THE METHODS OF REDUCING IMPACT LOADS ON OCCUPANTS IN THE CIVIL AIRCRAFT CRASH CONDITION

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ABSTRACT

In order to prevent the occupants from injury or loss of lives, impact loads should be reduced to sufficiently low levels. Four feasible reduction methods, which are protectors, brace positions, a shoulder-harness and a rear facing seat, were selected and evaluated by both impact tests and analyses.

To analyze the dynamic behavior of a occupant on a seat, two-dimensional simulation computer program was developed.

The total of thirty impact tests were carried out. Anthropomorphic test dummies sit on the two seats on the sled of HYGE impact tester were loaded forward at several acceleration levels. The maximum acceleration level was 30G.

The results obtained from impact tests and analyses gave us useful information to improve design of air transport seat-restraint system and occupant's crash protectors.

Some recommendations were provided for greater survivability in future accidents.

INTRODUCTION

Recently more attention has been paid to safety inside the cabin in the accident of airplane crash. Knowledge of the method to reduce impact loads on occupant is significant consideration in the improved design of air transport seat-restraint system and occupant's crash protectors.

Three viewpoints should be considered to gain greater survivabilities of the occupants during aircraft crash accidents.

* Reduction of the accelerations and forces sustained by occupants.

* Prevention of fire.

* Emergency escape.

The problem to reduce the acceleration and the force on occupant should be first addressed since occupants can only escape after surviving during crash condition.

The study as presented here is the investigation into the methods to reduce the impact load on air transports occupants during crash accidents. First, referring to some other reports, four reduction methods were chosen as subjects of this study. Then impact test and computer simulation were conducted to evaluated the effect. Some recommendations were provided for greater survivability in future crash accidents and these are presented in the report.

This study has been done from the *joint research by Japan airlines(JAL)* and Fuji Heavy Industries, Ltd.(FHI). The investigation of papers and impact test were conducted by JAL and computer simulation by FHI.

INVESTIGATION OF REDUCTION METHOD

Many studies have been conducted and various methods have been proposed to reduce impact loads on occupants. The following methods had been discussed in the papers.

* a rear facing seat [1,2,3]
* a lap belt with shoulder-harness [2,3,4,5,6,7]
* restraint systems [4]
    - passive net system
    - air bag system
    - inflatable belt system
    - etc.
* protectors
    - a pillow
    - a blanket
    - a helmet
    - etc.
* brace positions [8]

A rear facing seat can be expected to reduce the impact load due to receive occupants in the seat bottom and the seatback.

It is easy to understand that shoulder-harness can restrain the upper body so that it prevents the contact between the head of occupant and the objects, a seatback of the seat in front of occupant for example.

Some restraint systems were employed in the seats of automobile. However it is difficult to apply these restrain systems to air transport seats.

No documentation has been found to support the effect of protectors, pillow and blanket, as the energy absorber. However the ability to prevent minor injury can not be denied.

The studies of brace positions have been investigated in detail for a long time. Taking the optimum brace position is the easy way to reduce impact load without special tools.

From the investigation following methods were chosen as the subjects of this study.

* PROTECTORS
  a helmet
  a blanket
  a pillow
* BRACE POSITIONS

* A LAP-BELT WITH SHOULDER-HARNESS

* A REAR FACING SEAT

HUMAN INJURY CRITERION

There are two categories of human tolerance specified whether whole body or regional impact is involved. The human tolerance for whole body has been defined by two factors, magnitude, direction and time duration of impact load. From FAA, Federal Aviation Agency, AC21-22, the following injury criteria have been specified for regional impact.

* HIC(Head Injury Criterion) for head
* The force applied to shoulder-harness for chest
* The force applied to femur for leg
* The axial load applied to the spine for spine

These criteria are shown in Table 1.
The injury criterion for whole body is too rough to evaluate the effects of the reduction methods. On the other hand the human tolerances for the regional impact were so useful to evaluate in detail that these were employed as the human injury criteria.

IMPACT TEST

The impact tests were performed to evaluate effect of the reduction methods and to verify the computer simulation program. The computer simulation will be described after in detail.

TEST FACILITY

The test facility consisted of impact tester, two seats and anthropomorphic dummies. The impact acceleration conditions were simulated by the controllable and variable acceleration sled, HYGE IMPACT TESTER, shown in Fig. 1, at the Japan Automobile Research Institute, Inc.(JARI).

The following two kinds of seat were prepared.

* The triple seat equipped in economy class of DC-10 airplane with a little reinforcement to endure high impact load.

* The single seat newly produced for the rear facing seat and the shoulder-harness seat.

These seats were set up on the sled and one anthropomorphic dummy,49 CFR Part 572 Subpart B, was sit on the center of the each seat. Two seats were located in front and in the rear at 32 inch pitch, see Fig. 2.

Helmets, pillows, magazines and blankets were also prepared as the protectors. The helmets were certified by Snell Foundation for bicycling. The pillows and the blankets which equipped in the cabin were used for the head and the abdomen protectors, also the inflight magazines for the abdomen protectors.

New seat belts were prepared to endure the dynamic loads more than 9G, maximum impact acceleration.

MEASUREMENT

The following data, time histories, were measured in the tests.

* The impact acceleration at the sled.

* The G forces in three axes, frontal, lateral and vertical, at the C.G of the head and the chest of the dummies.
* The pelvis loads of the dummies.

* The femur loads of the dummies.

* The lap and shoulder-harness belts loads.

The locations of the contact points between the dummies and the objects were also checked. In addition the behaviors of the dummies were recorded by the two cameras set on the ground and the sled.

