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Computer Simulations of Contact Forces for Airbags with Different Folding Patterns During Deployment Phase

An explicit finite element method was used to study the neck load and the contact force between an occupant and an airbag during an out-of-position frontal automobile crash. Two different folding patterns and two different mounting angles of the airbag were simulated. For the four cases simulated, the occupant's neck axial force ranged from 156 to 376% of the data obtained from in-position sled tests using the Hybrid III dummy. The neck shear force ranged from 87 to 229% and the neck flexion moment ranged from 68 to 127% of in-position experimental results. In both 30° mounting angle simulations, the neck axial forces were higher than that of the two simulations with 0° mounting angles, but the trend for the neck shear force was the opposite. Although the kinematics of the model appear reasonable, the numbers generated by the model must be reviewed with great caution because the model has not been fully validated. © 1995 John Wiley & Sons, Inc.

INTRODUCTION

The idea of using an air cushion can be traced back to a patent awarded to A. H. Parrott and H. Round in 1920. Reed (1991) reported that in 1953 John Hetrick, an engineer from Newport, PA, received the first United States automotive airbag patent. The system he described included the use of a mechanical knob pull cable to open a reservoir to inflate an air cushion. Now years later, airbags are being installed as a supplemental restraint system in large numbers of passenger motor vehicles. This year, over 50% of new cars sold in the United States have airbags. Sorenson and Werner (1992) estimates that between 32–33

million cars on the road will be airbag equipped by 1995.

Huelke et al. (1992) reported the lifesaving benefits of the airbag from detailed field investigations. Zador and Ciccone (1991) in their Insurance Institute for Highway Safety (IIHS) report stated that driver deaths in frontal crashes were reduced by 28% in airbag-equipped cars for 1985 through 1991, based on comparisons with similar cars equipped with manual lap/shoulder belts only. About 10% of drivers of vehicles with airbags involved in an accident received moderate to severe injuries. Most, if not all, of these people would have been more seriously injured or killed without the airbag. In June 1992, NHTSA

Received December 6, 1993; Accepted August 12, 1994.

Shock and Vibration, Vol. 2, No. 3, pp. 237–245 (1995)
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CCC 1070-9622/95/030237-09

published a report indicating a 68–77% effectiveness rate with combined seat belt and airbag usage.

In relatively few cases, there are injuries specifically attributed to the airbag. Conover (1992) and Huelke et al. (1992) observed that skin abrasions, bruises, and burns are the most common problems. Eye injuries such as chemical keratitis or even severe ocular trauma after the airbag deployed has been reported in several papers (Braude, 1992; Ingraham et al., 1991; Mishler, 1991; Rimmer and Shuler, 1991; Rosenblatt et al., 1991; Scott et al., 1993; Smally et al., 1992). Lancaster et al. (1993) reported a case in which a nonbelted female driver sustained ruptures to the right atrium in a low speed collision. Aortic valve injury has also been described by Reiland-Smith et al. (1993).

An interesting statistics is found when comparing the male and female drivers for injury severity in cars with airbags. For male drivers, a total of 4% or less are involved in accidents that the driver sustained an Abbreviated Injury Scale (AIS) rating of three or more. However, Sorenson and Werner (1992) found that for elderly females, 17% were involved in crashes with AIS rating greater than three, and 5% of young females receive the same. Female drivers tend to maintain a shorter distance between the steering wheel and the torso. In an airbag-equipped car, if the occupant comes into contact with the deploying airbag, the occupant is generally referred to as out-of-position. In a severe frontal crash, these out-of-position occupants could come into contact with the high-speed deploying airbag. It has been estimated that the speed of a deploying airbag reaches an average of 140 mph. More research is needed, especially in cars equipped with airbags designed for elderly females.

In a recent case report by Traynelis and Gold (1993), a 40-year-old male driver sustained a severe cervical spine (C2) fracture while restrained with a three-point belt and an airbag. In 1982, Cheng et al. (1982) at Wayne State University conducted a series of sled tests using cadavers restrained by predeployed airbags and knee bolsters. The airbag was lined up with the cadaver's chest with a mounting angle parallel to the vertical line. Three of the eight cadavers tested sustained nonsurvival AIS 6 neck injuries such as C1–C2 separation or ring fracture. Yang et al. (1984) subsequently estimated the neck load revealed that the neck resultant forces were over 10 kN for those three tests with fatal injuries. No

conclusions were drawn regarding the efficacy of the system because the airbag used in that study has no ventilation holes.

There are relatively few studies specifically designed to study the out-of-position occupant responses. Horsch et al. (1990) studied the airbag deployment forces and injury patterns in vivo using animal subjects. Reed et al. (1992) reported minor injuries due to the sweeping and wing abrasion during the deployment phase. Yang et al. (1990) attempted to address the unfolding problem with a simple two-dimensional model. The model was too simple to apply in the real-world crashworthiness analysis. The purpose of this study was to investigate the out-of-position contact forces for airbags with different folding patterns during the deployment phase.

