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The Study of Head and Neck Injury in Traffic Accidents

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Abstract: To reduce human injury severity through improved automobile design and designing protection devices, the dynamic response and injury of occupants in collisions must be analyzed. This study investigates frontal and rear-end collisions using the MSC/DYTRAN finite element code. The dynamic response of the human body to crashes is discussed. Additionally, the head and neck injuries of car occupants are simulated. The simulated results obtained here have potential for evaluating vehicle crash safety and guiding the future development of safety technologies.

Key words: Crash, head-neck injury analysis, finite element method

INTRODUCTION

Traffic accidents in Taiwan have dramatically increased recently owing to rapid economic growth providing individuals with increasing private transportation options. Data over a ten year period indicates an annual average of 3324 reported traffic accidents in Taiwan. Among reported accidents, 2853 persons were fatal and 2576 persons caused serious injuries. Research performed at Harvard predicts that in 2020, traffic accidents will rank third among causes of death and labor capacity loss around the world, ranking after circulatory disease and natural disasters. Safety and efficiency are the two primary objectives of transportation engineering. Traffic accidents are considered a danger to human safety and health, as well as causing significant loss of human life. Injury prevention thus is useful and significant for its relationship with the happiness of individuals and families. According to accident statistics[1], injury and fatality rates in frontal collisions exceed those from side collisions and rear-end impacts. Notably, head and neck injuries are frequent in frontal and rear-end automobile accidents, even at low-speeds. From general accident statistics 58.1% of those injured in accidents suffered head injuries, 70% suffered thorax injuries, 50% suffered arm injuries, 53% suffered leg injuries and 23% suffered neck injuries[2]. To effectively and efficiently reduce traffic accident injuries, the dynamic response of the human body to traffic accidents should be analyzed, with a particular focus on head and neck injuries.

Generally, two methods exist for investigating dynamic response and injury analysis for human bodies involved in car crashes, namely: the experimental method and the numerical simulation method. The experimental method can be further divided into real car collision tests and sled experiments. Although real car collision tests can achieve results closely resembling a real accident, this method is complicated and expensive. Practical and ethical concerns also restrict the use of actual occupants for risk assessment. Research and development tests using dummies now can simulate human responses in a car collision. The Hybrid and ATD (Anthropomorphic test dummy) series of test dummies developed by General Motors are industry standards in car collision testing. These test dummies have been demonstrated to be highly repeatable, reproducible, durable and serviceable test devices. Test dummies thus have been widely used in numerous applications related to human dynamic simulations. Recently, rapid advances in computer

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technology have enabled applied mathematicians, engineers and scientists to achieve significant progress in solving previously intractable problems. Numerical crash simulations provide a valuable tool for automotive engineers. In vehicle collision analysis, finite element modeling is essential for investigating dynamic behavior of occupants and also in injury analysis. The software packages considered include MSC-DYTRAN, LS-DYNA/3D, Pam Crash and so on. Crash simulations and analyses with numerical methods have been extensively studied. For example, a nonlinear mathematical model of the human body and constraint system was formulated by Huang[3]. Moreover, equations of motion were developed for the human body model using Kane's equations. These equations of motion can be used in general three-dimensional impact conditions. Norin and Helleman[4] presented a method whereby the safety potential of a safety design feature in a certain accident configuration can be predicated before the system is exposed to real traffic conditions. Pal[5] developed a finite element side impact dummy model based on the initial NHTSA model. A number of modifications are performed based on the combined simulation and experimental verifications of the dynamic characteristics of different materials. Wu and Cheng[6] presented a few examples of crash simulations performed using FCRASH, developed in-house by Ford Motor Company. Moreover, Omar *et al.*[7] applied an advanced Artificial Neural Network to story the nonlinear dynamic characteristic of the vehicle structure. Several impact scenarios can be analyzed quickly with considerably less computational cost by using the trained networks. Furthermore, Abe *et al.*[8] investigated various vehicle-to-vehicle collision phenomena in three dimensions by applying a simple method which makes it possible to perform calculations on a personal computer and yields a satisfactory result. Moreover, Londsdale *et al.*[9] introduced parallel programming paradigms for nonlinear, explicit finite element simulations, mainly employed for crashworthiness and occupant safety simulation in the automotive industry. Additionally, Brown *et al.*[10] described a strategy for both the computational mechanics and parallel computing communities in solid mechanics simulation. Watanabe *et al.*[11] developed a practical and simplified human body FEM model. This model is a specialized model for automotive crash injury analysis used mainly to calculate injury data. Finally, Noureddine *et al.*[12] developed a finite element model for computer crash simulation with the Hybrid III crash test dummy. The reasonable accuracy of the model makes it useful for crashworthiness simulation.