IMPACT TEST CONDITION

The impact pulses are shown in Table 2. The sled was accelerated in frontal direction.

The dummies took upright and four brace positions. The brace positions are described below.

* TYPE A
This position is taken by the occupant who sit on the seat spaced at large pitch.
(see Fig. 3, on the left side)
* TYPE B
This position is taken by the occupant who sit on the seat spaced at narrow pitch.
(see Fig. 3, on the right side)
* TYPE C
In addition to the TYPE B, the seatback in front of the occupant are fold down before crash accident.

* TYPE D
It was the recommended brace position by the report[9]. The lower limbs are inclined slightly backwards to reduce foot and lower leg injuries.
(see Fig. 4)

Fig.5 and Fig.6 illustrate the set up for the shoulder-harness seat and the rear facing seat respectively.

EXPERIMENTAL RESULTS

The 30 impact tests were performed on the HYGE Impact Tester. The experimental results are summarized in Table 3.

In the upright position the HIC value exceeded 1000, allowable limit value. It should be noted that HIC value sitting on the rear seat were likely to larger than on the front seat because of the contact between the head and the seatback of the front seat.

The head protectors could not reduce HIC values than the upright position. The protectors for abdomen could not reduce lap belt loads too.

The four brace positions made good results on HIC value. The values didn't exceed 1000 in all brace position cases. It was clear that HIC values depended on the travelling distance between head and objects significantly. The brace position, which had the distance as short as possible such as Type c, was recommended.

The shoulder-harness reduced the HIC value extremely. Especially in comparison with the case of upright position on the rear seat, the great effect could be found. However the attentions should be paid to the followings to design.

* The submarining phenomenon.
* The large femur load.
* The large shoulder-harness load.
* The cervix injury.

where the submarining phenomenon means that the rotation of hip under lap belt and the lap belt slippage up into abdomen which causing severe flexing of spinal column.

The rear facing seat made the best results among those reduction methods. However the impact of the head against the headrest should be considered to design.

Some considerations of the impact test were derived. These are as follows.

* A measurement of distributed load on abdomen
To evaluate a abdomen protector or to identify submarining phenomenon a method to measure the distributed load on abdomen should be established.

* An anthropomorphic dummy
To simulate the injury of cervix or lower leg more accurate anthropomorphic dummy should be used. The 50th percentile Hybrid III dummies are recommended.

COMPUTER SIMULATION

It was clear that it cost much money and time to evaluate the effect of the reduction methods by impact test only. Moreover, impact facility had the limit to simulate high impact acceleration environment. Therefore the computer program was necessary to simulate the occupants behaviors in many cases and in a wide range of the impact acceleration.

REQUIREMENT FOR SIMULATION PROGRAM

The computer program was required to have the following capabilities.

The program can
(1) simulate the kinematic behavior of occupant.
(2) compute acceleration at head and thorax of dummy.
(3) consider contacts between occupant body and objects.
(4) compute acceleration of head with various head protectors.
(5) calculate loads on seat belts.
(6) consider displacement of seat.
(7) identify submarining phenomenon.

In addition to above requirements, source code of the program was needed to modify and upgrade.

According to our investigations there were no computer programs which satisfied all of the requirements. Therefore The program was prepared by modifying the two-dimensional simulation program which had developed by FHI.

COMPUTER SIMULATION PROGRAM

The following provides the general description of the program.

The program simulates the kinematic behaviors of a occupant and a seat in two dimensional crash environment, longitudinal and vertical axes. The program computes time histories of 13 degree of freedom(DOF), which describe the motion of a occupant and a seat. The non-linear equations of motion are written for each DOF and integrated numerically to obtain velocities, displacements and rotations. External force, internal force and moments are calculated also.

The program has the capabilities to (1) describe the motion of the occupant by 10 DOF and the motion of the seat by 3 DOF, see Fig 7.

(2) compute the acceleration , velocity and displacement of each element and inertial force between elements at each time.

(3) provide for the non-linear stiffness and damping properties of the joints,the seat belts, seat structure.

(4) provide for the non-linear properties of the contact between the dummy's body and environments and between the elements of the dummy.

(5) provide for the impact loads by defining the time histories of the acceleration in two directions,longitudinal and vertical, at the floor.

(6) calculate the injury parameters, Severity Index(SI) and Head Injury Criterion(HIC).

The flow chart of the program is shown in Fig. 8.

ANALYTICAL MODEL

The simulation program models a occupant, single seat,a lap belt, a shoulder-harness and environments, see Fig. 9.

The occupant model consists of the eight rigid elements which have each inertia property, connected by the joints. Each joint has the non-linear characteristics of elastic torque, friction torque and damping torque.

The seat model, connected to the floor by the non-linear spring, has three DOF, longitudinal, vertical and rotational.

The environments mean the objects which have possibilities to contact with the occupant's body, for example the seatback, the floor and the seat cushion.

The contact model consists of the circles on the dummy's body and planes on the environments. In the program the contact occurs when the contact circle intersects the contact plane. Each element of the dummy has the contact circles and the seatback, seat cushion and floor are modeled by the contact plane. The lap belt and the shoulder-harness are available for belt model.

EXPERIMENTAL VERIFICATION

The experimental verification of the program was performed by comparing the results between the computer simulation and the experiment in the following four cases.

* FRONT SEAT MODEL

* REAR SEAT MODEL

* SHOULDER-HARNESS MODEL

* REAR FACING MODEL

These analytical models are described in the next section.

The comparison of the three parameters, the resultant acceleration of the head C.G, the lap belt load and the HIC value, are shown in Fig. 10 to Fig. 13. These figures show that the analytical results are in good agreement with the experimental.