METHODS

Finite element meshes were created to represent airbags with two different folding patterns using a pre- and postprocessor program FEMB (Finite Element Model Builder, ETA Inc. Madison Heights, MI). The two folding patterns simulated were identified as an accordion fold (Fig. 1) and

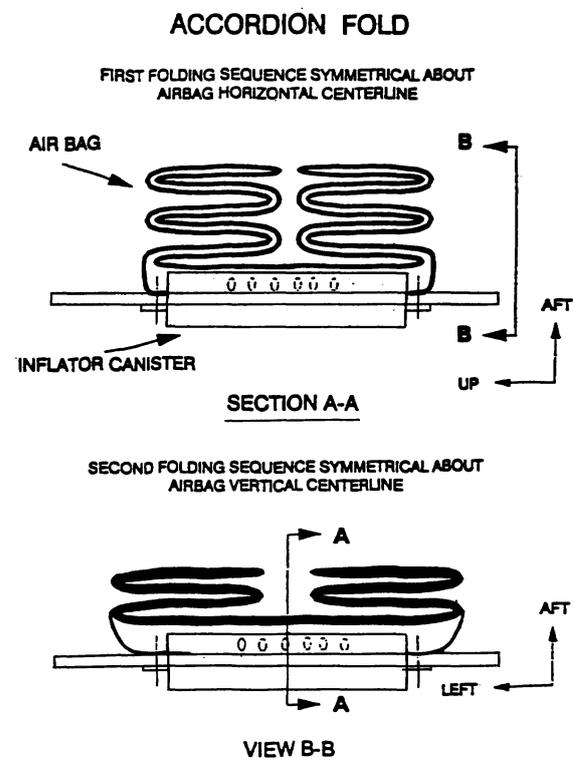


FIGURE 1 Sectional view of an accordion folded airbag.

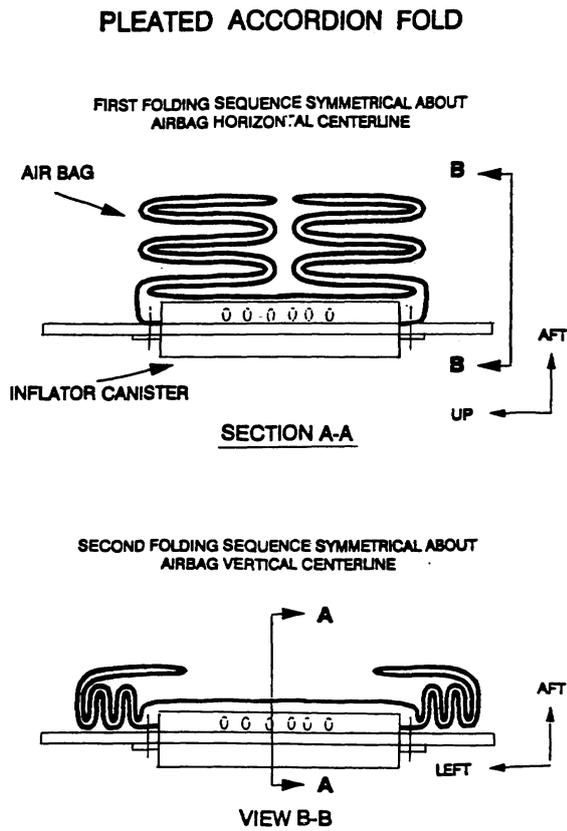


FIGURE 2 Sectional view of an pleated accordion folded airbag.

pleated accordion fold (Fig. 2). The airbag folding method was described by Li (1993).

Two airbag mounting angles, 0 and 30° with the vertical, were used to simulate the driving with either a standard steering wheel (30°) or a tilted one. A total of four cases were simulated. Case I represented accordion fold at 0°. Case II represented pleated accordion fold at 0°. Case III represented accordion fold at 30° and case IV represented pleated accordion fold at 30°.

The accordion fold model represented five folds in the A-P direction and three folds in the lateral direction. For the pleated accordion fold, the airbag was symmetrically folded three times about the horizontal center line first followed by a symmetrical folding about the vertical line. A total of 1200 membrane elements were used to represent the airbag.

Two 15-mm diameter ventilation holes with a ventilation discharge coefficient of 0.62 were used. The Young's modulus in the reinforced direction was assumed to be 0.15 GPa and the fabric weight density was assumed to be 0.21×10^{-5} kg/mm². The fully inflated airbag had a diameter

of 640 mm and a maximum volume of 41 L. The fabric thickness was assumed to be 0.6 mm. Figure 3 shows the inflator mass flow rates time history. Tethers were not used in any simulations. A rigid knee bolster was used to provide contact protection for the lower extremities. The initial distance between the occupant and the center of the steering wheel was assumed to be 226 mm.

