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METHODOLOGIES FOR MOTORCYCLIST INJURY PREDICTION BY MEANS OF COMPUTER SIMULATION

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ABSTRACT

Methods for predicting motorcyclist injuries by means of computer simulation have evolved since the 1970's and are critically reviewed in the context of International Standard ISO 13232. The latter was approved in 1996 in order to establish minimum scientific requirements for motorcyclist protective device research, including calibration of simulations against laboratory and full-scale test data. Data from an example ISO-compliant simulation are presented which indicate substantial agreement between the distribution of predicted and real injuries in n=501 accidents in Los Angeles and Hannover. Other data indicate that multi-body and finite element models can produce similar buckling responses when they incorporate similar levels of detail. Key emerging technologies and issues are identified.

Computer simulation, motorcycles, injury, finite element, multi-body

COMPUTER SIMULATION METHODS for predicting motorcyclist injuries due to impacts have evolved since the early 1970's, from single mass models, to multi-rigid-body (MB) models, to finite element (FE) models, and to hybrid FE/MB models. This paper begins with an historical review of the development of these simulation methodologies, their standardisation under ISO 13232 (1996), their capabilities to predict the distributions of rider injury severities observed in real accidents, and some comparisons between multi-body (MB) and finite element (FE) simulation methods and results. Conclusions and discussion are provided regarding the levels of agreement between simulations and real accidents, MB and FE models, and emerging technologies and issues that relate to future progress in this field.

RESEARCH QUESTIONS

This paper addresses the following research questions:

1) What is the history and current status of motorcyclist injury prediction by means of computer simulation?
2) What standards exist for motorcyclist injury simulations, and what are their purpose and requirements?
3) How well can current simulations predict rider injuries distributions observed in real accidents?
4) Can either multi-rigid-body (MB) or finite element (FE) methods be used to predict structural phenomena such as buckling?
5) What are the key emerging technologies and issues in the motorcyclist injury simulation field?

METHODS

HISTORY AND STATUS OF MOTORCYCLIST INJURY PREDICTION BY COMPUTER SIMULATION: In order to address research questions 1 and 2, a global English language literature search and review was conducted of references that had key or title words including "motorcycle," "crash" or "impact," and "simulation." The resulting papers are reviewed herein.

PREDICTION OF RIDER INJURIES: In order to address research question 3, multi-body computer simulations of 501 LA/Hannover car/motorcycle accidents were run, as specified in ISO 13232 (1996). The results in terms of distribution of predicted body region injury severities were compared to the corresponding injury distributions from the real accidents, as also described in ISO 13232-2, annex C (1996). The model is described subsequently.

Model: As described by Kebschull et al. (1998), an ISO Motorcyclist Anthropometric Test Dummy (MATD) was modeled using the US Air Force Articulated Total Body (ATB) code for multi-rigid body systems. The MATD includes 28 standardized modifications to a Hybrid III 50th percentile male dummy in accordance with ISO 13232-3, in order to make it compatible with motorcycle postures and multi-directional impacts. The motorcycle that was modeled was a Kawasaki GPZ 500, and for the current investigation this was examined in its baseline, unmodified condition. The opposing vehicle that was modeled was a production Toyota Corolla 4 door sedan, as specified in ISO 13232-6. Mass properties, dimensions, joint locations, and suspension properties for the motorcycle and opposing vehicle were determined by laboratory measurements of exemplar vehicles.

Model calibration: ISO 13232-7 specifies that 20 dynamic and 11 static laboratory component tests be done and quantitatively compared with the corresponding computer simulations of these tests. In addition, a motorcycle barrier test is specified in order to provide a comparison between the modelled and measured response characteristics related to the front wheel, front suspension, and front fork bending properties and their effects on the motorcycle forces and motions resulting from frontal impact. As required by the Standard, Kebschull et al. (1998) graphed the force vs. displacement for these 42 static and dynamic tests overlaid with the simulation results. As required, the simulation parameters used for the calibrations were used for all subsequent simulation runs.

The Standard also requires comparison and correlation of the simulation with full-scale impact test results. Data from 14 full-scale tests were used for correlation, and for the peak resultant head acceleration correlation the r2 correlation coefficient was found to be 0.91. The percentage of femur fractures, knee dislocations and tibia fractures correctly predicted by the simulation was reported to be 93%, 93%, and 100% respectively.

In addition, Kebschull et al. (1998) presented the "overlaid" full-scale and simulation helmet displacement time histories. The authors reported that the limitation of this particular calibration method is that it compares only the end points of the time histories. An alternate, revised method to compare these time history variables, has been proposed as an amendment to the Standard. With this proposal, a correlation factor, analogous to an r^2 correlation coefficient, is calculated over the time history as follows:

$$C = 1 - \frac{\sum_{i,k}\left(d_{i,k} - \bar{d}_i\right)^2}{\sum_{i,k}\left(r_{i,k} - \bar{r}_i\right)^2}$$

where:

C = correlation factor

i = subscript for each impact configuration

k = subscript for each time step

$d_{i,k} = r_{i,k} - \hat{r}_{i,k}$

$\bar{d}_i$ = average value (over time) of $d_{i,k}$

$r_{i,k}$ = value for test i at time k

$\bar{r}_i$ = average value (over time) of $r_{i,k}$

$\hat{r}_{i,k}$ = value for computer simulation i at time k

Using this method, the average correlation across all tests and all 13 variables was found to be 0.82.