NUMERICAL SIMULATION

The following 9 analytical models were prepared for the simulation.

* FRONT SEAT MODEL (Fig. 14)
* REAR SEAT MODEL (Fig. 15)
* SHOULDER-HARNESS MODEL (Fig. 16)
* REAR FACING SEAT MODEL (Fig. 17)
* BRACE POSITION MODEL
  - TYPE A (Fig. 18)
  - TYPE B (Fig. 19)
  - TYPE C (Fig. 20)
  - TYPE D (Fig. 21)
  - TYPE E (Fig. 22)
* HEAD PROTECTOR MODEL

The FRONT SEAT MODEL expresses the occupant sitting on the seat spaced at large pitch or the front low. The REAR SEAT MODEL shows the majority of seat in economy class of air transports, spaced at narrow pitch. The SHOULDER-HARNESS MODEL and the REAR FACING MODEL express the reduction methods which corresponded to the impact test. The BRACE POSITION TYPE A and TYPE B can be seen on safety instruction sheets of airlines widely. The TYPE C is similar to the TYPE B except folding the seatback before setting up the brace position. The TYPE D, recommended in the paper , is the same as the TYPE B with the lower limbs inclined slightly backwards. The TYPE E is the mixture brace position of the TYPE C and the TYPE D.

The HEAD PROTECTOR MODEL is the same as the FRONT SEAT MODEL which includes the contact property of the each protector in the contact model between the head and the objects.

The crash pulses used in these analyses were generated by multiplying the magnitude of the acceleration history at the sled, based on the test No.16-1, in proportion to the peak value.

ANALYTICAL RESULT

The parametric studies were performed to obtain the allowable limit accelerations of all reduction methods. Table 4 summarizes the allowable limit accelerations.

The following useful information are derived from the computer simulation.

The protectors give a little effect on reducing the impact level on the occupant.

The brace position reduces the impact level, especially the BRACE POSITION TYPE E increases the allowable limit G from 16 G to 25 G in comparison with TYPE B.

The shoulder-harness reduces the injury level at the head. The submarining phenomenon, however, tends to occur at a low impact level, over 10 G.

The rear facing seat reduces the levels of the impact on the occupant without the submarining phenomenon. On the other hand more attention has to be paid to the impact between of the head against the headrest. The impact level can be decreased by the improvement of the headrest stiffness.

CONCLUSION

The following four feasible methods were selected and evaluated by the impact tests and the computer analyses.

* protectors
  - a pillow
  - a blanket
  - a pillow
* brace position
* a lap belt with shoulder-harness
* a rear facing seat

In order to analyze the dynamic behavior of the occupants on the seat, two-dimensional simulation program was developed.

The total of thirty impact tests were carried out by HYGE impact tester.

The results obtained from the impact tests and the analyses are as follows.

1) The protectors have little effect on reduction of impact loads.

2) In comparison with brace position currently used, the newly proposed brace position can allow the occupants to withstand 1.6 times larger floor impact level.

3) The lap belt with shoulder-harness reduces the impact loads on the head of occupant. However the submarining phenomenon which causes sever injury of abdomen can occur even at low impact level. In order to suppress this dangerous submarining, the flexibility of shoulder-harness should be carefully selected.

4) The rear facing seat reduces impact loads significantly. For practical application, however, some attention has to be paid for head to strike against the headrest of the seat.

ACKNOWLEDGEMENT

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REFERENCES

1. Daniel A. Johson, "Just in case, Passenger's Guide to Airplane Safety and Survival" Plenum Press, 1984

2. Richard G. Snyder, "Impact Protection in Air Transport Passenger Seat Design" SAE Technical Paper 821391, 1982

3. E.Widmayer, Otto B. Brende, "Commercial Jet Transport Crashworthiness" NASA CR-165849, 1982

4. Richard G. Snyder, "Advanced Techniques in Protection & Emergency Egress from Air Transport Aircraft" AGARD-AG-221, 1976

5. FAA Federal Register, "Shoulder Harnesses in Normal Utility, and Aerobatic Category Airplanes:final Rule" Amdt No.23-32, 1985

6. Stephen J. Soltis, John W. Olcott, "The Development of Dynamic Performance Standards for General Aviation Aircraft Seats" SAE Paper 850853, 1985

7. US Government, "Cabin Safety in Large Transport Aircraft" 1981

8. US Government "Airline Passenger Safety Education: A Review of Methods Used to Present Safety Information" PB85-917014, 1985

9. Civil Aviation Authority, "Occupant modelling in aircraft crash conditions" CAA Paper 90012, 1990

TABLE 1. Human Injury Criterion

HEAD	Axial	$HIC \leqq 1000$ HIC: Head Injury Criterion $HIC = [(t_2 - t_1)(\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt)^{2.5}]$ max $t_2 - t_1 < 0.05$ sec a (t) : Resultant acceleration at C.G of head
CHEST	Forward	Load on Shoulder-harness P_s $P_s \leqq 7.8$ kN
UPPER LEG	Axial Lateral (Downward)	Axial femur load $P_a \leqq 10$ kN Knee load $P_k \leqq 2.5$ kN Lateral load $P_l \leqq 4.45$ kN
SPINAL COLUMN	Axial	load on pelvis $P_p \leqq 6.7$ kN