A finite element model of the occupant was modified from a CAL3D 17-segment dataset. A special joint element available in the Pam-Crash element library was used to replace the joint between CAL3D segments. The head and neck complex was replaced with a deformable head and neck model developed by Yang and Le (1992) in order to eliminate the artifact due to the unrealistic simplification of the CAL3D model.

The anterior edge of the midsagittal plane of the occupant's upper torso was lined up with the anterior-center of the airbag at a distance of 350 mm for the 30° standard steering wheel simulation. For a tilted steering wheel, the anterior-center of the airbag was lined up with the junction of the occupant's upper and middle torso at the same distance. The approaching velocity for the occupant was assumed to be 6.25 m/s. The commercially available program PAM-CRASH (Engineering Systems International, Paris, France) was used for dynamic simulations.

RESULTS

Although the kinematics of the model appear reasonable, the numbers generated by the model must be reviewed with great caution because the model has not been validated. The kinematics of the four simulated cases are shown in Figures 4–7. Both hands of the occupant were removed from the display to show the interaction between the airbag and the occupant. For the accordion folded airbag with 0° steering angle (case I), the deploying airbag strikes both the upper and middle torso simultaneously (Fig. 4). In case II, the airbag contacts the lower torso first because the airbag was folded along the longitudinal direction. In both cases, the head was not restrained until 22 ms after the airbag began to deploy. In the two cases with a 30° steering wheel angle (cases III and IV), the airbag initially contacted the upper torso and gradually moved to restrain both the upper torso and the head-neck complex (Figs. 6–7). The head contact began at 14 ms after the airbag initiated deployment. Due to the

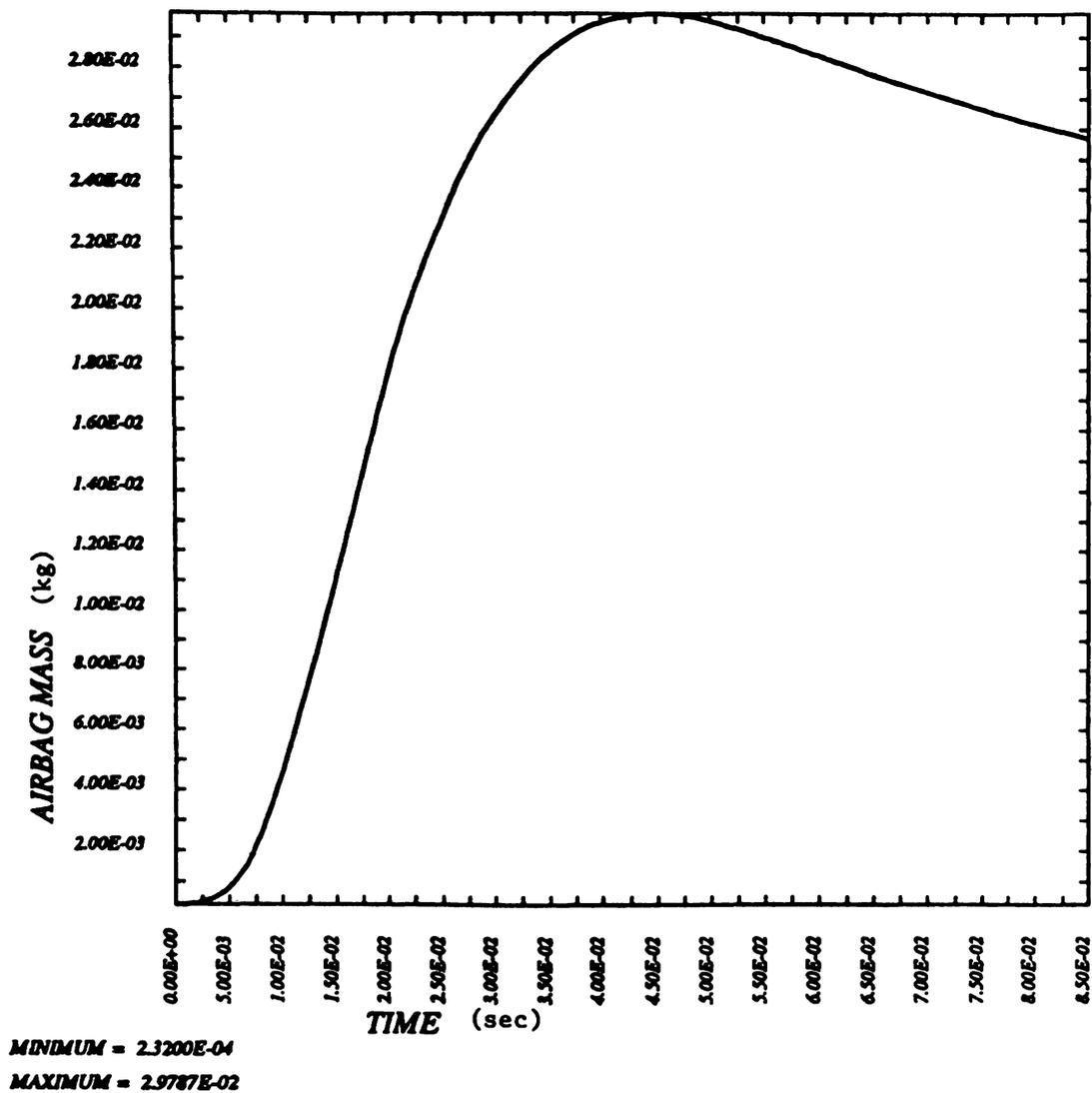


FIGURE 3 The airbag mass flow rate time history used in the simulation.

limited head room, the airbag deployment was also restricted by the windshield.