Model validation: The injury (AIS) severities for each of six body regions that were calculated for the baseline motorcycle in the n=501 LA/Hannover impact configurations analyzed by Kebschull et al. (1998) were compared to the actual injury severities from the real n=501 accidents. These new results are described subsequently.

COMPARISON OF MB AND FE SIMULATIONS OF A SIMPLE STRUCTURE: In order to address research question 4, the aforementioned published references in this area were reviewed. Various references, discussed subsequently, have suggested that MB may be unsuitable for modeling buckling or energy absorption phenomena. In order to address this question, an MB model and an FE model of a deformable cantilever were developed, run and compared for various buckling-type impact conditions, in terms of their resulting deflections, velocities and buckling behavior. The two alternative models were constructed with the same span-wise number, size and initial shape of elements, and such that they had the same overall static force-deflection characteristics for the type of calibration test defined in ISO 13232-7. This type of simple structure occasionally occurs in MC structures such as the front fork or the handlebars, for example; or in more 3 dimensional forms in car structures such as the bonnet. The example cantilevers were used to explore the buckling and energy absorption phenomena rather than the responses of specific motorcycle or car components. The two models are described subsequently.

MB model: 100 rigid hyper-ellipsoids comprising a curved cantilever were modeled with ATB, each hyper-ellipsoid with dimensions 12.5 mm long x 25 mm high x 100 mm wide. Six degrees-of-freedom joints were placed between each pair of hyper-ellipsoids. The mass, moments of inertia, and 6-axis force-deflection characteristics were calculated based on aluminum alloy material characteristics. Linear damping with different compression and extension characteristics were used in order to model structural hysteresis (i.e., energy absorption), although other forms of energy absorption could have been used. The elements at one end were constrained by a rigid joint to a wall. The cantilever was impacted span-wise at its outboard end by a 150 kg rigid sphere 300 mm in diameter traveling toward the supporting wall at 13.6 m/s. The cantilever radius of curvature was 1.566 m.

FE model: A stack of 1600 8-bricks (100 x 4 x 4 bricks) comprising the cantilever were modelled using MSC DYTRAN, each brick having dimensions 12.5 mm long x 12.5 mm high x 25 mm width. Material properties of the same aluminum alloy as was used for the MB cantilever were used, as described in Table 1. The elements at one end of the cantilever were rigidly constrained to a wall. The cantilever was impacted in the same manner as was the MB cantilever.

Table 1 - Material properties used in MB and FE model formulation

Property	Value
Material	ISO R209 AlMg1SiCu
Density	2700 kg/m^3
Mu	0.33
E	69 GPa
Yield stress	0.275 GPa

DATA SOURCES

ISO 13232 (INCLUDING N=501 SUB-SAMPLES OF LA/HANNOVER DATABASES): As a basis of comparison for the predicted injury severity distributions, the real injury severity distributions from the n=501 LA/Hannover car/motorcycle accidents were generated, based on the data in ISO 13232-2, annex C. The latter comprise sub-samples of "car-motorcycle/seated-single-rider/upright-motorcycle" accidents which were provided for use in the ISO Standard, which were drawn from the n=900 census of accidents investigated by Hurt et al. (1981), as well as a similarly sized sample of accidents investigated by Otte et al. (1981), as reported by Pedder et al. (1989).

RESULTS

LITERATURE REVIEW: The global review of literature revealed the papers listed in the references. These are critically reviewed subsequently. A key aspect that is noted is the extent to which each simulation was quantitatively "calibrated" against laboratory and full-scale test data.

Early research: Perhaps the earliest published attempt to model rider/motorcycle/barrier impacts was that of Knight et al. (1971) as summarized by Bothwell et al. (1971) in their phase I research for the US/DOT/NHTSA. This involved a 2 dimensional multi-rigid-body Lagrange formulation of a 5 mass rider and a single mass motorcycle. Single-point non-linear contact forces acting on the masses were dependent on displacement and/or time. The rider model contacted the motorcycle at its hands, feet and pelvis, and the motorcycle front wheel contacted the ground and a rigid barrier. The rider was initially in contact with the motorcycle, and could separate from the motorcycle after it contacted the barrier. Time histories of the dummy cg displacement, front wheel force, pelvis/motorcycle force and torso pitching rate are presented, but these were not compared to the full-scale tests that were done. There was no discussion of parameter measurement or component calibration tests. Plans were described for adding an airbag model.