TABLE 2. Impact Pulse Shape

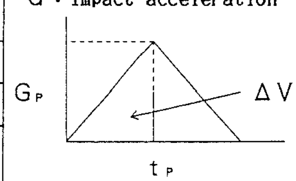
	IMPACT PULSE				PULSE SHAPE
	9G	16G	23G	30G	
PULSE SHAPE	Approximated with a triangular pulse				G : Impact acceleration 
PEAK G G_P	9	10	23	30	
t_P	$t_P \geqq 0.05$ SEC				
VELOCITY CHANGE Δ t ft/sec	22	44	51	59	

TABLE 3. Experimental Results (HIC,LAP BELT LOAD,16 G)

			HIC (0, 500, 1000, 1500)	LAP BELT LOAD [kN] (0, 5, 10, 15)	REMARKS
LAP BELT ONLY	FRONT	UPRIGHT POSITION			
		BRACE POSITION TYPE A			
		BRACE POSITION TYPE D			
		PROTECTOR (HELMET)			
	REAR	UPRIGHT POSITION			
		BRACE POSITION TYPE B			
		BRACE POSITION TYPE C			
		BRACE POSITION TYPE D			
		PROTECTOR (HELMET)			
LAP BELT WITH SHOULDER-HARNESS		FRONT			SHOULDER-HARNESS LOAD =3.36 kN
		REAR			SHOULDER-HARNESS LOAD =2.89 kN
REAR FACING SEAT		FRONT			
		REAR			

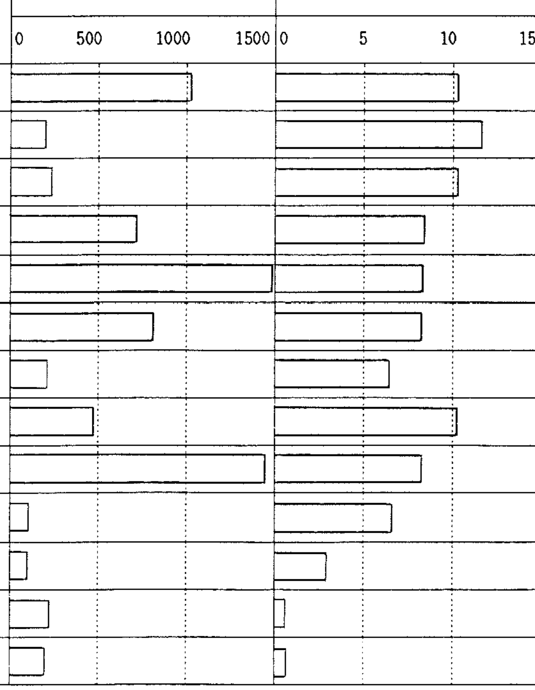


TABLE 4. Allowable Limit Acceleration

UNIT: G

				HIC	LAP BELT RUPTURE	LAP BELT SUBMARINE	CHEST CRITERION	REMARKS
LAP BELT ONLY	FRONT	UPRIGHT POSITION		16	20	1)	——	
		BRACE POSITION	TYPE A	26	19	1)	——	
		HEAD PROTECTOR	HELMET	16	20	1)	——	
			BLANKET	16	20	1)	——	
	REAR	UPRIGHT POSITION		14	27	1)	——	
		BRACE POSITION	TYPE B	16	25	1)	——	
			TYPE C	26	24	1)	——	
			TYPE D	17	24	1)	——	
			TYPE E	38	25	1)	——	
		HEAD PROTECTOR	HELMET	15	27	1)	——	
			BLANKET	14	27	1)	——	
LAP BELT WITH SHOULDER-HARNESS				43	34	10	22	
REAR FACING SEAT				30	2)	1)		

1) No submarining could be identified within the limit of this analysis.
2) The load on the lap belt was very small.