Table 1 shows contact forces between the airbag and the upper torso in the sagittal plane. In the vertical direction (superior–inferior), the sign for head and chest contact force was reversed because they were pushed by the airbag in two opposite directions. In both cases with a 0° steering wheel angle, the head and chest A–P forces were higher than the two cases with a 30° steering wheel angle.

The neck loads calculated at the head-pivot and the HIC (Head Injury Criteria) are listed in Table 2. In the axial force, the accordion fold at 30° (case III) was 290% higher than the average in-position experimental data. In the neck shear

force, the accordion fold with a 0° angle (case I) was 130% higher than that obtained experimentally for the in-position in-house sled test. The neck resultant force was lowest for the pleated accordion fold at 0°, followed by the accordion

Table 1. Head and Upper Torso Contact Forces in A–P (Shear) and S–I (Axial) Directions

	Head A–P	Head S–I	Chest A–P	Chest S–I
Case I	3.5 kN	–1.5	10.3	1.0
Case II	3.0	–1.1	9.0	2.4
Case III	2.7	–1.6	6.1	4.7
Case IV	2.6	–1.7	6.6	3.4

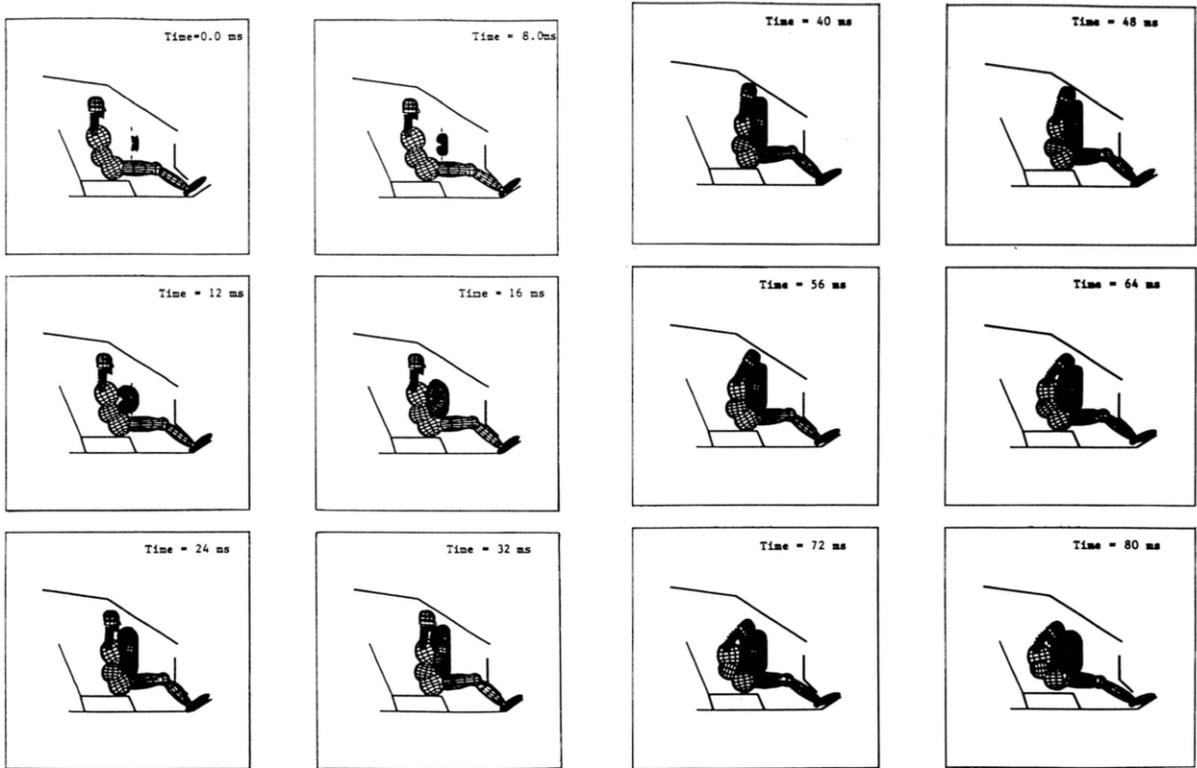


FIGURE 4 The occupant kinematics in a car with an accordion fold airbag at 0° (case I).

