METHODOLOGY FOR ESTIMATING THORACIC IMPACT RESPONSE IN FRONTAL CRASH TESTS

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ABSTRACT

This study has investigated the feasibility of estimating chest acceleration from the pelvic acceleration and shoulder belt forces measured on a vehicle occupant exposed to a frontal crash. The method of estimating chest acceleration is based upon a simple two-mass one-dimensional model of a vehicle occupant in which pelvic acceleration and shoulder belt force are applied as forcing functions. The predictive power of the model was evaluated by comparing the estimated and measured chest acceleration of 18 Hybrid-III crash test dummies subjected to 56 km/hr full frontal barrier crash tests. The crash test dummies were restrained by airbags and three-point belt systems with pretensioners and load-limiting shoulder belts. The combined loads exerted on the chest by the pelvis and the shoulder belts were shown to be a reasonable estimate of force on the chest early in the crash event prior to significant airbag loading.

Keywords: Chest, Pelvis, Acceleration, Thoracic Injury, Chest Injury Model.

INTRODUCTION

Chest injury is second only to head injury as the leading cause of serious injury, social costs and fatalities in automobile crashes[1, 2]. Chest acceleration is a widely used metric for determining the risk of thoracic injury in frontal crash tests. In a crash test, an instrumented crash test dummy can provide an estimate of human chest injury risk based on chest acceleration measurements. However, in some tests, the chest acceleration is not known either because it was not measured or because the chest accelerometer failed. It is our hypothesis that the chest acceleration can be reconstructed from other parameters measured in the test – specifically, seat belt loads and forces on the lower body.

METHODS

Our approach was first to develop a two mass, one-dimensional model of a vehicle occupant exposed to crash loading, and then to test the predictive capabilities of the model using data from a series of controlled frontal crash tests.

Model

As shown in Figure 1, the deceleration of an occupant chest in a collision is controlled by the shoulder belt loading, the airbag loading and the forces of the lower body acting on the chest. For our model, the human body is represented by two interconnected masses – the chest mass and the pelvic mass. In this simplified model, we assume that all mass in the lower body, including the pelvis, abdomen, and lower extremities, can be represented by a point mass located at the pelvis center of gravity. We assume that all mass of the upper body, which includes the chest, head, neck, and upper extremities, can be represented by a point mass located at the position of the chest accelerometer. In crash test dummies, forces can be transmitted between the chest mass and the pelvis mass via the lumbar spine as shown in earlier studies [3,4]. The pelvis is restrained by the lap belt while the chest is restrained by the shoulder belt.

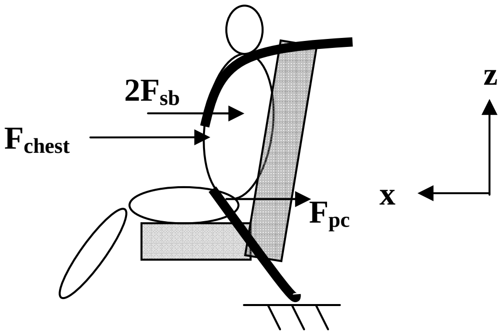

Figure 1. The principal forces acting on an occupant involved in a frontal crash. F_{sb} = shoulder belt force, F_{chest} = force exerted on the chest and F_{pc} = force exerted on the chest by the pelvis.

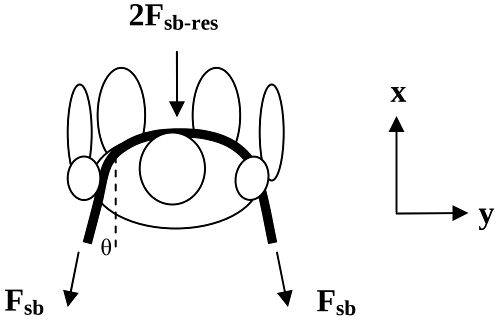

Figure 2. Top-view diagram expressing the manner in which the belt load is transferred to the chest. F_{sb} = measured shoulder belt force and $F_{sb\text{-}res}$ = resultant shoulder belt force.