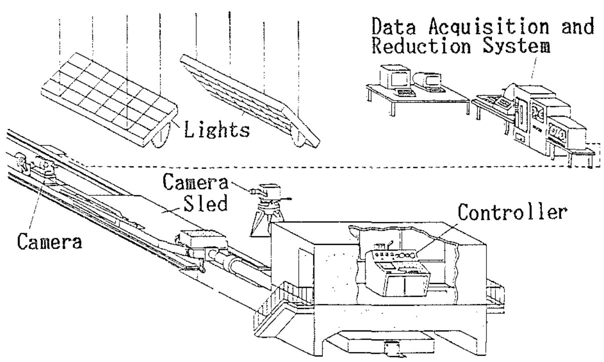


Fig. 1 Test Facility

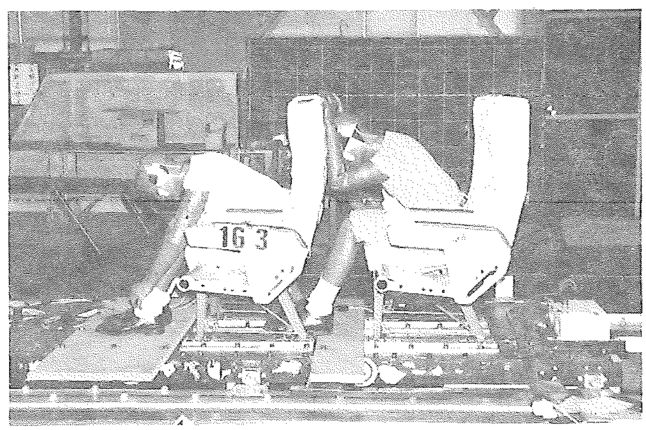


Fig. 3 Brace Position TYPE A and TYPE B

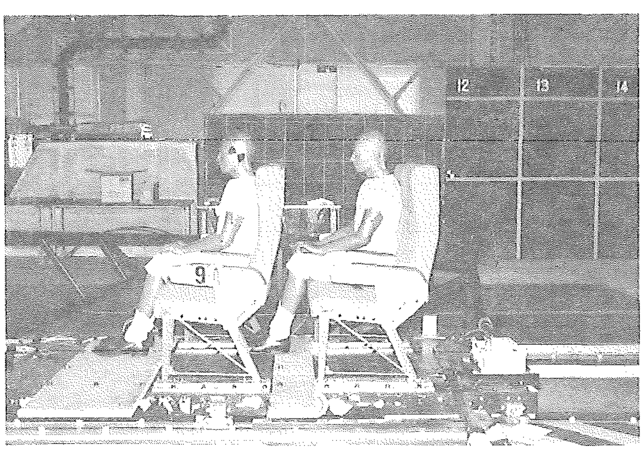


Fig. 2 Photograph of Seats and Dummies

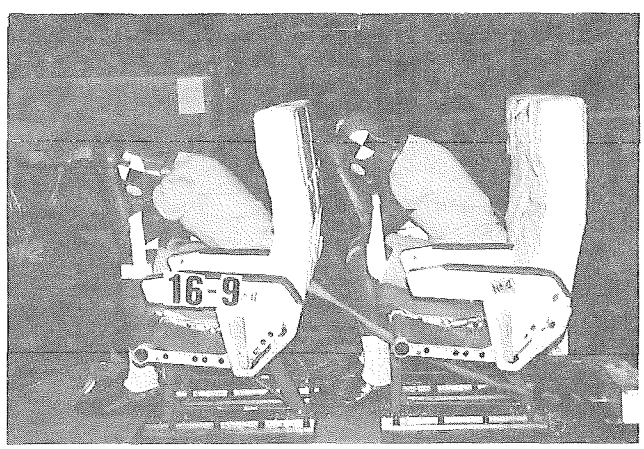


Fig. 4 Brace Position TYPE D

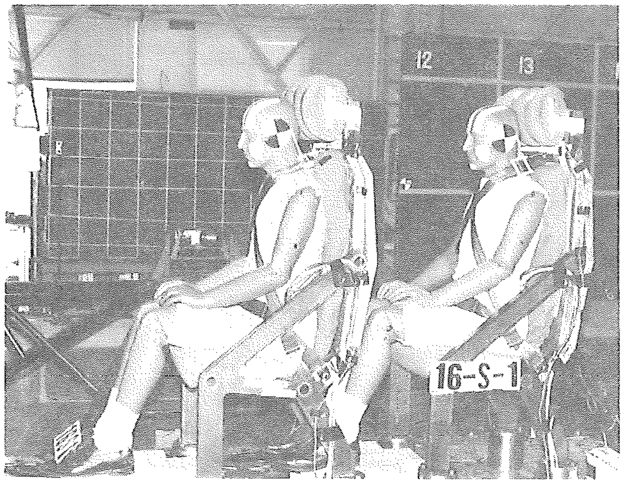


Fig. 5 Shouler-harness Seat

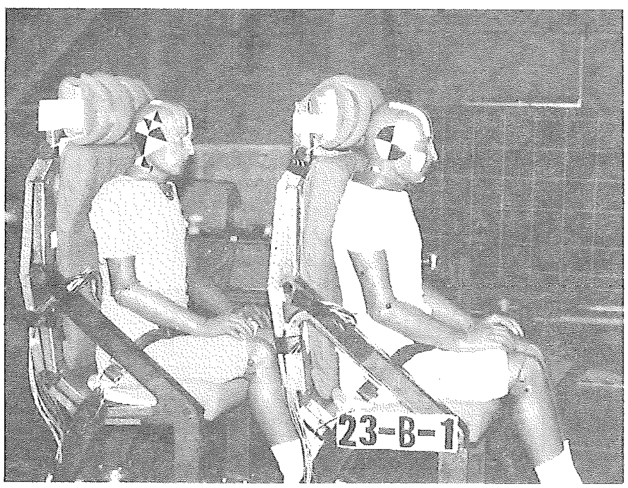


Fig. 6 Rear Facing Seat

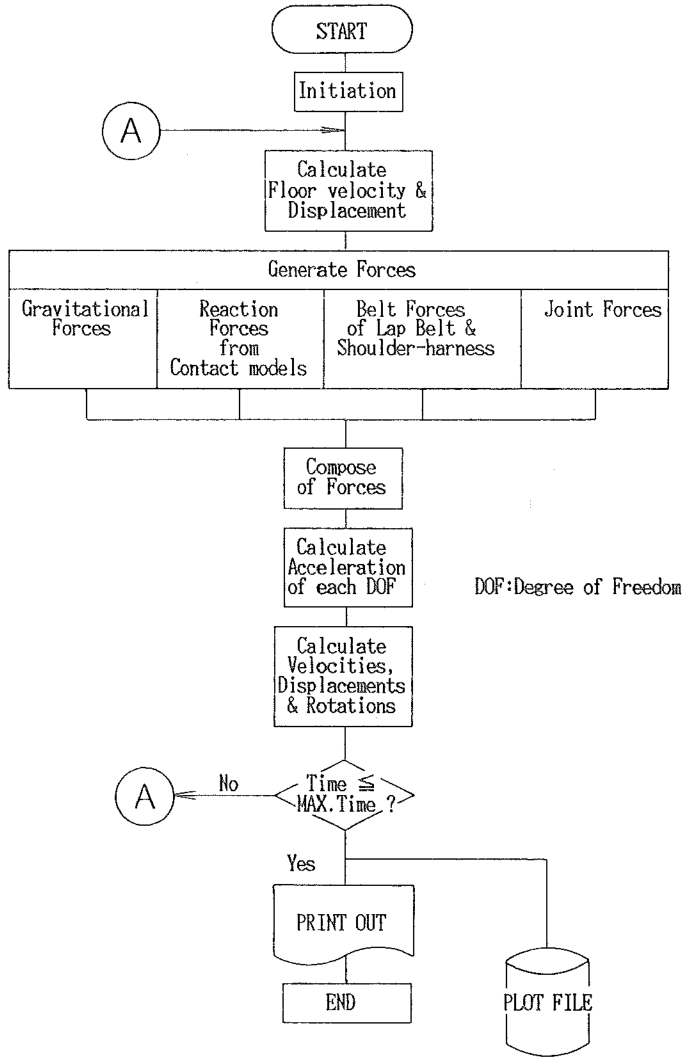
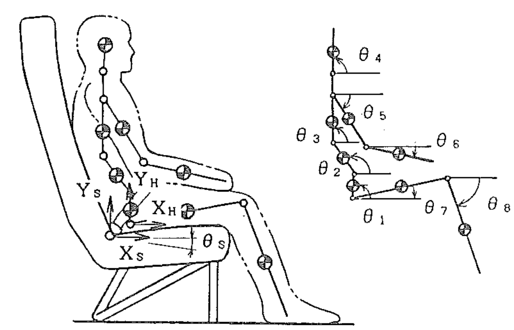