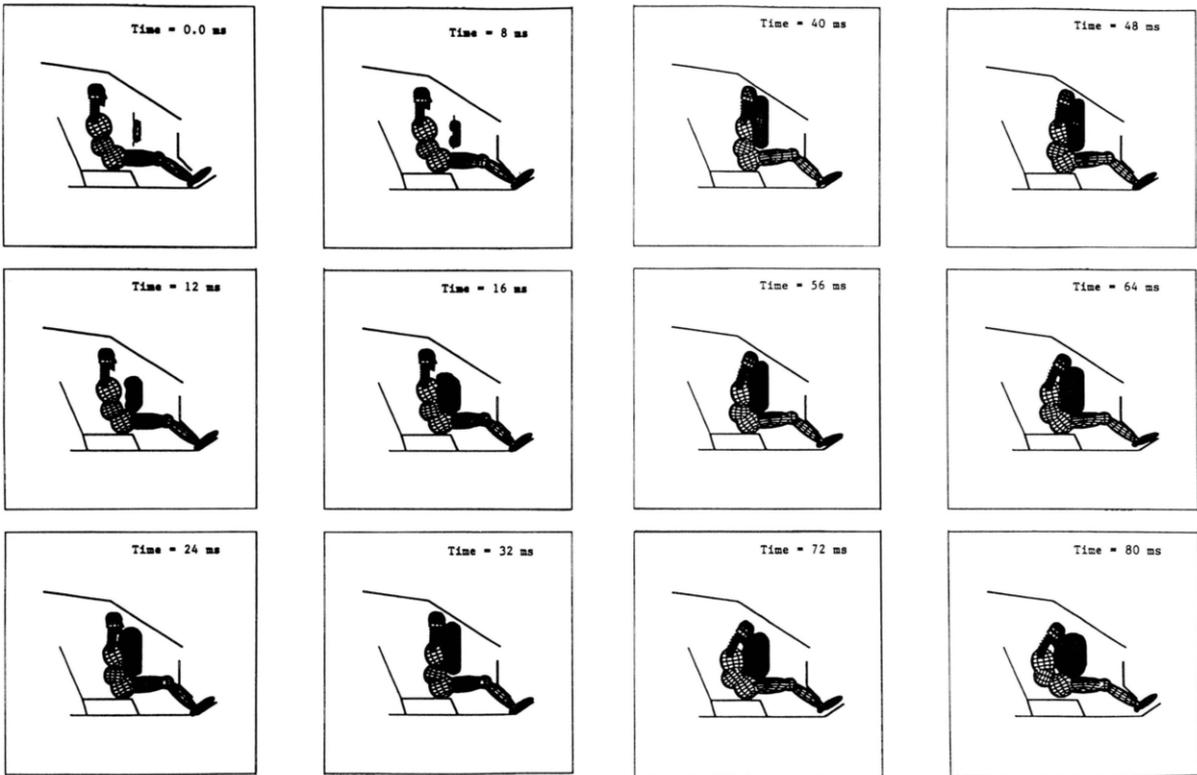


FIGURE 5 The occupant kinematics in a car with a pleated accordion fold airbag at 0° (case II).