Bothwell et al. (1973) report on the addition of an airbag model, and the further work of Knight et al. (1973) to develop a 3 dimensional multi-rigid-body motorcycle, rider and barrier simulation. This involved an attempt to combine a new, 4 mass motorcycle model with the 15 mass CAL 3D human model simulation developed by Calspan Corporation for the US government. Some preliminary time histories are presented for the motorcycle portion of the model (with a simplified, rigid, point-mass rider) impacting a rigid barrier. Knight et al. (1976) present further derivations of and example runs with this model, as well as with the integrated 19 mass model. These include time histories of forces and displacements, and stick figure animations of the rider model. As with the earlier work there was no discussion of parameter measurement, or component or full-scale calibration tests.

Sporner (1982), as a doctoral dissertation, developed a 2 dimensional 10 degrees-of-freedom multi-body simulation of a seated rider that collides with a stationary obstacle representing a passenger car. This was accomplished by converting a multi-body model of a car occupant. The motorcycle handlebars and car were rigid bodies against which the rider interacted. Danner et al. (1985) describe how this simulation was used to assess the change in rider trajectory (but not the forces or injuries) resulting from fitment of knee-baffle pads on the motorcycle, without calibration against full-scale test data.

Happian-Smith et al. (1987) describe a 2 dimensional, 3 mass model of a motorcycle mainframe, front wheel and rider torso, with single-point contact forces. This was used for analyzing motorcycle cg acceleration as the front wheel and headlamp assembly impacted a rigid barrier. The effects of cast wheels versus wire-spoked wheels were described, as well as the effects of a 120 l airbag (data for or details of which are not shown in this paper). Happian-Smith and Chinn (1990) describe a similar simulation that was developed to include a gas-volume model of an airbag, and the effects of this on the angular and linear displacement and velocities of a single-mass rider. Some limited calibrations against laboratory test data are included.

Chinn et al. (1987) and Chinn et al. (1989) describe a 2 dimensional single mass model of a motorcycle impacting an angled rigid barrier. The model "assumed that the rider was either immediately flung clear or was rigidly attached to the motorcycle." The effects of motorcycle and prototype leg protector geometry on the yaw rotation of the motorcycle (i.e., tail toward or away from the barrier) was studied, with both a purely rigid-body model, and with spring-dampers placed at the contact points. Rider motion, forces or injuries were not modelled. One example is presented which compares the simulation to full-scale test in terms of motorcycle linear and angular displacement. Happian-Smith et al. (1990) describe further details and results with this model.

Models leading up to the ISO Standard: Zellner et al. (1991) describe a 3 dimensional multi-rigid-body model based on the ATB code. This comprised a 4 mass motorcycle, 25 mass Motorcycle Anthropometric Test Device (MATD) dummy, 7 mass car and 62 elliptical and planar contact surfaces. The model was applied to 163 impact configurations based on groupings of accidents in LA and Hannover. The simulation results were input to an injury cost model developed by Biokinetics, Ltd. No time histories comparing the simulation with either laboratory or full-scale test were presented. Comparisons between the simulation and n=14 full-scale tests are shown in terms of peak resultant head accelerations and simulated leg fractures. The correlation coefficient for head accelerations was 0.80, and the percentage agreement for upper and lower leg fractures and knee dislocations was greater than 90%. A comparison between one frame of an animation and a test film was shown.

Nieboer et al. (1991) describe a hybrid MADYMO 2830 element FE airbag model and MB model of a motorcycle sled and modified Hybrid II dummy, along with some comparisons of measured and simulated dummy acceleration time histories. Nieboer et al. (1993) describe an extension of this to a 6 mass motorcycle model including comparisons of some component tests and some test data of dummy and motorcycle time histories. It is noted that for "the motorcycle model as it is presented…the energy absorption is underestimated for large structural deformations," and that the [then] current v 5.0 of MADYMO "offers adequate [MB] features to improve" this.

Yamaguchi et al. (1993) describe an FE model of a motorcycle frame for barrier impact analysis. The FE frame model was connected to ground and barrier via spring and dampers. Time history comparisons of material strain are presented.

Rogers (1994) describes simulations of rider injuries with a baseline and a modified sports motorcycle. The model was similar to that reported by Zellner et al. (1991). Time histories of laboratory and full-scale tests are not shown, however correlations of peak resultant head acceleration and leg fractures are reported. These indicate correlation coefficients of 0.84 for the head, and between 82 and 88% for the upper and lower legs and knees. The model was applied to 163 LA and Hannover impact configurations.

Yettram et al. (1994) describe a 3 dimensional multi-rigid body model of a rider, motorcycle and rigid barrier. The rider comprises 16 masses, the motorcycle 4 masses, and the barrier an infinite mass. Contact surfaces in general consist of "cylinders" (consisting of a series of overlapping spheres) and planes. The models are calibrated against 14 dummy laboratory tests and 6 motorcycle laboratory tests. Time histories for the overall model are then compared to full-scale test data in terms of motorcycle and dummy head and pelvis forward linear displacement and velocity.

Zellner et al. (1994) describe extensions of the Zellner et al. (1991) simulation model, including a control volume airbag, an airbag mechanical sensor model, an igniter time delay, separate helmet mass, deformable chest and abdomen models, and a refined injury cost model. Calibration data for a laboratory test of an airbag deployment with a prone dummy are included, comparing measured and simulated head and neck forces.

