Small Female Head and Neck Interaction With a Deploying Side Air Bag

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ABSTRACT

This paper presents dummy and cadaver experiments designed to investigate the injury potential of an out-of-position small female head and neck from a deploying side air bag. Three seat mounted, thoracic type, side air bags were used that varied in inflator aggressivity. The ATB/CVS multi body program was used to identify the worst case loading position for the small female head and neck. Once the initial position was identified, a total of three Hybrid III 5th percentile dummy and three small female cadaver tests (51 $\pm$ 9 years, 64 $\pm$ 8 kg, 159 $\pm$ 10 cm) were performed. Instrumentation for the dummy included upper and lower neck load cells, while both the dummy and the cadavers had accelerometers and angular rate sensors fixed to the head and T1 vertebrae in order to provide head and neck kinematic data. Head center of gravity accelerations for the dummy ranged from 71 g's to 154 g's, and were greater than cadaver values, which ranged from 68 g's to 103 g's. Peak neck tension as measured at the upper load cell of the dummy increased with inflator aggressivity from 992 N to 1670 N. A conservative modification of the United States National Highway Traffic Safety Administration's N_{ij} proposed neck injury criteria, which combines neck tension and bending, was used. All values were well below the 1.0 injury threshold for the dummy and suggested a very low possibility of neck injury. The results of the cadaver tests agreed with this prediction in that no injuries were observed. The dummy neck tension and dummy and cadaver head accelerations correlated very well with air bag inflator characteristics. These tests suggest that the side air bag may be designed to minimize the risk of head and neck injury to the out of position small female.

Recently, automobile manufacturers have begun implementing side air bags as a safety feature to mitigate injuries resulting from side impact collisions. Unlike the case for the driver and passenger side air bag, the injury potential to an out-of-position occupant in side airbag loading has not been presented in the literature. The purpose of this research is to evaluate the response of a Hybrid III 5th percentile female dummy and small female cadaver subject to loading by a deploying side air bag.

BACKGROUND

The United States National Highway Traffic Safety Administration (NHTSA) established injury tolerance values based on a review of all accident and laboratory data (Table 1). Independent load and moment values were recommended for single component analysis, while separate critical values are given for combined loading analysis. To account for combined loading of the cervical spine in frontal impacts, NHTSA proposed the N_{ij} criteria [NHTSA, 1998]. It explains four types of combined loading that are noted by the 'ij' parameters of N_{ij}: tension and flexion, tension and extension, compression and flexion, and compression and extension.

Table 1: NHTSA neck injury criteria values for the 5th percentile adult female.

Parameter	Independent	N_{ij} Critical Values
Compression (Z-axis)	2520 N	3200 N
Tension (Z-axis)	2080 N	3200 N
Shear (X-direction)	1950 N	--
Flexion Moment (Y-axis forward)	95 Nm	210 Nm
Extension Moment (Y-axis back)	28 Nm	60 Nm

Equations 1 and 2 explain how N_{ij} would be calculated for a neck loaded in tension and flexion. Based on a combined stress analysis, the forces and moments from the upper neck load cell are transformed to the occipital condyles, divided by the relevant critical injury value, and added as a function of time. The addition of the normalized injury criteria assumes that each loading component can contribute equally to the injury relative to its critical value. An N_{ij} value above 1 indicates a 15% risk of an AIS ≥ 3 injury and N_{ij} value above 1.4 indicates a 30% risk of an AIS ≥ 3 injury to the cervical spine.

$$N_{ij} = \frac{\text{Tension}}{\text{Critical Tension}} + \frac{\text{Flexion Moment}}{\text{Critical Flexion Moment}} \tag{1}$$

$$N_{ij} = \frac{F_Z}{3200\text{N}} + \frac{M_Y}{210\text{Nm}} \tag{2}$$

Since N_{ij} was developed for the study of frontal collisions, it does not include any bending other than that directly in the sagittal plane. To allow for the inclusion of lateral bending, a more conservative formulation was constructed, entitled the modified N_{ij}, as shown in equations 3 and 4 [Duma, 1998]. It is suggested that this version may be used for frontal and side impact situations in which the neck sustains a combined load of tension with flexion and lateral bending.