Human injuries are unavoidable in traffic accidents and the safety of occupants in car crashes cannot be disregarded. To reduce human injury severity through improved automobile design and designing protection devices, the dynamic response and injury of occupants in collisions must be analyzed. This study investigates frontal and rear-end collisions using the MSC/DYTRAN finite element code. The dynamic response of the human body to crashes is discussed. Additionally, the head and neck injuries of car occupants are simulated. The simulated results obtained here have potential for evaluating vehicle crash safety and guiding the future development of safety technologies.

MATERIALS AND METHODS

Finite element calculation: This study performs drop simulations using the computer program, MSC/DYTRAN, which is based on the finite element method. The MSC/DYTRAN program is a three-dimensional analysis code for analyzing dynamic, nonlinear behavior of solid components, structures and fluids. The program uses classic explicit finite element technology to solve dynamic structural analysis problems. The program includes all element types and material models required to solve various practical engineering problems, including problems involving 3-D contact and sliding effects. Problems involving 3-D contact and sliding effects arise in structural crashworthiness analysis, component drop test simulations, tri-hub burst containment analysis and sheet metal stamping.

The crash event is a highly nonlinear transient dynamic process, involving various difficulties in computational mechanics. This study used the MSC/DYTRAN nonlinear finite element code, which is suitable for large deformation impact problems involving contacts. Moreover, the Lagrangian processor was used. Crash analysis is theoretically simulated using continuum mechanics to describe the process of material deformation and the explicit direct time integration. The explicit methods are conditionally stable and depend on the selected time step but do not require the solution of the simultaneous equations. The pre-and post-processor MSC. Patron is used to prepare and evaluate the MSC/DYTRAN results.

Injury criterion

Head injury criteria: Motor vehicle crash dynamic experiments focused on human head injuries generally cited some data or/and scale to describe the scale of potential head injuries resulting from impact. Head Injury Criteria (HIC) were defined in Federal Motor Vehicle

Safety Standard (FMVSS) No.208 and adapted for the occupant safety rules of NHTSA in the USA. The FMVSS standard No.208 specifies performance requirements for protecting vehicle occupants in crashes. This criterion evolved from the Wayne State Tolerance Curve[13] based on various empirical data from cadaver, animal and human tests and presents injury as a function of effective acceleration and pulse duration. This criterion used the amplitude and duration characteristics of the head acceleration at the center of gravity of the dummy head. The HIC is calculated by the formula:

$$HIC = \max\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)\,dt\right]^{2.5}(t_2 - t_1) \quad (1)$$

Where, a (t) is the resultant head acceleration at dummy head CG and $(t_2\text{-}t_1)$ is the time interval maximizing HIC. For any two time points, t_2 and t_1, during the event which are separated by not more than a 36 millisecond time interval, the head injury criterion is denoted as HIC_{36}. According to the FMVSS No.208 specification, the maximum calculated HIC_{36} value shall not exceed 1,000.

Neck injury criteria: The axial loads (compression or tension), shear loads (force perpendicular to the neck column) and bending moments (flexion and extension) can be measured using the dummy upper neck load cell for the duration of the crash event. The resulting criteria are referred to as N_{ij}, where "ij" represents indices for the four injury mechanisms; namely N_{te}, N_{tf}, N_{ce} and N_{cf}. Notably, the first index represents the axial load (tension or compression) and the second index represents the sagittal plane bending moment (flexion or compression). The current FMVSS No. 208 includes injury criteria for the neck injury criteria consisting of individual to tolerance limits for compression (compression of the neck), tension (force stretching the neck), shear (force perpendicular to the neck column), flexion moment (forward bending of the neck) and extension moment (rearward bending of the neck).