Chinn et al. (1996) describe a multi-rigid-body MADYMO simulation with FE airbag model. Descriptions of the models are not provided, except that the dummy was a Hybrid III rather than a motorcyclist dummy. Although the model is reported to be based on and compared to laboratory and full-scale tests, no data or calibrations are shown.

<u>The ISO Standard for motorcyclist injury research</u>: Van Driessche (1994) describes development of ISO/CD 13232, which specifies "Test and analysis methods for research evaluation of rider crash protective devices fitted to motorcycles. The paper summarizes the ISO committee process involving experts from 10 nations, at the request of United Nations ECE/TRANS Working Party 29. The Standard was subsequently approved at a worldwide level as ISO 13232 (1996).

The ISO Standard provides a set of common requirements and assumptions for *minimum levels* of modelling detail, parameter measurement, output variables, post-processing (in terms of three dimensional animations and injury indices), quantitative (rather than qualitative) calibrations, correlations and comparisons against recorded test data.

Specifically, the calibration procedures in the Standard are intended to enable physics-based simulations to be used to *interpolate* between conditions that have been tested in full-scale or in laboratory. For example, simulations are to be done only up to the component force levels that have been measured in laboratory tests, and not extrapolated beyond these. The purpose of the simulation tool, and the ISO Standard itself, is to assess the relative injury benefits and risks of protective devices across large (e.g., n=200) representative samples of conditions reported in real accidents, a task which is too costly to do exclusively by means of full-scale impact tests.

Efforts were made during development of the Standard to ensure that it was "technology-independent" and not "technology-restrictive." Measures were taken to ensure that, for example, either MB or FE techniques could be used, and that the minimum level of modelling detail for each was consistent with what was achievable at the time, consistent with the large number of simulations needed to support the purpose of the Standard. The Standard is not intended to be either a workbook or user manual for "how to" implement a motorcycle crash simulation, but rather a standard which ensures that minimum levels of detail, performance and calibration are used, so that the results of the overall analysis may be relied upon.

<u>Models since the ISO Standard was approved</u>: Kebschull et al. (1998) describe the only published work to date that reports all laboratory and full-scale test calibrations and conventions required by the ISO Standard. The simulation comprised a 7 mass motorcycle, a 30 mass MATD dummy and a 7 mass car. Seventy-two time histories are shown comparing simulation to laboratory tests for various

dummy, motorcycle and car components. One series of time histories is shown comparing simulation to full-scale helmet displacement in one full-scale test. Simulation/full-scale correlation data are reported, and the correlation coefficient was 0.91 for peak resultant head accelerations, and the percentage of injuries correctly predicted was between 92 and 100% for the leg regions. The model was subsequently applied to the n = 200 LA/Hannover impact configurations.

Iijima et al. (1998) describe a hybrid FE/multi-body simulation involving the LS-DYNA3D and ATB codes. This comprised a 7 mass motorcycle, a 614 element FE airbag, a 30 mass dummy and a 7 mass car. Time histories were not shown, but the correlation coefficient for peak resultant head accelerations was 0.88, and percentage injury agreement for the leg ranged from 94 to 97% across the n=14 required ISO full-scale impact configurations. One frame comparing a simulation animation to a test film is shown. The model was subsequently applied to the n = 200 LA/Hannover impact configurations.

Wang and Sakurai (1999) describe a multi-rigid-body MADYMO model of a Hybrid III dummy, a motorcycle and ISO Toyota Corolla saloon car. The dummy comprises 21 masses, the motorcycle 8 masses, and the car 14 masses. The contact surfaces are ellipsoids, cylinders and planes. The model is described as being an initial model, which was not yet developed, calibrated or correlated in accordance with ISO 13232. The paper shows general comparisons of simulation animations against test films, but does not present any time histories. The paper notes that "shape inaccuracy" may occur and notes that "introducing finite element models for some related parts may be an effective way to remove most of the influences of the limitations."

Chawla et al. (2001) describe a finite element model of a motorcycle and car using the PAMCRASH software, and a reverse-engineering approach to generate the model. This is based on digitizing exterior portions of the motorcycle and car, and adjusting the simulation data in order to match component test data. The standard PAM-CRASH Hybrid III dummy model is used. The objective was to simulate the side-of-car impacts of ISO 13232, however, this preliminary paper did not address the other requirements of ISO 13232, or present any quantitative data. A comparison of an animation with a test film of a motorcycle-to-rigid barrier test, without dummy, is shown. The paper also mentions the need for a finer mesh size in high deformation zones in FE simulations. Mukherjee et al. (2001) describe this model in more detail, and state that the goal at this stage was to examine the overall kinematics of the motorcycle and car in side-of-car impacts, and that in the future an MATD dummy model should be used to examine the finer details of the response. The motorcycle model involved 1K elements, and the car model involved 15K elements. Only animation/film comparisons and subjective summaries are provided. They also point out the effect of some of the differences between the MATD model and the H-III model and specifically discuss the importance of the MATD hand grip in affecting the car-MC kinematics. Nakatani et al. (2001) describe this same finite element model of a motorcycle (without rider) that impacts a rigid wall. The paper describes calibration of the simulation against various component tests, as well as the barrier force, displacement and acceleration time histories. Comparison of a simulation animation with a full-scale test film is presented.