$$\text{Modified } N_{ij} = \frac{\text{Tension}}{\text{Critical Tension}} + \frac{\text{Total Bending Moment}}{\text{Critical Bending}} \tag{3}$$

$$\text{Modified } N_{ij} = \frac{F_Z}{3200\,\text{N}} + \frac{\sqrt{M_Y^2 + M_X^2}}{210\,\text{Nm}} \quad (4)$$

Given the lack of available neck data, the modified N_{ij} assumes that the lateral bending criteria is the same as the flexion bending criteria. This assumption is based on the anatomical structure of the cervical vertebrae and flexibility of the neck in lateral bending. The spinous process and vertebral arch play a role in lowering the bending criteria for extension, but are assumed not to be load bearing in flexion and lateral bending conditions. The vertebral body and supporting ligaments and musculature are taken as similar load bearing components in flexion and lateral bending. Additionally, experimental tests with cadavers showed only minor injury in two of seven tests in which the neck was forced into lateral bending as a result of side impact to the body [Kallieris, 1990]. The low incidence of injury was attributed to the flexibility of the neck in lateral bending. While the inclusion of lateral bending in the modified N_{ij} does require several assumptions, it is suggested as the best conservative option for evaluating neck loading outside of the sagittal plane.

METHODOLOGY

Six (n = 6) static side air bag deployments were conducted in a mid-sized test buck: three with an instrumented Hybrid III 5th percentile female dummy, and three with small female cadavers (Table 2). The cadavers were obtained through the Virginia State Anatomical Board with permission given by the family to conduct biomechanics research. All test procedures were approved by the institutional review board at the University of Virginia. Screening for Hepatitis A, B, C, and HIV was conducted with each cadaver prior to acceptance into the research program.

Table 2. Test configuration and occupant anthropometry.

Test	Air Bag	Occupant	Occupant		
			Mass (kg)	Height (mm)	Age (years)
1	A	5th Percentile Dummy	48	1525	--
2	B	5th Percentile Dummy	48	1525	–
3	C	5th Percentile Dummy	48	1525	–
4	A	Female Cadaver	49	1590	50
5	B	Female Cadaver	59	1610	66
6	B	Female Cadaver	53	1665	74

Four types of seat mounted, thoracic side air bags were used that varied only in their level of inflator output (Table 3). The inflators utilize hybrid technology, while the bags have two vents on the outboard side.

Table 3. Side air bag classification as measured in a 1 ft^3 (0.0283 m^3) tank test.

Inflator Type	Increase in Peak Pressure Relative to Type A	Increase in Pressure Onset Rate Relative to Type A
A	0%	0%
B	23%	63%
C	54%	160%

OCCUPANT POSITIONING - A computer model of the deploying side air bag was created using the Articulated Total Body multi-body dynamics software package [Sieveka, 1998]. This model was used to identify occupant positions that produced the most severe loading to the head and neck. A 'worst cases' position was identified given that the simulated head accelerations and neck loads for this position under side air bag deployment were higher than any of the other positions investigated (Figure 1). This position has the dummy leaning outboard against the door facing forward with the head in contact with the seat and door. The head center of gravity is aligned with the center line of the air bag deployment path. This position maximizes tension and extension of the neck, and was designed to represent a occupant sleeping with his head on the armrest. All tests were performed on the left side.