Fig. 8 Flow Chart



13 degrees of freedom

$$q = \{\underbrace{\theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6, \theta_7, \theta_8, X_H, Y_H}_{\text{OCCUPANT}}, \underbrace{X_S, Y_S, \theta_S}_{\text{SEAT}}\}$$

Fig. 7 Degree of Freedom

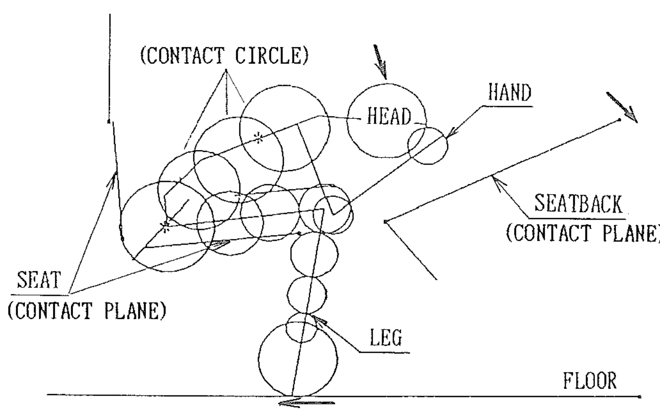
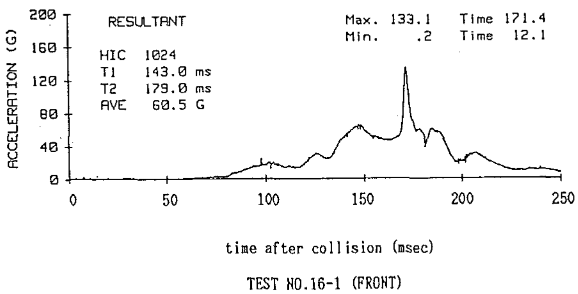
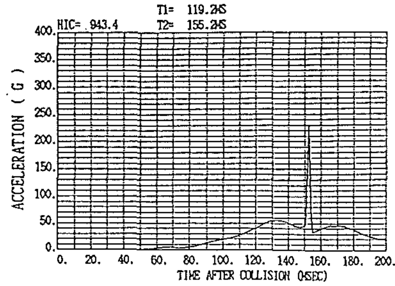
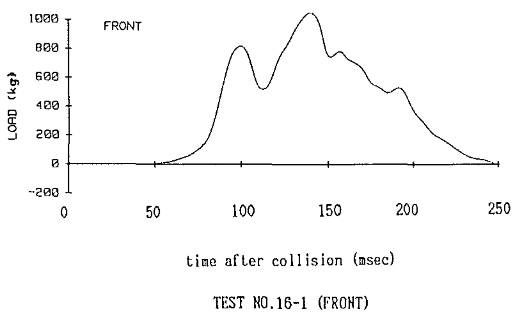