The proposed neck injury criteria thus can be expressed as the sum of the normalized loads and moment.

$$N_{ij} = \frac{F_z}{F_{int}} + \frac{M_y}{M_{int}} \quad (2)$$

Where, F_Z denotes the axial load, F_{int} represents the critical intercept value of load used for normalization, M_Y is the flexion/extension bending moment and M_{int} denotes the critical intercept value for the moment used for normalization.

The FMVSS No.208 specification requires that none of the four N_{ij} values exceed 1.4 at any time during the event. That is, any neck injury criteria value exceeding 1.4 indicate that the impact causes lasting neck impairment.

RESULTS AND DISCUSSION

For the sled simulation, numerical dummies are placed in the front seats in the sled and secured with the safety belts. Figure 1 shows an impact acceleration curve for simulating the crush pulse, which is equivalent to

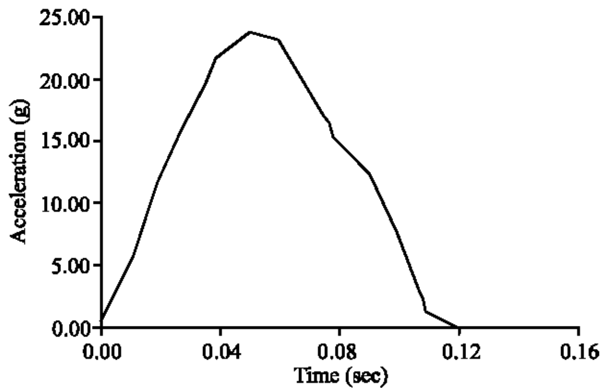

Fig. 1: Impact acceleration curve at a velocity of 55 km/h

a collision between two identical vehicles each moving at 55 km/h. Figure 2 to 4 illustrate the dynamic response of the human body in frontal collisions at a velocity of 55 km/h. The maximum displacement during the collision phase was 0.09 sec. The dummy was returned to the original position by the three-point belt restraint system at 0.15 sec. Throughout the dynamic response, the possibility of the body impacting the vehicle is reduced due to the constraining force provided by the safety belt. However, the safety belt only constrained the upper torso and upper thigh areas and could not constrain the forward motion of the head and neck. The rapid and large movement causes muscle and ligament tears and the cervical spine can suffer still more serious injuries.

Figure 5 to 7 present the dynamic response of the human body in rear end collisions at a velocity of 55 km/h. The results are completely different from those for frontal impact collision at the same velocity. Basically the dynamic response comprises three parts.

Ramping period: The torsos ramped up along the inclined seatback during the initial impact. If the collision speed is too fast or the degree of seatback is too large, upward movement may occur and the occupant may strike the roof of the vehicle. As Fig. 5 shows, the dummy moves upwards along the direction of the seatback at 0.0675 sec.

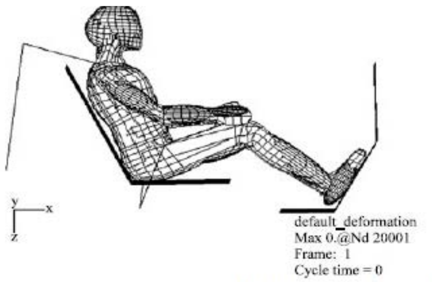

Fig. 2: Dynamic response of the dummy in frontal collisions (t = 0 sec)

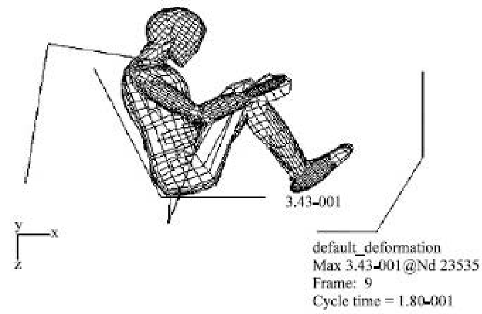

Fig. 5: Dynamic response of the dummy in rear collisions (Ramping, t = 0.0675 sec)