Canaple et al. (2002) describe a multi-rigid body MADYMO model of a motorcycle, dummy and car, used to generate head acceleration time histories for input to a finite element model of a human head and brain. The motorcycle model consists of 6 masses, and the dummy is the standard MADYMO Hybrid III (rather than the ISO MATD) apparently with the head modified in order to represent a helmet. The car is a rather unique multi-body model involving 25 or more rigid-body masses, modeled by a combination of physically cutting up and measuring various structural elements and by calculating force-deflection characteristics based on sub-structure FE modelling. Component calibrations are mentioned but not presented in the paper. Comparisons with an ISO-like full-scale test with an MATD dummy include time histories of motorcycle and dummy accelerations (although with different dummies), and an animation/film comparison.

Chawla et al. (2003) subjectively compare FE simulation animations with films of ISO 13232 car front impact tests. The simulation is a FE model of a Hybrid III frontal car occupant dummy (rather than the ISO MATD dummy used in the tests), a GPZ 500 motorcycle and the Toyota Corolla saloon car specified in ISO 13232. The paper provides only animation / film comparisons and subjective summaries. Certain statements made in the paper appear to be misleading. While the ISO Standard evaluates safety quantitatively, this paper only provides a qualitative comparison of the kinematics. This paper gives a preliminary, subjective and general comparison of animations against full-scale test films, and should not be misinterpreted as a direct comparison, as different dummies were used in the simulation and in the full-scale tests. The paper also reports using "nominal values" (rather than measured values) of impact conditions. The authors of the paper suggest that a quantitative comparison should be taken up only after a qualitative match is obtained. The paper also seems to imply that the Standard is only aimed at rigid body simulations. However, Part 7 of the Standard describes simulation requirements for both FE and rigid body models. The paper argues that "bonnet folding cannot be *effectively* modeled using rigid body models" probably because of the somewhat more predictive nature of FE models (based on material laws and detailed geometry) vis-à-vis rigid body models. However, both FE and rigid-body models require empirically determined input parameters, as well as empirical calibration against both component tests and whole vehicle tests, as discussed previously. The paper lists components which in the opinion of the authors were "critical" for simulating motorcycle impacts. However, the criticality of these components may vary from vehicle to vehicle and from impact to impact. Hence, it may be better to emphasize how well the simulation quantitatively agrees with the test data, rather than on mandating a "design" standard for simulation models. The ISO Standard uses this approach.

Deguchi (2003) describes a hybrid FE/multi-body MADYMO model comprising a 21 mass motorcycle, 2200 membrane element airbag, a Hybrid III dummy (rather than a MATD dummy) and a rigid barrier. Force-displacement data comparing the simulation and laboratory tests are shown for the MC front structure, the MC cowl, the seat and the handlebars. The motorcycle and dummy models are then used in a “prescribed motion” simulation (using as inputs the motorcycle motions recorded on a full-scale test film) in order to predict chest and head accelerations for two car side impacts, for which time history comparisons are shown. For a barrier test, simulation/full-scale comparisons are also shown for barrier force, MC cg and front fork accelerations, for a motorcycle-alone test.

Namiki et al. (2003) describes a hybrid FE/multi-rigid body model using the LS-DYNA code, comprising a 35K element motorcycle, a 5K airbag, a 36K element dummy and a 169K element car. Time histories comparing simulation to full-scale are shown for various component tests and for full-scale car side impact tests. In order to reduce run time requirements, which were substantial, “contact search” and “non-involved rigid model” adaptive algorithms were used, which reduced the run time by 30%. Comparisons were made between animations and test films for 45 and 90 degrees car side impacts. A quantitative comparison between simulation and full-scale test was also made in terms of the torso angle and head velocity just before ground impact.

MB SIMULATIONS OF 501 LA/HANNOVER ACCIDENTS: Figure 1 compares the predicted injury distributions from the ISO-compliant simulation of Kebschull et al. (1998) to the injury distributions from the real LA/Hannover accidents, for the head, chest, abdomen, upper and lower legs and knees. There is substantial agreement for all body regions and all injury severities. Note that only certain severity levels exist for the lower extremities fractures and dislocations, as described in the AIS definitions and in ISO 13232, and the simulation is in reasonable agreement with those. Head AIS 1 injuries (i.e., headache, dizziness) are typically underreported in real motorcycle accidents, but the sum of “no head injuries” and “AIS 1 head injuries” closely match, between the actual and simulated accidents.

COMPARISON OF MB AND FE SIMULATIONS OF A SIMPLE STRUCTURE: Figures 2 and 3 compare the MB and FE simulation results in terms of time histories for the cantilever end longitudinal deflection and velocity and mid-span transverse velocity, for a 150 kg 300 mm sphere impacting at 13.7 m/s. As can be observed, the MB and FE results are in generally close agreement in terms of longitudinal deflection and velocity. The transverse rigid-span velocity responses in Figure 3 are also similar in terms of peak velocity and decay time, with the MB model exhibiting a lightly damping mode. Each of these responses could be compared to actual test data for calibration purposes.