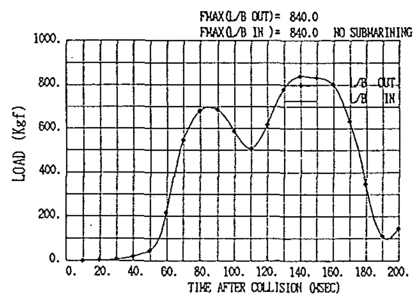
Fig. 9 Analytical Model





Resultant Acceleration of Head

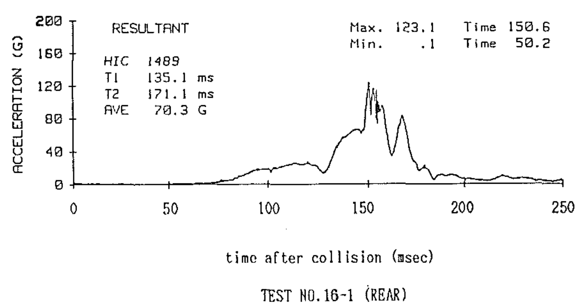


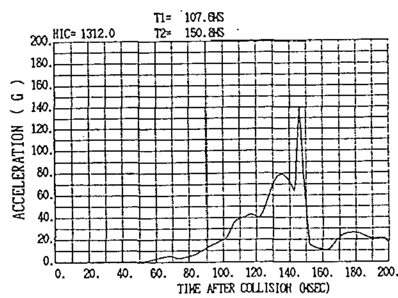


Belt Load

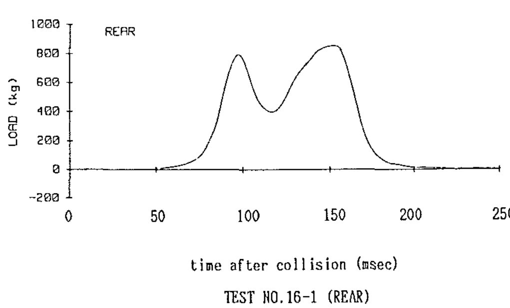
EXPERIMENTAL ANALYTICAL

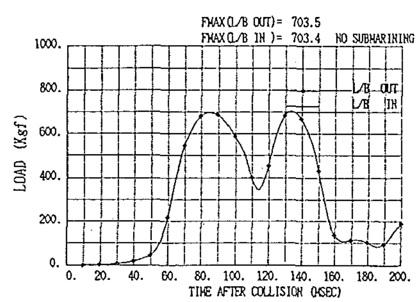
Fig. 10 Comparison of Head Acceleration and Belt Load between Experiment and Analysis (Front Seat)





Resultant Acceleration of Head

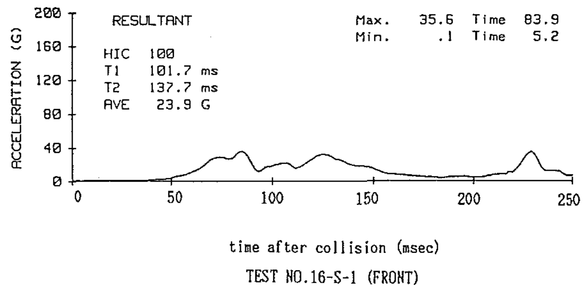


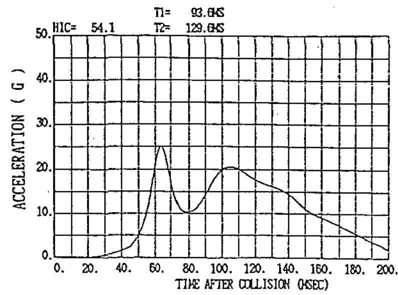


Belt Load

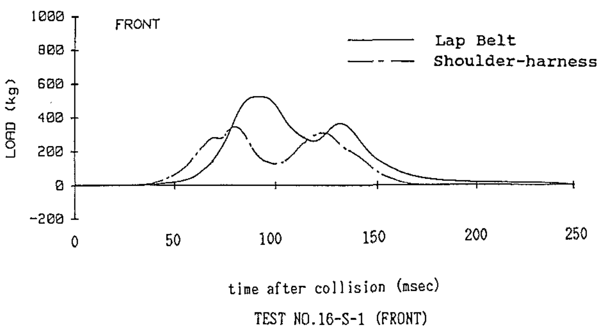
EXPERIMENTAL ANALYTICAL

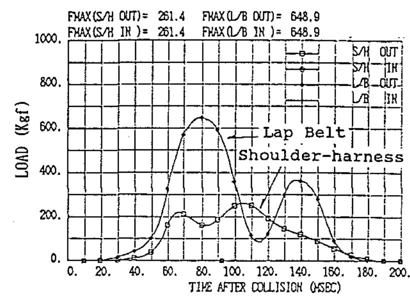
Fig. 11 Comparison of Head Acceleration and Belt Load between Experiment and Analysis (Rear Seat)





Resultant Acceleration of Head

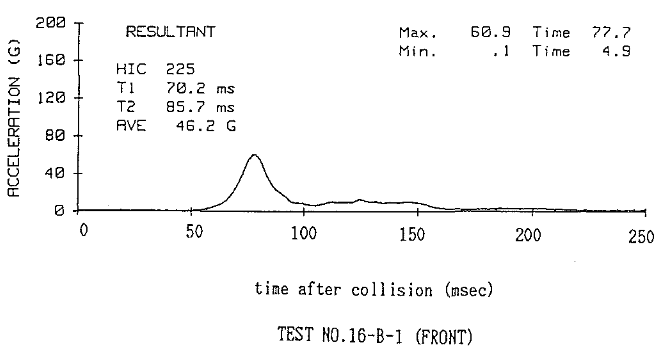


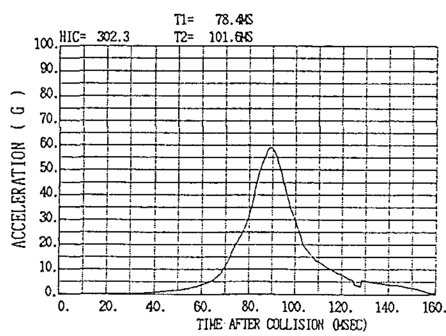


Belt Load

EXPERIMENTAL ANALYTICAL

Fig. 12 Comparison Of Head Acceleration and Belt Load between Experiment and Analysis (Shoulser-harness)





EXPERIMENTAL ANALYTICAL

Resultant Acceleration of Head

Fig. 13 Comparison of Head acceleration and Belt Load between Experiment and Analysis (Rear Facing Seat)