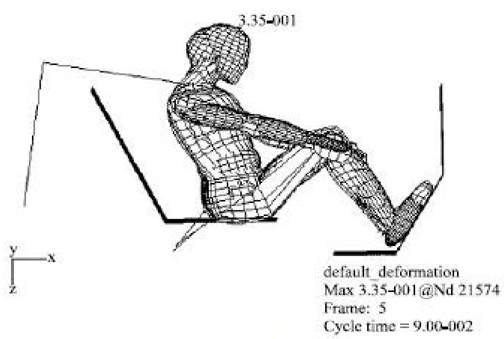

Fig. 3: Dynamic response of the dummy in frontal collisions (t = 0.09 sec)

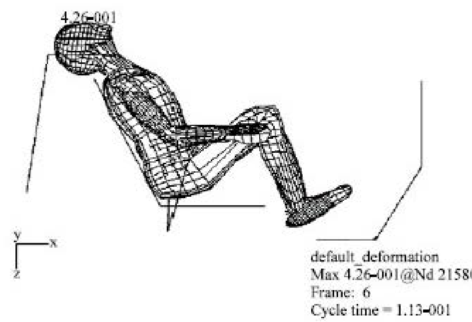

Fig. 6: Dynamic response of the dummy in rear collisions (Whiplash, t = 0.113 sec)

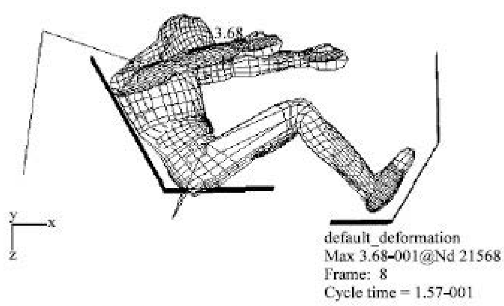

Fig. 4: Dynamic response of the dummy in frontal collisions (t = 0.157 sec)

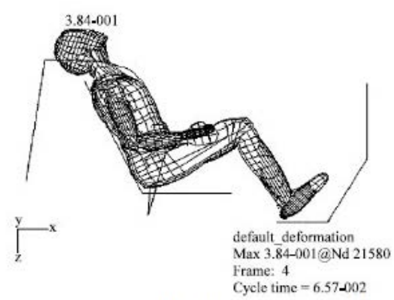

Fig. 7: Dynamic response of the dummy in rear collisions (Rebounding, t = 0.18 sec)

Thighs and buttocks of the occupant have leave the seat and the head also moves backwards. Simultaneously, the upwards movement of the occupant is reduced owing to the constraining force from the safety belt. The ramping movements generally do not cause serious injuries in low-speed impacts.

Whiplash period: From Fig. 6, the backward movement of the head reaches its limit at 0.113 sec. The neck moves backwards quickly after the ramping period when the seat has no headrest or when the headrest is fixed in a low position. The head of the occupant suddenly jerks backwards and then forwards.

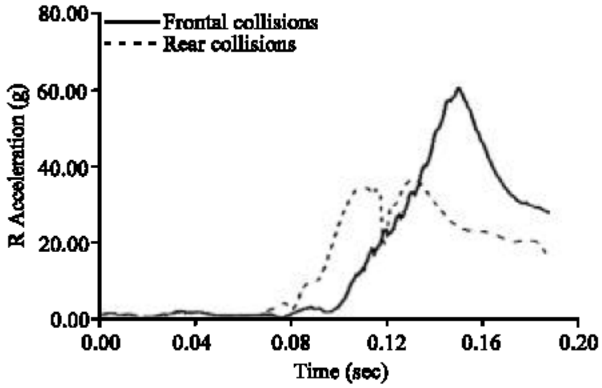

Fig. 8: The acceleration of the head in frontal and rear collisions (V = 55 km/h)