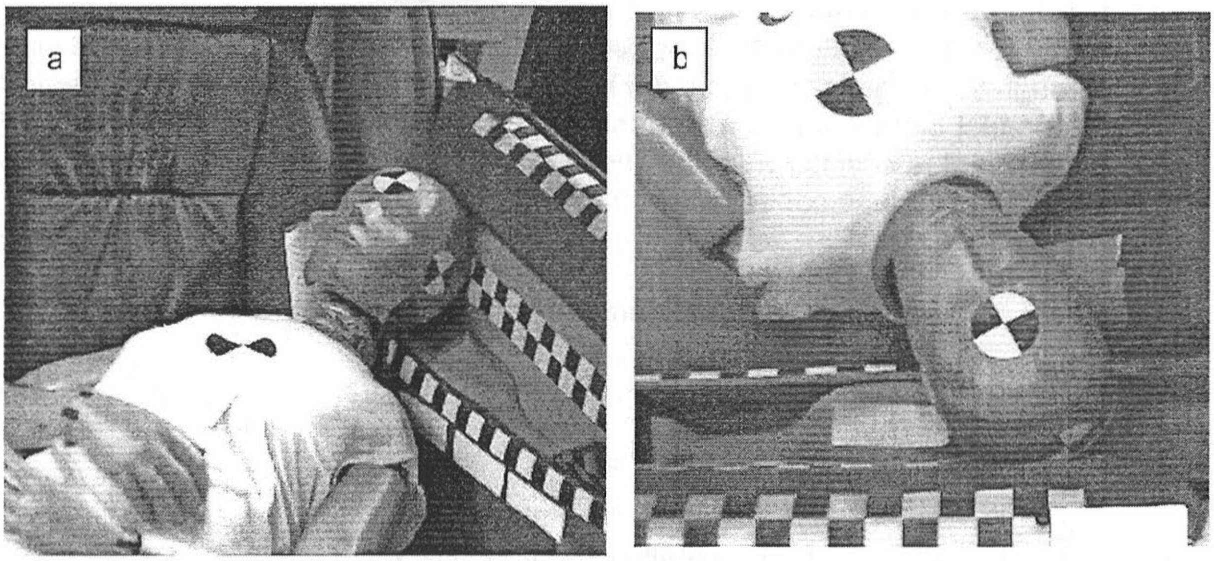

Figure 1. Occupant position for posterior head loading, oblique view (a) and superior view (b).

INSTRUMENTATION - The instrumentation on the Hybrid III 5th percentile dummy included both upper and lower neck six-axis load cells (Denton Inc., Model 1716). Angular rate sensors (ATA Sensors Inc., Model ARS-04E), which measured the angular displacement, velocity, and acceleration of the head relative to the thorax, were installed in the head and upper spine of the dummy and cadavers. Accelerometers (Endevco Inc., 7264A) in the head, spine and sternum were also used in the dummy and cadavers. All test were recorded with three views of high speed video (Kodak RO, 1000 fps) and one view of high speed film (Hycam, 3000 fps).

RESULTS AND DISCUSSION

The resultant head center of gravity (CG) acceleration ranged from 71 g's to 154 g's for the dummy (Table 4). A strong correlation was observed between the dummy peak head CG acceleration and the inflator pressure onset rate as well as peak pressure using a linear regression analysis (R^2 = 0.99) for both comparisons. The peak acceleration occurred between 8 ms and 10 ms during the 'punch out' phase of deployment. The acceleration decreased quickly after the peak for all three types of inflators (Figure 2).

Table 4. Peak resultant head CG acceleration, upper load cell tension (F_z) at the occipital condyles, flexion moment (M_y), lateral bending moment (M_x).

Test	Occupant	Air Bag	Acc. (g's)	Time (ms)	F_z (N)	Time (ms)	M_y (Nm)	Time (ms)	M_x (Nm)	Time (ms)
1	Dummy	A	71	10	992	8	21	37	26	30
2	Dummy	B	112	8	1292	20	16	28	55	40
3	Dummy	C	154	8	1670	20	33	30	45	40
4	Cadaver	A	68	12	--	--	--	--	--	--
5	Cadaver	B	80	10	--	--	--	--	--	--
6	Cadaver	B	103	10	--	--	--	--	--	--