Figures 4a through 4c show the deflected cantilever shape at three points in time, for the FE model and the MB model. This indicates that both methods are capable of generating a very similar, non-linear buckling response. The notion that MB simulation methods cannot be used to predict buckling is not supported by these results.

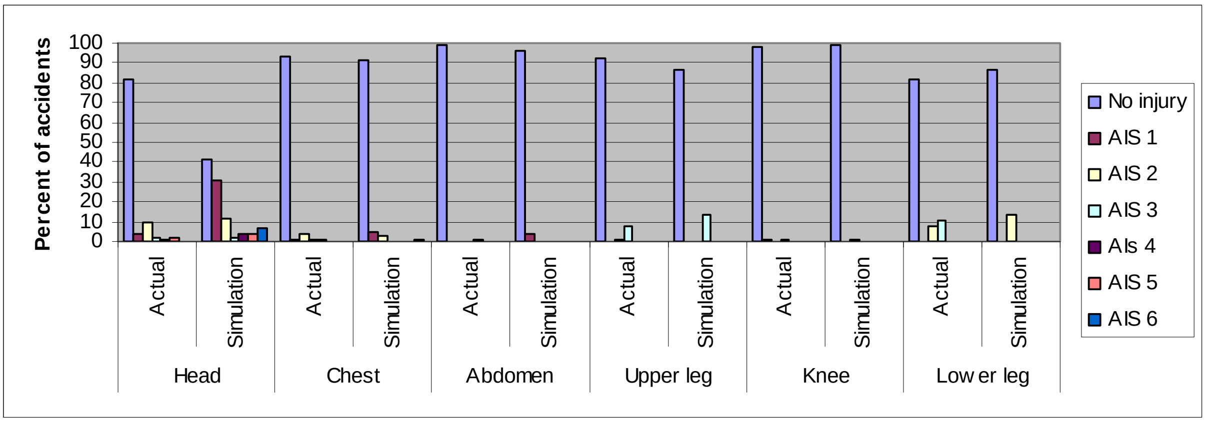


Fig. 1 - Comparison of simulated and real injury severities for n=501 LA/Hannover accidents by body region

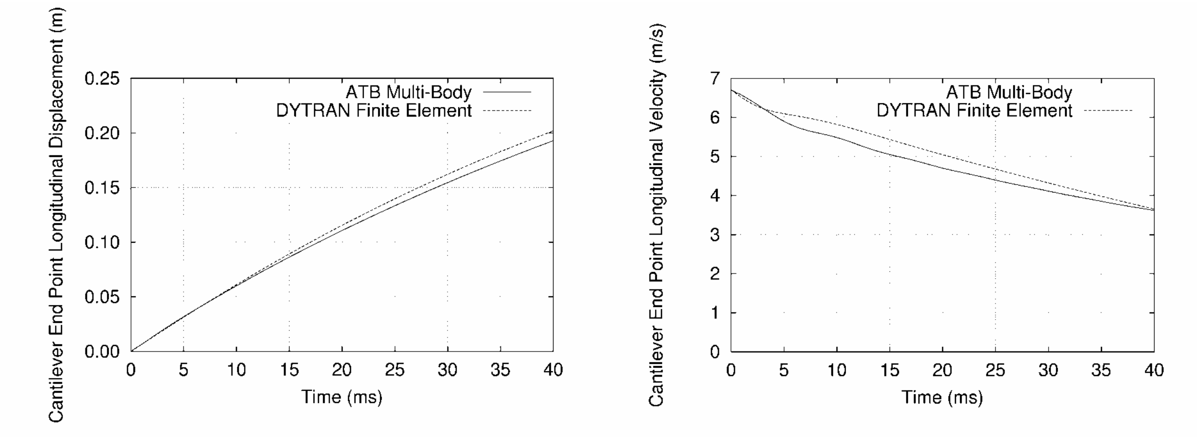


Fig. 2 - Comparison of MB and FE time histories for cantilever end longitudinal deflection and velocity for 13.7 m/s span-wise impact