As shown in Equation 1, chest acceleration, a_{chest}, can be computed from Newton's second law. For consistency with the sign of the forces on the chest depicted in Figure 1, deceleration is defined to be positive in this model. The resultant force on the chest, F_{chest}, is the sum of the seat belt forces, the airbag force, and the force of the pelvis upon the chest, F_{pc}. In crash tests, shoulder belt tension is measured by a load cell mounted on the belt above the shoulder. As shown in Figure 2, the total seat belt force is twice the force measured by the seat belt tension load cell, F_{sb}.

$$F_{chest} = m_{chest}\, a_{chest} \qquad \text{(Equation 1)}$$

$$F_{chest} = 2F_{sb} + F_{airbag} + F_{pc} \qquad \text{(Equation 2)}$$

Forces on the pelvis include loads from the lap belt ($F_{lapbelt}$), the seat cushion (F_{seat}), the loads transmitted through each femur (F_{femur}), and the force exerted by the chest upon the pelvis (F_{pc}). Airbag interaction with the lower body is insignificant in these crash tests. The resultant force on the pelvis can be estimated as shown in Equation 3:

$$F_{Pelvis} = F_{Seat} + 2F_{femur} + 2F_{lapbelt} - F_{pc} \qquad \text{(Equation 3)}$$

One challenge in applying this model is that unlike shoulder belt load, the force of the airbag upon the occupant is not typically measured in crash tests, and was unavailable for our reconstruction. In our initial model, we observed however from inspection of high speed video that the airbag did not interact significantly with the chest until 40-50 milliseconds after impact. Hence, $F_{airbag} \approx 0$ for this period. Also, we empirically observed in our sample of crash tests that for the first 40-50 milliseconds of the crash $m_{pelvis}a_{pelvis} \approx F_{lapbelt} + F_{femur}$. We also assumed that F_{seat}, the force produced by the seat cushion, was negligible compared to belt forces. Combining these assumptions with Equations 1-3, we proposed the following simplified model for estimation of chest acceleration:

$$a_{chest} \approx \frac{1}{m_{chest}}\left(2F_{sb} + m_{pelvis}a_{pelvis}\right) \qquad \text{(Equation 4)}$$

A more complete model would also include the force of the airbag upon the occupant. However, we anticipated that this simplified model could be used to produce reasonably accurate estimates of chest deceleration prior to significant chest-airbag interaction. During the later portion of the crash event, our assumption of a negligible airbag load was expected to cause our model to under predict the total restraint force on the dummy chest.

Our model assumes that the seat belt tension acts on the dummy in the x-axis. Actually, only the component of the seat belt tension force aligned with the x-axis acts on the occupant chest in the x-axis. It was not possible however in the crash tests available for this study to determine the angle θ between the seat belt and the x-axis in a crash test. The initial angle could be estimated for some tests, but this angle changes throughout the test as the crash test dummy loads the seat belt and moves forward toward the steering wheel or instrument panel. By assuming the angle $\theta=0$, the model will overestimate the actual seat belt load applied to the dummy.

Data Set

The model was evaluated by analyzing the impact response of 12 frontal crash tests conducted by the National Highway Traffic Safety Administration (NHTSA). All of the tests were 56 km/hr full frontal crashes into a rigid barrier. Each test contained a 50th percentile male Hybrid-III crash test dummy seated in the driver and the right front passenger positions. All dummies were belted with three-point belt systems. The vehicles in our data set were passenger vehicles of model year 2005-2007. All vehicles were equipped with frontal airbags and advanced seat belts with pretensioners and load limiters. Analysis was conducted on 12 drivers and 6 passengers. All data was obtained from the NHTSA Vehicle Crash Test database [5] .

The mass of the upper body includes the chest, head, neck, and upper extremities. The mass of the lower body includes the pelvis, abdomen, and lower extremities. For the Hybrid-III dummy, the known masses for the upper and lower subdivisions are 55kg and 23 kg respectively [2]. In the crash tests, chest acceleration was measured by a tri-axial accelerometer mounted on the thoracic spine. The pelvic accelerometer was located at the center of gravity of the pelvis. In each case, the resultant chest and pelvis accelerations were computed from tri-axial accelerometers mounted in the chest and pelvis. The resultant acceleration was filtered at 60 Hz. The shoulder belt load was measured above the shoulder of the crash dummy and along the length of the belt.

Our approach was to estimate chest accelerations using known pelvis acceleration and seat belt loads in crashes for which chest acceleration is also known. We then computed the error between the estimated and known chest acceleration.

RESULTS

The analysis was conducted for each of the 18 crash test dummies in the dataset. The figures below show the calculation for one test (NHTSA Test 5561). Figure 3 presents the resultant chest and pelvic acceleration. Figure 4 presents shoulder belt load. Figure 5 presents the computed pelvic force, shoulder belt force, and computed chest force. Figure 6 compares the actual chest force vs. the chest force estimated from pelvic force and shoulder belt load. For this test, the agreement between the two was very good during the first 70 milliseconds of the event. Peak forces differed by 13.1%.