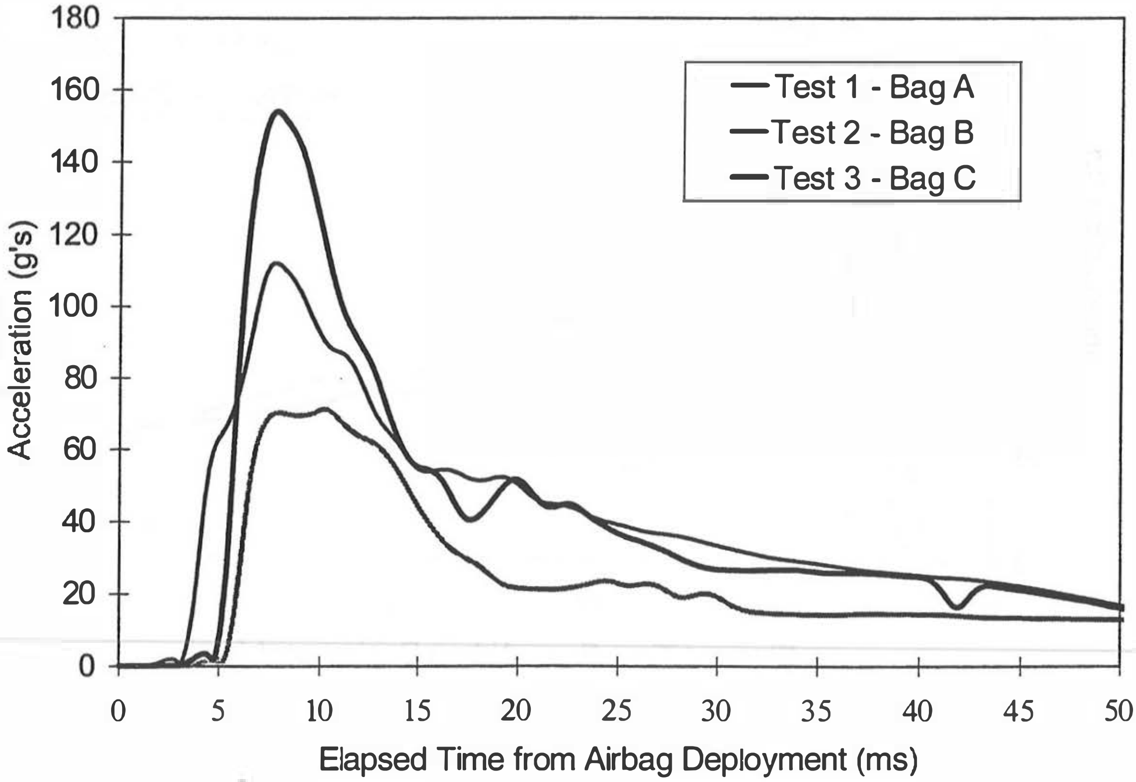

Figure 2. Head center of gravity acceleration for the dummy tests.

The cadaver peak head CG accelerations ranged from 68 g's to 103 g's. As expected, the cadaver accelerations were lower than the dummy given the damping associated with the soft tissues not present in the dummy. The same correlation was seen for the cadaver peak head CG acceleration for both the pressure onset rate and peak pressure (R^2 = 0.99). As seen in the dummy tests, the peak acceleration occurred during the 'punch out' phase for the cadavers as the peak times ranged from 10 ms to 12 ms. Also, the time history of the acceleration was similar between the dummy and cadaver tests for a given inflator (Figure 3).

The peak tension values for the upper neck load cell in the dummy tests ranged from 992 N with air bag A to 1670 N with air bag C (Table 4). Peak tension correlated very well with both the pressure onset rate and the peak pressure (R^2=0.99). The peak tension values occurred after the peak head CG accelerations for tests 2 and 3, but earlier for test 1 with the least aggressive air bag. An additional anomaly was observed in test 2 with air bag B, the initial neck tension was followed by slight compression between 8 ms and 12ms and then the peak neck tension at 20 ms (Figure 4). Analysis of the high speed video suggested that this difference was due to a slight difference in the initial interaction pattern of the deploying air bag. In test 2 the air bag impacted the head and interacted with the door to produce the slight compression prior to lifting the head forward.