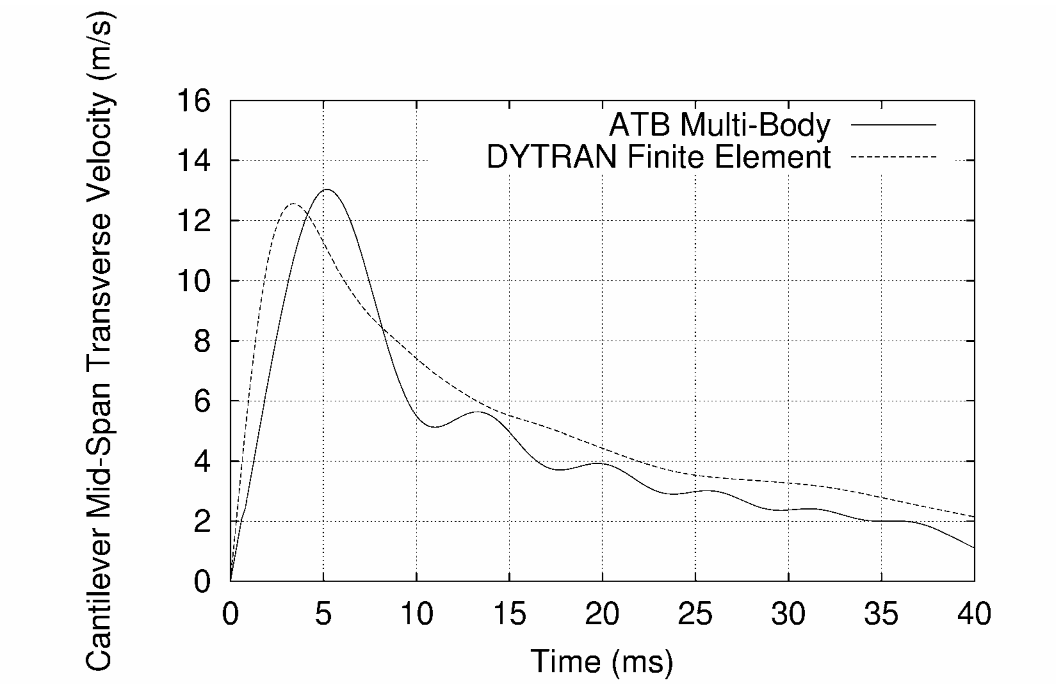
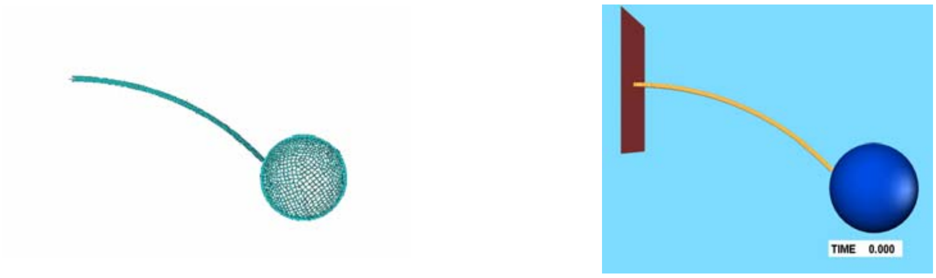


Fig. 3 - Comparison of MB and FE time histories for cantilever mid-span transverse velocity for 13.7 m/s span-wise impact



a) t = 0 ms

b) t = 20 ms

c) t = 40 ms

Fig. 4 - Comparison of FE (left) and MB (right) cantilever shape at peak deflection for three impacts

CONCLUSIONS

REGARDING CURRENT STATUS OF MOTORCYCLIST SIMULATION METHODS: The review of the substantial literature on the subject indicated that much progress has been made since the 1970's in the field of computer simulation of motorcyclist injuries. Early single and multi-mass models with single-point contacts indicated the usefulness of simulation as a crash analysis tool, and led to multi-rigid-body with multiple contact surfaces in the late 1980's, followed by finite element and hybrid MB/FE models. This evolution was made possible by the emergence of affordable high-capacity software and computational speeds. In the early 1990's, the question arose as to the purpose of such simulations in rider protection research, and the minimum requirements that they should they meet, in order to be relied upon in providing accident sample-based analysis of the overall effects of various rider protective concepts. This led to standardisation of minimum requirements in ISO 13232 (1996).

REGARDING STANDARDIZING MOTORCYCLIST INJURY SIMULATIONS: The review of the technical literature indicated that there are strong reasons why "performance" (and not "design") standardisation of simulation methods is of vital importance. Without *minimum* provisions for factors such as quantitative calibration, level of modelling detail, outputs and so on, there may be little or no connection to real experimental data, no means for comparing alternative simulations of the same protective device, and therefore little reliability for evaluating the complex phenomena of motorcycle crashes. Typically, a qualitative comparison (for example, as suggested by Chawla et al, 2003) will be done before a quantitative comparison is attempted, but finally the quantitative calibration of simulation "performance" as required in ISO13232 is of vital importance. Simulation "performance" standardisation as found in ISO 13232 provides minimum requirements that are aimed at those aspects which are most important, namely, rider motions and injury indices, regardless of whether multi-rigid body, finite element or other emerging methods are used. Specifically, the calibration procedures in the Standard are intended to enable simulation models to be used to *interpolate* between conditions for which the simulation has been calibrated against laboratory and full-scale tests, enabling a large, representative samples of real accidents to be simulated. At the same time, it is essential that such standardisation be in no way restrictive of new simulation technologies. A simulation standard must allow for evolution of emerging technologies, including for example, modal, continuum, voxel and hybrid methods. Finally, the currently continuing and open work of ISO/TC22/SC22/WG22 to improve and to revise ISO 13232 in order to reflect the experience of users is a process that benefits all researchers in the rider safety field.

REGARDING PREDICTION OF RIDER INJURY DISTRIBUTIONS: The example ISO-compliant multi-body simulation described by Kebschull et al. (1998), which was previously calibrated against data for 31 laboratory tests and 14 full-scale impact tests, was found herein to be capable of accurately predicting the general distributions of locations, types and severities of rider injuries across the head, chest, abdomen, upper and lower legs and knees in 501 real accidents.

