploiting the general nature and versatility of the model should make it possible to analyse man-vehicle interactions under the most disparate conditions.

References

1. F. Gay, A. Carro, P. Uslenghi - Structural Analysis Role in FIAT Ritmo Design - ATA Torino Maggio '78
2. A. Carro - Some Considerations on Crash Problems - To be published on ATA - Torino
3. A. V. Hill - The Mechanics of Active Muscle - Proc. Roy. Soc. of London B-141 (1953)
4. S. A. Tennison, A. I. King - A Biodynamic Model of the Human Spinal Column- SAE 760771 (1976)
5. U. R. Pontius, Y. K. Liù - Neuromuscolar Cervical Spine Model for Whiplash- SAE 760770 (1976)
6. D. H. Robbins, R. O. Bennet - User Oriented Mathematical Crash Victim Simulator - Proc. Sixteenth Stap Car - SAE (1972)
7. H. Yamada, F. G. Evans - Strenght of Biological Materials-William & Wilkins Co. Baltimore MD (1970)
8. F. G. Evans - Mechanical Properties of Bone-Charles C. Thomas Publisher Springfield - Illinois (1973)
9. N. M. Newmark - A Method of Computation for Structural Dynamics - Proc. ASCE 85, EM3, 67-94 (1959)