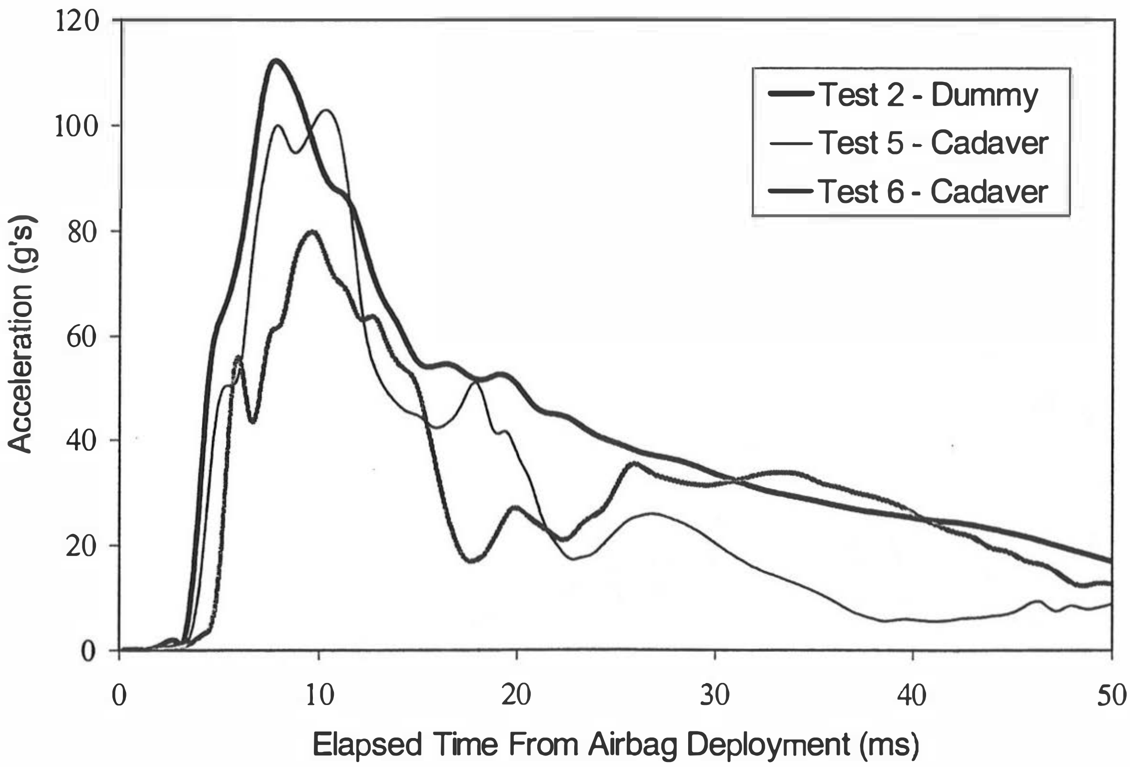

Figure 3. Head center of gravity acceleration for the dummy and cadaver tests with air bag B.