There appears to be no fundamental reason why FE (or hybrid MB/FE) models, or other types of models (e.g., continuum, modal, voxel, etcetera) could not also achieve this or a higher level of accuracy, although to date there has been no published research describing such calibration, validation and comparison for these types of models.

REGARDING COMPARISON BETWEEN MB AND FE SIMULATION METHODS: The comparison of MB and FE simulations of cantilever buckling-type impacts indicated that very similar deflections, velocities and deformed shapes were obtained when the models had the same span-wise number, size and shape of elements. This was the case for both longitudinal and transverse deflections and velocities and the buckling phenomenon itself. The notion that MB is unsuitable for simulating dynamic buckling is not supported by these results.

DISCUSSION

Both multi-body (MB) and finite element (FE) simulations, when suitably calibrated against laboratory and full-scale impact tests in accordance with ISO 13232, have a strong potential to accurately predict rider injury severities outcome of motorcycle impacts. This of course relies on the existence of a suitably biofidelic motorcyclist dummy and corresponding injury probability curves which are used to generate the underlying laboratory and full-scale test. It is observed that committee ISO/TC22/SC22/WG22 continues to identify limitations of and areas for improvement in both the dummy and injury probability curves. Recently these have included upgrades for the motorcyclist dummy neck, to be in better agreement with the existing biomechanical and accident data, and as well as discussion of the potential improvements to other components of the MATD.

In general, the cantilever comparison herein provides one example where FE and MB can give similar results, when a similar level of detail is included. The FE model uses a somewhat more “predictive” approach based on material laws and empirically measured material properties, while the MB model is based on empirically determined relations and the laws of rigid-body mechanics. This illustrates the point that it may be the "number and size of elements", and the “empirical relations used”, which may have stronger effects on the detailed accuracy, rather than whether the "calculation method" is FE, MB, continuum or some other method. This distinction is sometimes overlooked in the technical literature. With regarding to modelling alternatives, on the one hand, FE provides a somewhat more “predictive” method, as the structure’s material properties (e.g., elasticity and strength) can be specified *a priori*, but like MB, FE methods also require careful empirical verification of structural damping and energy absorption. In addition, in order to be predictive, FE requires close attention to sufficiently small mesh size in high deformation zones, internal surface geometry, bracing and stiffening bends, as well as co-ordinated mesh sizes on contacting surfaces, which has not always been the case in MC/car crash simulations to date. Typically, FE (or MB using similar numbers of elements) require extensive human and machine resources, and to date, no work has been published which uses FE model for simulation of the 200 impact configurations in ISO 13232, which is the main purpose of the simulation tool defined in the Standard. Further automation and optimization of FE and hybrid methodologies, as well as “contact search” and “non-involved rigid model” adaptive algorithms, and expected further increases in computational speeds, may improve this situation in the future and appear to be key emerging technologies. This needs to be done, however, with due attention to the calibration and correlation norms of ISO 13232. Needed updates, based on experience, to ISO 13232 and to the underlying methodologies include further allowances for new modelling techniques, and probably more rigorous calibration criteria, without the Standard becoming overly restrictive or difficult to conform to. At the same time, the Standard is not intended to be a workbook or users’ manual for “how to” implement a given type of simulation, but rather a guideline for a simulation’s reliability and performance in comparison to real test and accident data. The current Standard specifies calibration and correlation methods, but has minimal criteria for these, and it is clear that the quality and reliability of simulations would be further improved by implementing simulation performance criteria. In addition, a key issue continues to be the need for more detailed biomechanical and accident data, which have limited both the resolution and the domain-of-validity of the methodologies used to date.

LIMITATIONS OF THIS STUDY

In the 501 simulations of real accidents reported herein, the overall injury distributions rather than the “case-by-case” outcomes were compared between the simulated and real accidents. “Case-by-case outcomes may not compare as closely, due to detailed differences between the modelled and the real motorcycle, opposing vehicle and rider types, and other extensive details of the real accidents. Further case-by-case validation work would be useful. Nevertheless, as found herein, it is considered that at a macro level, the distributions of injury severities are highly reliable, and provide the “best available information” regarding the outcomes of representative samples of motorcycle accidents.

In addition, a key issue continues to be the need for more detailed biomechanical and accident data, which have limited both the resolution and the domain-of-validity of the methodologies used to date.

In the comparison between MB and FE models, the example used was a cantilever, which although it may be representative of some structures like motorcycle forks or handlebars, is less typical of opposing vehicle surfaces or motorcycle surfaces such as fuel tanks, which behave more as shells or more complex 3 dimensional structures. Analogous comparisons between MB and FE for these more complicated cases could reveal other results. All such models however, should be quantitatively calibrated against real dynamic test data in order to clarify the significance of such findings. In addition, this preliminary analysis did not examine in detail the contribution of individual finite element “shape” changes, or detailed differences in total damping and energy absorption, or their significance, which could be further quantified in the future.

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