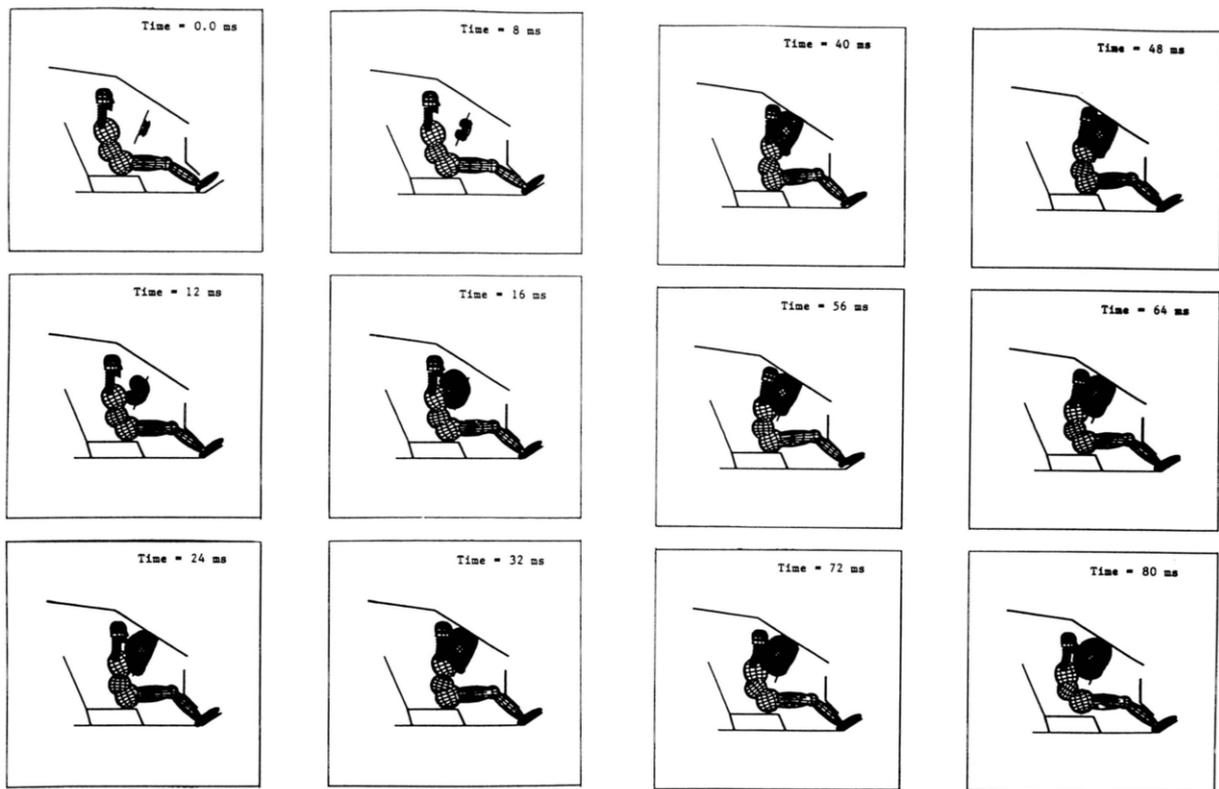


FIGURE 6 The occupant kinematics in a car with an accordion fold airbag at 30° (case III).

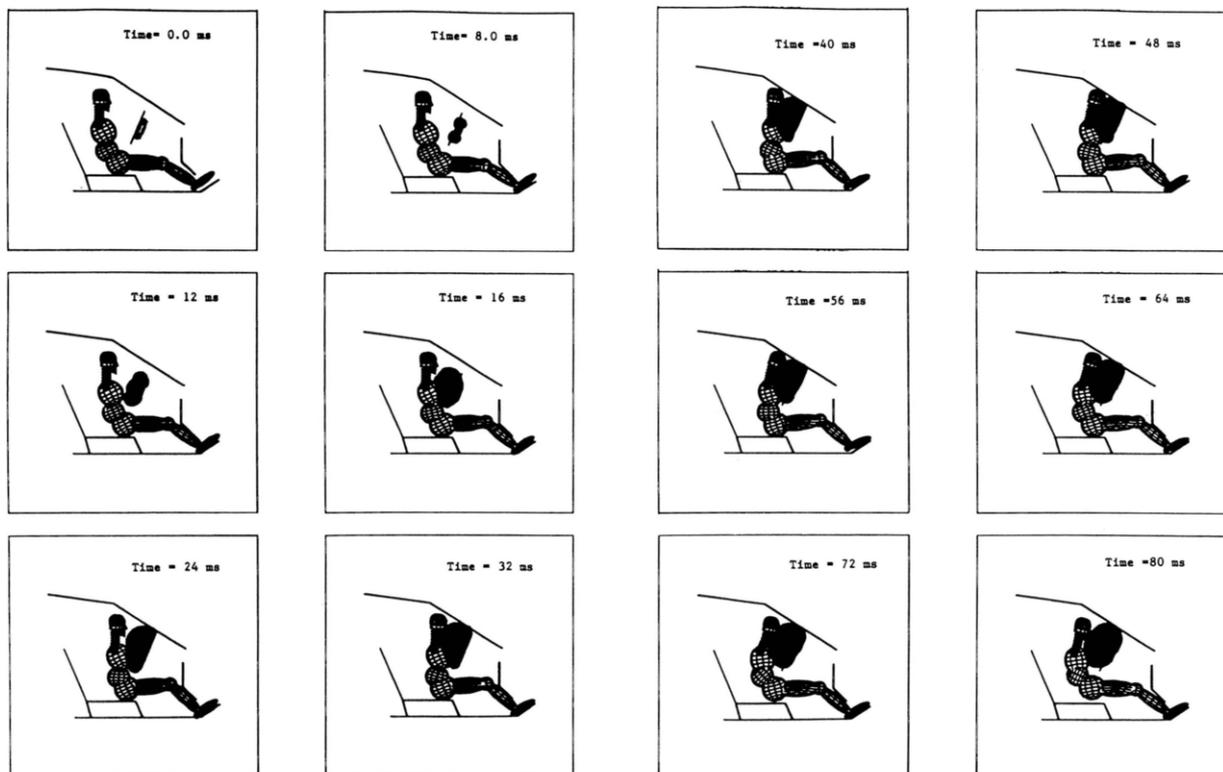


FIGURE 7 The occupant kinematics in a car with a pleated accordion fold airbag at 30° (case IV).