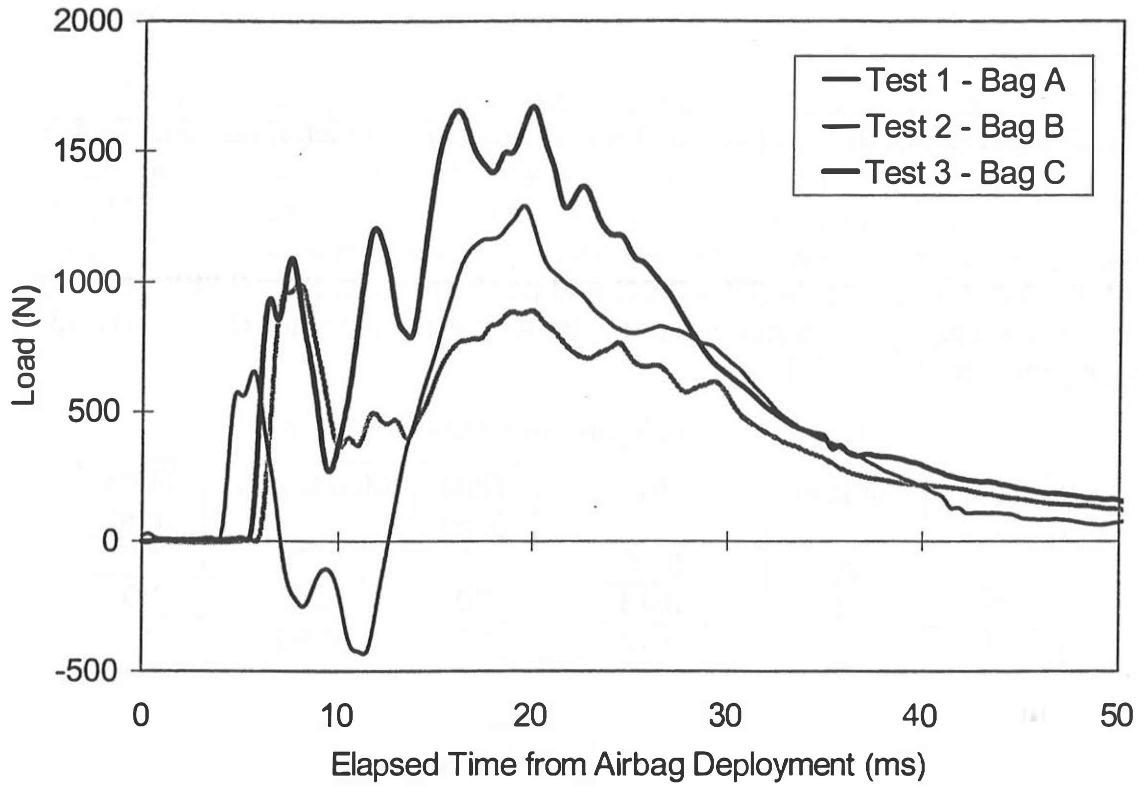

Figure 4. Neck tension for the dummy tests.

Unlike the peak head CG acceleration and the peak neck tension, the neck moments occurred much later in the event (Table 4). The peak flexion values ranged from 16 Nm to 33 Nm and occurred between 28 ms and 38 ms. The peak moment loading was a result of the inertial loading of the head onto the neck as the head reached the highest flexion angle and began to return to the neutral position. This movement corresponds to the large inertial flexion moment applied to the neck as the head changes directions. The flexion moments were not correlated to the pressure onset rate ($R^2 = 0.59$) or the peak pressure ($R^2 = 0.55$). The lateral bending moment values ranged from 26 Nm to 55 Nm and occurred between 30 ms and 40 ms.

The poor correlation between the peak neck moments and the inflator properties was due to a different interaction pattern between the types of air bags. The more aggressive air bags B and C deployed onto the head and bounced upward. The less aggressive air bag A maintained contact with the head longer which allowed a similar impulse to be delivered to the head compared to air bags B and C. Since the peak moment occurred as an inertial load at the end of neck flexion, the different interaction patterns allowed for similar peak moments and explain why they did not correlate with the inflator properties. This trend was also observed in tests performed with the Hybrid III 3 year old dummy in a similar test configuration [Duma, 1998].

INJURY ASSESMENT – Post-test radiographs and necropsy were performed on each cadaver and revealed no injuries for all three tests. The lack of observed injury in the cadavers corresponds well with the injury criteria as all neck loads and moments were below the NHTSA independent neck injury assessment reference values. The greatest tension was recorded for air bag C at 1670 N which was lower than the 2080 N criteria. The largest flexion moment was also observed for air bag C at 33 Nm and below the 95 Nm criteria.

Using the combined stress approach, all peak N_{ij} and modified N_{ij} values were below the 1.0 threshold and accurately predicted no injury in the cadaver tests (Table 5). Given the complex loading of the side air bag and the resulting lateral bending out of the sagittal plane, the N_{ij} values were 16 % to 53 % lower than the modified N_{ij} values. The N_{ij} values correlated reasonably well with the inflator onset rate ($R^2 = 0.84$) and peak pressure ($R^2 = 0.86$); however, the modified N_{ij} values correlates much better with onset rate ($R^2 = 0.95$) and peak pressure ($R^2 = 0.93$).

Table 5. Peak N_{ij} and modified N_{ij} values.

Test	Air Bag	N_{ij}	Time (ms)	Modified N_{ij}	Time (ms)
1	A	0.30	7	0.46	16
2	B	0.43	20	0.50	20
3	C	0.47	20	0.68	16

The tension component of N_{ij} was much larger than the bending moment contribution early in the event during the 'punch out' and 'membrane loading' phases (Figure 5). After 26 ms for test 3 with air bag C, the inertial load applied to the neck as the head reached maximum flexion resulted in the bending moment contribution to be larger than the tension component after 26 ms for test 3 with air bag C.