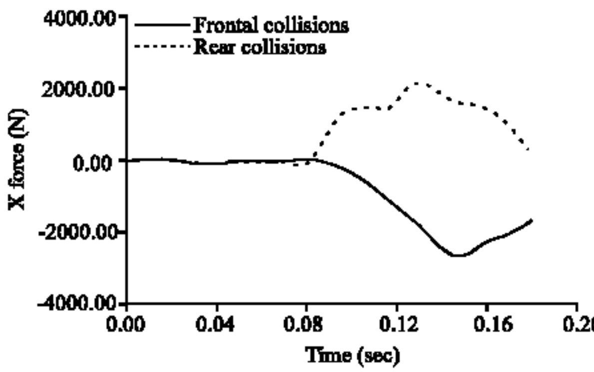

Fig. 9: The x-axis shear force of the neck in frontal and rear collisions (V = 55 km/h)

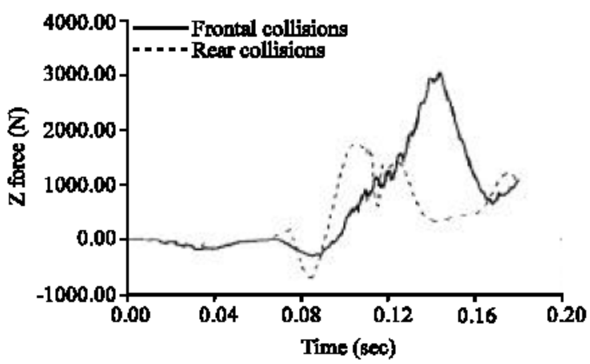

Fig. 10: The z-axis tension force of the neck in frontal and rear collisions (V = 55 km/h)

As the head rocks backwards, the neck absorbs the backwards force as it is transformed into backwards and downwards thrust. As a result, the neck overextends at this moment. The neck then endures fresh forward and downward thrust when the head moves forward, causing the neck to over bend.

Rebounding period: As Fig. 7 shows, the dummy changed to a forward-moving state from a backward-moving state

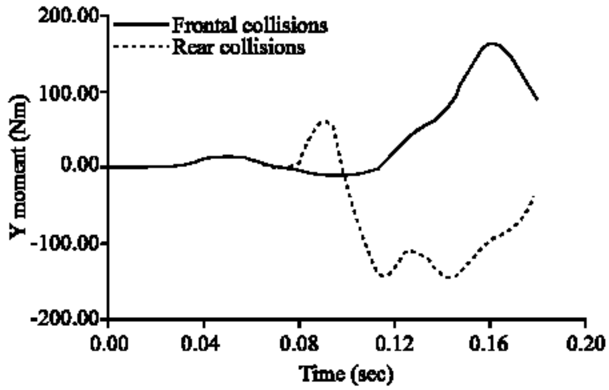

Fig. 11: The y-axis moment of the neck in frontal and rear collisions (V = 55 km/h)

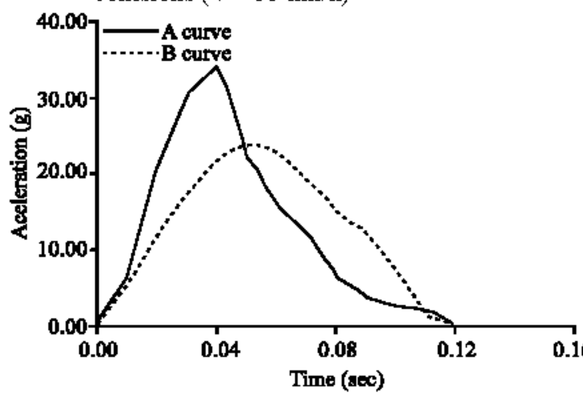

Fig. 12: Impact acceleration curve of cars with different star ratings at 55 km/h of impact velocity

at 0.18 sec. This phenomenon results from the bouncing energy absorbed from the seat in the whiplash period. This energy completely transfers to the occupant at the end of the collision period. Consequently, the occupant is subjected to a rush of force. The occupant can easily strike the steering wheel or windshield if no safety belt is used and may even be thrown from the vehicle.

Injury analysis of head and neck under crash: Figure 8 shows the acceleration of the head in frontal and rear collisions at a velocity of 55 km/h. For frontal collisions, the acceleration curve increased rapidly and peaked at 61.4 g. Meanwhile, for rear collisions the acceleration curve appeared to be oscillating because the seatback can be regarded as a buffer against backwards movement. The peak acceleration reached 37.6 g. Table 1 lists HIC values calculated from the acceleration plot for frontal and rear collisions. All of the HIC are well below the existing tolerance limit for the frontal and rear impacts. Moreover, comparison of the results shows the potential for serious head injury is greater in frontal collisions and rear collisions.