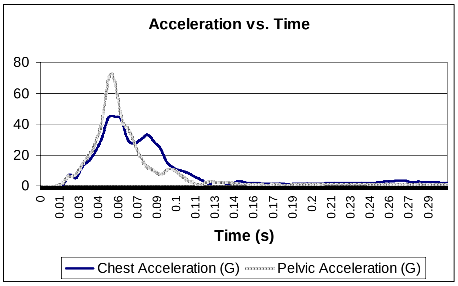

Figure 3. The resultant accelerations of the chest and pelvis respectively vs. time (NHTSA test no. 5561)

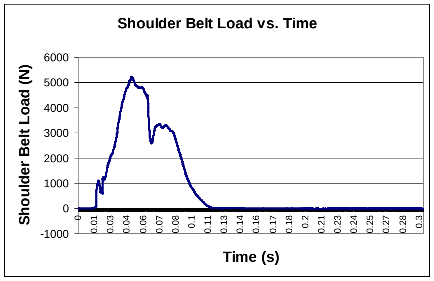

Figure 4. Shoulder belt load vs. time (NHTSA test no. 5561)

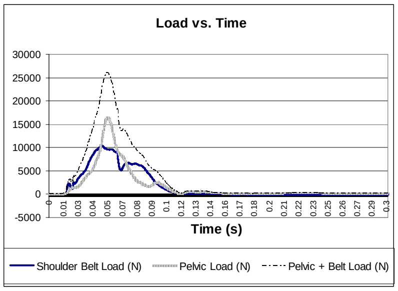

Figure 5. Chest, pelvic and shoulder belt forces vs. time. (NHTSA test no. 5561)

Figures 6-8 show the degree of correlation in these tests (5561, 5468, and 5603) between the known chest force as compared to the calculated force resulting from the combination of the pelvic and shoulder belt components.

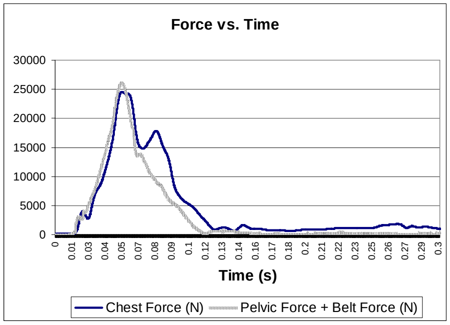

Figure 6. The calculated chest force and combined pelvic and shoulder belt load forces vs. time for NHTSA test no. 5561.

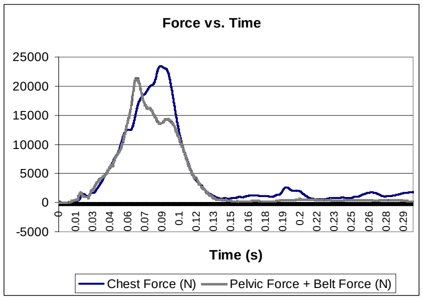

Figure 7. The calculated chest force and combined pelvic and shoulder belt load forces vs. time for NHTSA test no. 5468.

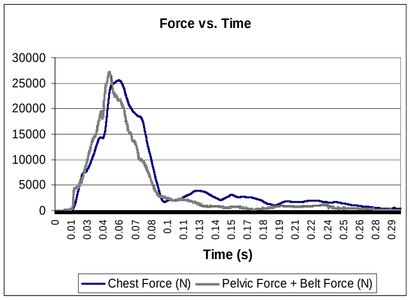

Figure 8. The calculated chest force and combined pelvic and shoulder belt load forces vs. time for NHTSA test no. 5603.

As shown in Figures 6-8, the combined loads induced on the chest from the pelvis and the belt loads were shown be a reasonable estimate of force on the chest. In each, the agreement between the actual and the estimated chest acceleration was better in the earlier part of the event before the airbag was fully deployed. As shown in Figures 6-8, the estimated peak chest acceleration later in the event was also similar in magnitude to the actual peak chest acceleration, although the two did not occur at the same time.

DISCUSSION

For all 18 tests, the peak occupant chest loads as well as the combined pelvic and shoulder belt loads were tabulated and converted back to chest accelerations. As shown in Figure 6-8, the model produced chest acceleration estimates in the first 40 milliseconds of the crash that were in excellent agreement with actual chest acceleration measurements. As shown in Figure 6-8 and Table 1, the model also gave unexpectedly good accurate estimates of peak chest deceleration over the entire crash event. The root mean square error between actual and estimated maximum chest acceleration over the entire crash event was only 6.5 G. The standard deviation in the error was 6.6G. The average difference between the actual and the estimated peak chest acceleration was 13.1%. This degree of agreement may only be coincidental however. Future studies will explore whether the predictions of the model have any physical significance for times beyond the early part of the crash event when airbag forces are negligible.