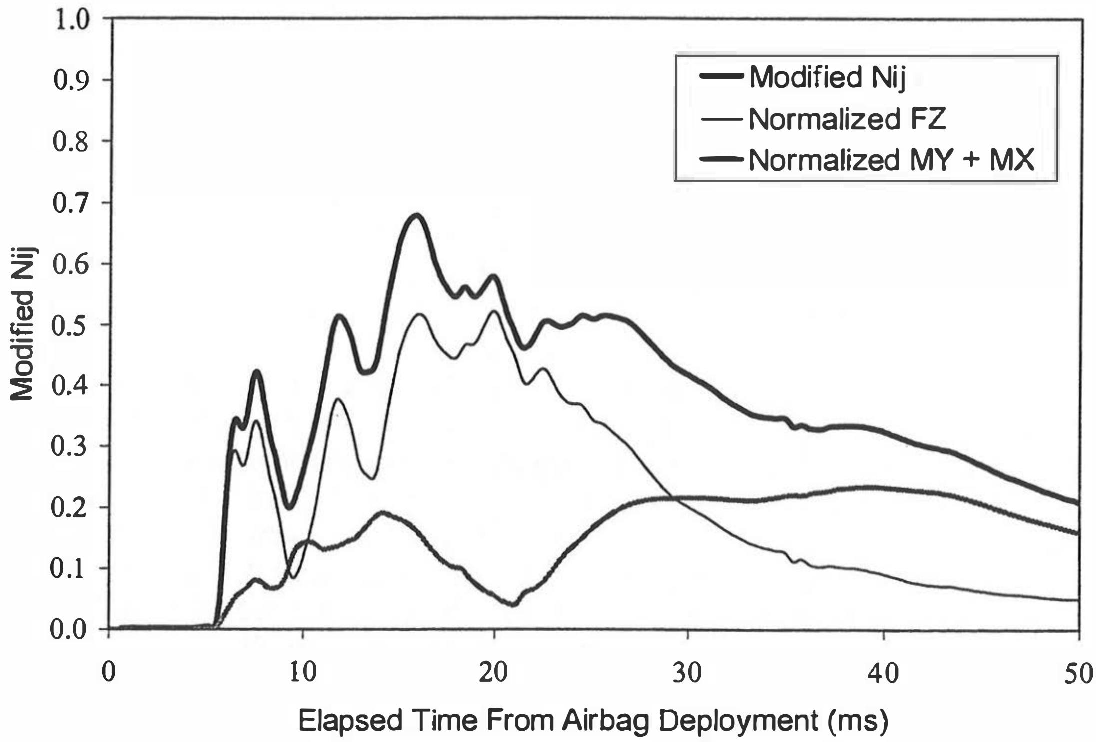

Figure 5. Modified N_{ij} for test 3 with air bag C showing normalized tension (FZ) and resultant moment (MY + MX) components.

CONCLUSIONS

This testing evaluated the 'worst case' position for the head and neck likely to be encountered with out of position small female and side air bags. The results of the dummy testing indicated that complex loading will result in forces and moments below injury threshold values. The results from cadaver tests in the same test configuration agreed with this prediction in that no injuries were observed. This study demonstrates that it is possible to remain below NHTSA neck injury criteria even in the worst case position. Although optimization of adult occupant protection in lateral collisions must be concurrently examined, the data suggests that the side air bag inflator characteristics and bag geometry can be designed to minimize the potential risk of injury to the out of position small female.

The data clearly indicate a relationship between airbag inflator properties and dummy response. Both the peak resultant head CG acceleration and peak neck tension correlated very well with the inflator onset rate and peak pressure. However, due to different interaction patterns between the less and more aggressive air bags, both the flexion and lateral bending moments are independent of inflator properties.

A modified formulation for the N_{ij} neck injury criteria was utilized that included both flexion and lateral bending moments. Although the assumption of similar injury criteria for lateral and flexion bending was made, the modified N_{ij} is advantageous in that it includes any bending outside of the sagittal plane. Due to its inclusion of the lateral bending component, the modified N_{ij} better correlates to inflator properties than the original N_{ij} or the lateral N_{ij}. While both the original N_{ij} and the modified N_{ij} both accurately predicted no injury in these tests, the use of the original N_{ij} to evaluate side air bag loading may not accurately estimate the risk of neck injury as long as bending outside of the sagittal plane is ignored.

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