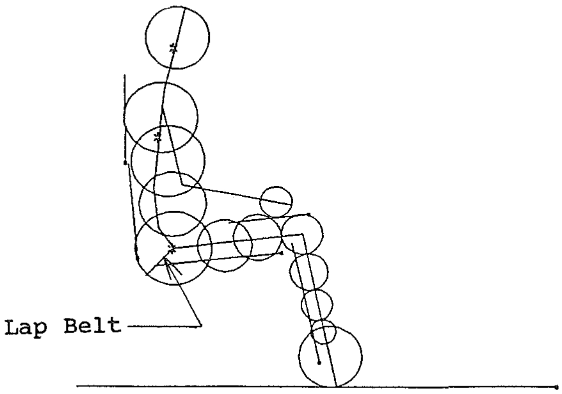


Fig. 14 Analytical Model (FRONT SEAT MODEL)

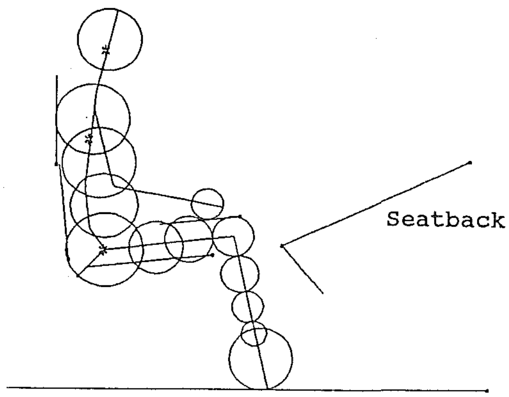


Fig. 15 Analytical Model (REAR SEAT MODEL)

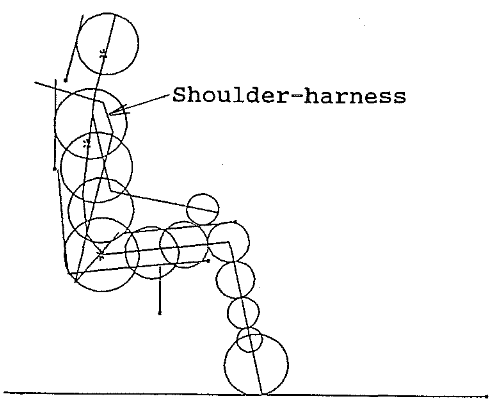


Fig. 16 Analytical Model (SHOULDER-HARNESS MODEL)

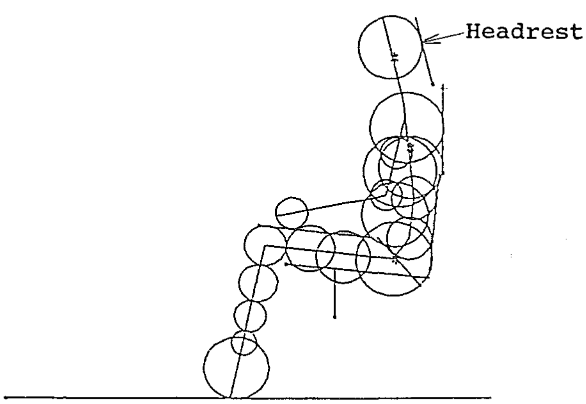


Fig. 17 Analytical Model (REAR FACING SEAT MODEL)

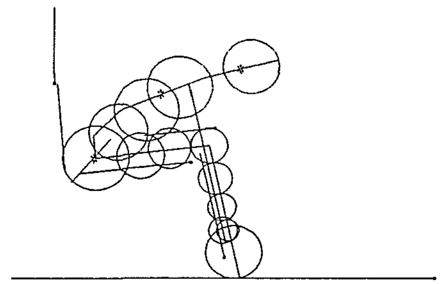


Fig. 18 Analytical Model (BRACE POSITION TYPE A)

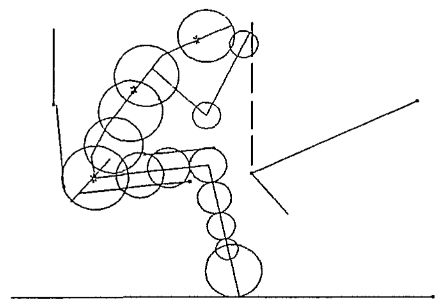


Fig. 19 Analytical Model (BRACE POSITION TYPE B)

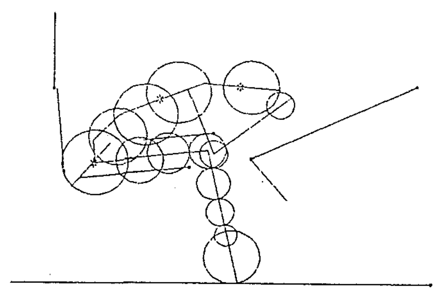


Fig. 20 Analytical Model (BRACE POSITION TYPE C)

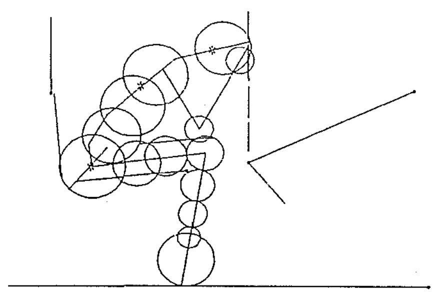


Fig. 21 Analytical Model (BRACE POSITION TYPE D)

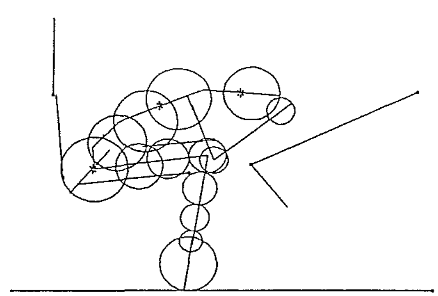


Fig. 22 Analytical Model (BRACE POSITION TYPE E)