Table 1: The acceleration and HIC values for frontal and rear collisions

	Head accel. (g)	HIC values
Frontal collisions	61.4	592.4
Rear collisions	37.6	220.8

Table 2: The neck injury criteria (N_{ij}) for frontal and rear collisions

	N_{tf}	N_{te}	N_{cf}	N_{ce}
Frontal collisions	0.89	0.10	0.06	0.11
Rear collisions	0.16	1.46	0.23	0.02

Table 3: The HIC values and AIS scores in frontal collisions for different curves

Curves	Max. impact accel. (g)	Max. head accel. (g)	HIC values	AIS scores
A	34.2	71.9	838.0	2~3
B	23.7	61.4	592.4	1~2

Table 4: The neck injury criteria in frontal collisions for different curves

Curves	N_{tf}	N_{te}	N_{cf}	N_{ce}
A	0.99	0.15	0.06	0.11
B	0.89	0.10	0.06	0.11

For the analysis of neck injuries, Fig. 9 to 11 illustrate the x-axis shear force, z-axis tension force and y-axis moment of the neck in frontal and rear collisions at a velocity of 55 km/h. Table 2 lists the neck injury criteria (N_{ij}), which were calculated according to the x-and z-axis forces and the y-axis moment. The neck injury criteria of N_{te}(tension and extension moment) was highest in rear collisions. Notably, the value of N_{te} exceeded the allowable limit value of 1.46. That is, it caused neck impairment during rear impacts. All of the neck injury criteria are well below the existing tolerance limit for the frontal impacts. Comparing the results shows that neck injuries are more likely to occur in rear collisions than frontal collisions.

Most vehicles are rated on how well they protect drivers and passengers during frontal and side collisions. A five-star system provides a useful basis for comparing vehicle safety, with five stars indicating the highest safety rating and one star the lowest. Figure 12 shows two impact acceleration curves representing the two cars with different star ratings at 55 km/h of impact velocity. Different impact acceleration curves represent cars with different safety rating levels. Table 3 lists the HIC values and AIS scores in frontal collisions for different curves. The head acceleration maximum associated with AIS=2~3 brain injuries resulting from curve A was 71.9 g and HIC was 838. Moreover, the head acceleration maximum associated with AIS=1~2 brain injuries resulting from curve B was 61.4 g and HIC was 592.4. The simulation results indicate that HIC values on curve A are actually higher than on curve B (HIC=838 versus 592.4). This phenomenon primarily results from the sharper acceleration spike and substantially shorter HIC interval than for the longer-duration HIC calculation. Table 4 lists the neck injury criteria in frontal collisions for different curves. The neck injury criteria of N_{tf}(tension and flexion moment) represent a very important index for neck injury severity in frontal collisions. This simulation result shows that the value of N_{tf} did not exceed the allowable limit of 1.4. For these two curves. The two impact acceleration curves do even have the same impact velocity. Notably, curve A causes more serious head and neck injuries than curve B. Therefore, choosing a high safety rating car is important for reducing injury severity.

This study employs the finite element method to explore frontal and rear-end collision phenomena. Specifically, this study discusses the dynamic response of the human body under a crash. Occupant head and neck injuries also are assessed in this simulation. The following conclusions are made based on the results of this study:

- Measuring human responses to car collisions using the numerical method is useful. Also, the analysis models demonstrated capabilities for predicting the severity of injury suffered by drivers in impacts involving vehicles.
- The head suffers serious but not life threatening injuries in frontal and rear collisions at a velocity of 55 km/h. Moreover, frontal collisions are associated with more serious head injuries than are rear collisions.
- The neck suffers serious injuries in rear collisions at a velocity of 55 km/h. Moreover, the probability of neck injuries occurring in rear collisions is greater than in frontal collisions.
- Selecting a car with a high safety rating car is important for reducing injury severity. Cars with sharp impact acceleration curves cause serious head and neck injuries.

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