Table 2. Calculated Maximum Neck Forces and HIC

	Axial (kN)	Shear (kN)	Moment (Nm)	HIC
Case I	2.0	2.3	92.0	541
Case II	1.6	2.0	151.0	350
Case III	3.9	1.1	82.9	915
Case IV	3.4	0.9	81.4	663
In-position experiment	1.0	1.0	116.8	

fold at 0°, the pleated accordion fold at 30°, and the accordion fold at 30°.

DISCUSSION AND CONCLUSIONS

This study shows that it is feasible to use the finite element method to study the occupant-airbag interaction for an out-of-position driver. Both the folding pattern and the steering wheel mounting angle had a significant effect on the occupant kinematics, head and torso contact forces, and neck loads. Figures 8–11 show the

midsagittal sectional view of the four cases simulated. The slice view generated by the computer program was not possible to obtain with standard photographic techniques.

During the course of this study, we observed that it is very important to make sure no penetrations occurred between each individual layer of the airbag and between the airbag and the occupant. Thus, it is very computationally expensive not only because of the large number of elements involved but also because several contact algorithms had to be used simultaneously to prevent penetrations. The number of elements for the unfolding of an airbag depends upon the complexity of the folding pattern. Each fold requires a line of nodes to represent the folding line. The contact algorithms used include the master-slave contact algorithm, master surface-slave nodes algorithm, and single surface contact algorithm.

In real life, the out-of-position contact could be far more sophisticated than the four cases simulated. For example, the steering wheel could have been turned at any angle when the crash occurred. The occupant could have positioned himself unsymmetrically about the airbag due to an impact prior to the severe one that triggered

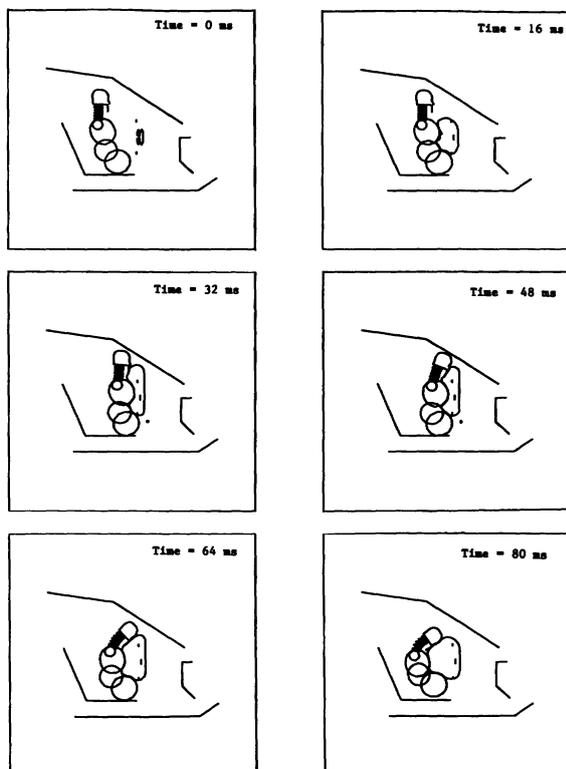


FIGURE 8 The midsagittal view of an occupant in a car with an accordion fold airbag at 0° (case I).

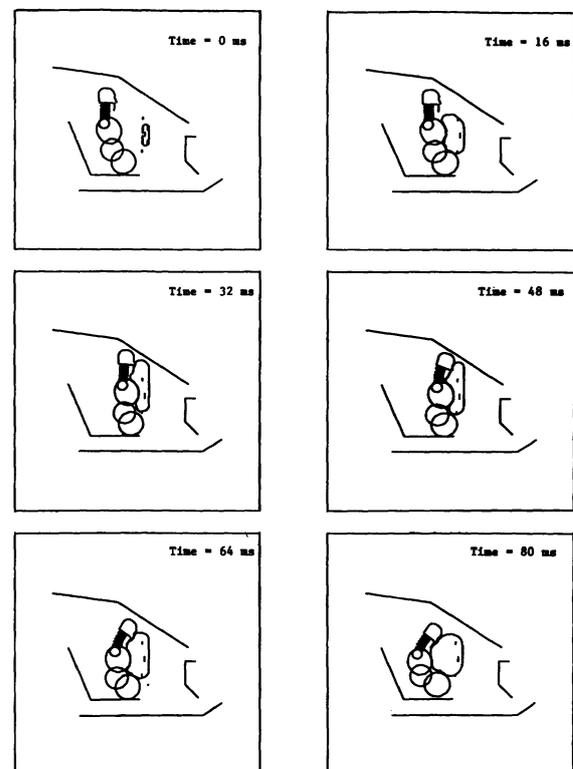


FIGURE 9 The midsagittal view of an occupant in a car with a pleated accordion fold airbag at 0° (case II).