The error of 13.1% showed that there was a degree of inconsistency in the data that can be accounted for with other interactions not included in this model. However, the purpose of this model was to express the relationship between the pelvic accelerations and the shoulder belt load in a manner that would predict reasonable chest acceleration in situations where the chest acceleration could not be directly measured. The model may not predict the chest acceleration with complete certainty, but it does provide a methodology to estimate the risk of injury for the occupants in cases where that would otherwise not be possible.

Test #	Chest Force (N)	Belt Load + Pelvic Force (N)	Actual Chest Acceleration (G)	Chest Acceleration from Combined Loads (G)	Difference in Chest Acceleration (G)
5603-D	25555.2	27234.4	47.4	50.5	3.1
5603-P	26496.4	24264.6	49.1	45.0	-4.1
5602-D	22527.9	22763.9	41.8	42.2	0.4
5602-P	20048.5	22355.9	37.2	41.4	4.3
5597-D	24016.1	21536.4	44.5	39.9	-4.6
5590-D	28453.0	22519.0	52.7	41.7	-11.0
5588-D	23262.0	26354.0	43.1	48.8	5.7
5587-D	24938.1	28485.1	46.2	52.8	6.6
5580 -D	19021.8	22604.7	35.3	41.9	6.6
5573-D	24066.5	26054.5	44.6	48.3	3.7
5573-P	23110.2	20264.0	42.8	37.6	-5.3
5561-D	24551.1	26100.9	45.5	48.4	2.9
5561-P	23714.1	26501.2	44.0	49.1	5.2
5547-D	17871.5	20871.2	33.1	38.7	5.6
5468-D	23456.1	21456.0	43.5	39.8	-3.7
5468-P	25873.8	18885.3	48.0	35.0	-13.0
5456-D	22429.8	23731.8	41.6	44.0	2.4
5456-P	19497.3	26115.3	36.1	48.4	12.3
				Root Mean Squared Error (G)	**6.5**
				Standard Deviation (G)	**6.6**

Table 1: The conversion of force loads into chest G's and the difference between those calculated from the chest force and those from the combined pelvic force and shoulder belt loads.

Limitations

1. The most important limitation is the assumption that the pelvic acceleration and the shoulder belt loads are the only components contributing to the chest acceleration. There are many components of vehicles that are specifically designed to regulate the chest acceleration. Devices such as airbags, load limiters, pretensioners and collapsible steering columns are put in place largely to prevent serious injury from large chest accelerations. Including the interactions of all these components in the calculation of the chest acceleration would improve the prediction of the chest acceleration. However, crash tests provide no estimate of the forces induced by these components.

2. Another assumption was that the entire shoulder belt load was applied to the chest. The force measurement was taken on the belt above the shoulder. At this location, the belt is at an angle that is not normal to the chest, as assumed by this study. An improvement would be to use the component of the seat belt force aligned with the x-axis. Also, it should be noted that as the excursion of the occupant increases with respect to the occupant compartment, the angle of the belt would change, thereby changing the component of force being directed into the chest.

3. Our model of the crash test dummy involved several assumptions. The center of gravity of the upper body, which included the chest, arms and head, was assumed to be located at the center of gravity of the chest. Similarly, the center of gravity of the lower body, which included the pelvis and legs was assumed to be located at the center of gravity of the pelvis. Furthermore, all forces on the chest were assumed to act through the center of gravity of the chest. This allowed the model to neglect chest rotation. Each of these assumptions will result in some error in the model.

4. This study only considers frontal crashes at a single impact speed. If this model was applied to frontal crashes at alternate speeds, or applied to other crash configurations such as off-set frontal or side impacts, it is unknown how well the estimated force values would correlate to the actual chest forces.

Despite these assumptions, there appears to be strong agreement between the forces exerted on the chest and the forces induced by combining the shoulder belt loads with the pelvic forces in the early phase of the crash event. Our study to date has not revealed whether the error introduced by these assumptions is negligible or is simply canceled out by the interaction between these assumptions.

CONCLUSIONS

This study has demonstrated the feasibility of estimating chest acceleration from the pelvic acceleration and shoulder belt load of a vehicle occupant exposed to a frontal crash. The method of estimating chest acceleration is based upon a simple two-mass one-dimensional model of a vehicle occupant in which pelvic acceleration and shoulder belt force are applied as forcing functions. The predictive power of the model was evaluated by comparing the estimated and measured chest acceleration of 18 crash test dummies subjected to 56 km/hr full frontal barrier crash tests. The combined loads exerted on the chest by the pelvis and the shoulder belts were shown to be a reasonable estimate of force on the chest early in the crash event before airbag forces are significant.

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