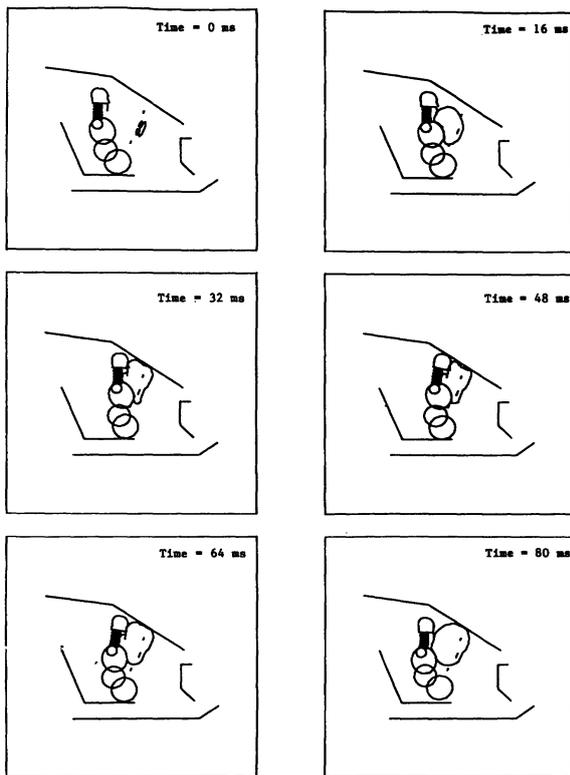


FIGURE 10 The midsagittal view of an occupant in a car with an accordion fold airbag at 30° (case III).

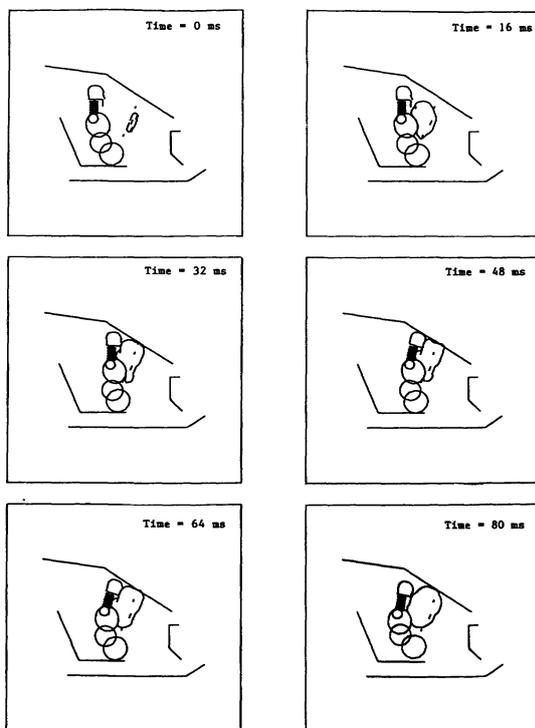


FIGURE 11 The midsagittal view of an occupant in a car with a pleated accordion fold airbag at 30° (case IV).

the airbag. Drivers who have their arms crossed over the steering wheel could sustain upper extremity injury and possible head injuries when the airbag is deployed. An individual leaning against the door is yet another example of out-of-position. The occupant's head could become wedged between the side window and the airbag.

The Hybrid III neck is composed of aluminum vertebrae and rubber discs to simulate human neck characteristics. In our simulations we noticed that the airbag quickly wrapped around the staggered Hybrid III neck. Theoretically, this phenomenon will not happen to a person with a smooth neck contour.

The peak head contact force calculated did not correlate well with the HIC calculation. However, the HIC number and the neck axial force happen to rank the four cases simulated in the same order (Table 2). More research is needed to investigate the relationship between the HIC and neck loads in the future.

Although the kinematics of the model look correct, validation is necessary prior to further application of the model. There were practical difficulties in validating the model. First, the manufacturer will not reveal the airbag folding pattern. We used folding patterns provided to us by NHTSA (1992). Second, the inflator characteristics is unknown. The mass flow rate used was obtained from a tank test. However, the same model was exercised with an initial distance of 442 mm to simulate an in-position frontal crash. Differences between the peak neck loads, chest accelerations, and head accelerations were within 15% of a sled test with the same test setup. In the future, different folding patterns and a tethered airbag should be studied. In addition, the jet effect during the airbag deployment, especially for the extreme case of an occupant who is leaning against the airbag, should be considered.

The following conclusions were drawn from this study:

1. Simulations of the unfolding of two airbag folding patterns with two mounting angles were completed.
2. For the four cases studied, the occupant head and chest contact forces were the highest for the accordion fold at 0° (case I), followed by the pleated accordion fold at 0° (case II), the accordion fold at 30° (case III), and the pleated accordion fold with a 30° airbag mounting angle.

3. The calculated neck load was the highest in the accordion fold at 30° (case III), followed by the pleated accordion fold at 30° (case IV), the pleated accordion fold at 0° (case II), and accordion fold with a 0° air-bag mounting angle (case I).

The authors wish to acknowledge Mr. J. Kossar of NHTSA for supplying the folding pattern, Ms. Mari Milosic for her help in preparing this manuscript, ESI for providing PAM-CRASH, and ETA for providing FEMB.

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