Analytical and Experimental Studies to Predict Response of Humans to Blast-Induced Blunt Trauma

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Analytical and Experimental Studies to Predict Response of Humans to Blast-Induced Blunt Trauma

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Recent interest in the vulnerability of humans exposed to the effects of a bomb detonation has prompted an experimental and analytical investigation into the physics of the phenomena involved, with a view towards the development of fast-running algorithms to predict human lethality. The approach utilizes technology developed for the automotive safety industry and applies these techniques toward predicting the level of injury sustained by a human impacted by various kinds of debris produced by a terrorist bomb blast outside a conventional office building.

The experiment in question was DIVINE BUFFALO 4, in which instrumented anthropomorphic test dummies were placed in rooms fully furnished and equipped as typical offices, and exposed to blast effects. Each room had a large picture window with anti-shatter film applied, but the loads greatly exceeded the glass capacity, resulting in the glass being blown into the room and impacting the dummies. Accelerometer data from the dummies' heads could then be used to predict the level of injury sustained by a human in that room. Analytically, the experimental results were replicated using the MADYMO kinematics code. To properly replicate the data, novel techniques were developed for estimating the load applied to the head from a high-velocity impact of a sheet of shattered, filmed glass. Of the four instrumented dummies, detailed analysis was performed for two which, due to differences in experimental configuration, were exposed to significantly differing debris hazard environments. The model was able to discriminate between the response of dummies in two rooms where one suffered a fatal injury while the other suffered only moderate levels of injury, based on head injury criteria.

INTRODUCTION

Over the past several decades, a great deal of improvement and refinement has taken place in the ability to predict the response of a structure to blast loads. Whether the blast comes from an accidental explosion, a terrorist bomb, or a conventional weapon, the airblast loads have been well characterized, and there are many assessment codes that incorporate simple engineering models which, given the loading on the structure, can predict the level of damage incurred by each component (e.g., columns, walls, windows).

However, there are no readily available means for quantifying the hazards to a building's occupants due to impact of debris from either structural (e.g., failed beams or walls) or non-structural (e.g., computer monitors or ceiling tiles) sources. To provide a comprehensive assessment and design tool for determining the risks associated with a particular explosive event, a capability is needed to estimate the numbers of casualties and/or fatalities caused by the blunt trauma produced by a blast environment in typical office spaces.

The work described in this paper is part of a larger study where human injury models are being built for incorporation as modules within assessment codes. The goal is to generate models that execute sufficiently quickly to allow their integration into assessment codes that use similarly fast-running engineering models to predict damage. These models can then be used to perform an assessment of a particular building for a particular threat, or to perform various kinds of design studies for mitigation purposes. Because the exact configuration of a room (e.g., location and orientation of people) at the time of a blast is unlikely to be known with any great certainty, it is important that these models approach the injury and casualty predictions in a probabilistic fashion.

The particular subject of this paper is an experiment in which anthropomorphic test dummies (ATDs) were positioned inside realistically furnished offices inside a typical building and then exposed to the effects of a blast outside the building. The data generated was then compared to criteria validated in the automotive safety industry to generate estimates of lethality for the dummies. Analytical calculations were also performed which simulated the test event and the response of the dummies. Because of the configuration of these test rooms, the focus of the experiment and calculations was on the impact of filmed glass sheets against the head of the ATD, creating high accelerations. And because the glass was filmed, the lethality mechanism was blunt trauma as opposed to penetration, as might occur when the blast produces sharp individual shards of glass.

METHODOLOGY FOR PREDICTING LETHALITY FROM BLUNT TRAUMA

Analytical models such as those discussed below can be exercised to predict key human response metrics, such as head acceleration. The same can also be experimentally measured from a test event, such as the one considered below. However, to be useful as a means of predicting levels of injury, these metrics must be correlated to accepted criteria of injury. While such measures of response have not yet been developed for blast scenarios, a number of metrics and criteria are widely used and available from the automotive safety industry.

Figure 1 presents an overview of the approach used to correlate measured (or analytically calculated) biodynamic responses to injury levels. In each case, we begin with a measured response: acceleration history in the head, forces and moments in the neck, acceleration/deflection/force in the thorax (chest area), or impact force characterization in the abdomen. These are then compared to various criteria appropriate for each metric to estimate the severity of the response. Comparison to criteria generates an injury level, generally characterized by the Abbreviated Injury Scale (AIS). The AIS is a numerical scale developed by the Association for the Advancement of Automotive Medicine and the American Medical Association [1, 2]. In the more than 20 years it has been in existence, it has become the most widely used injury rating system in this country and internationally. The scale covers all body parts, and hundreds of publications are written each year using it. Finally, having obtained an AIS rating for each affected body part, these may be combined into a single injury score for the individual using the Injury Severity Score (ISS), which is the sum of the squares of the three highest AIS levels for a particular individual. In this specific study only head trauma was taken into account in determining the overall lethality.

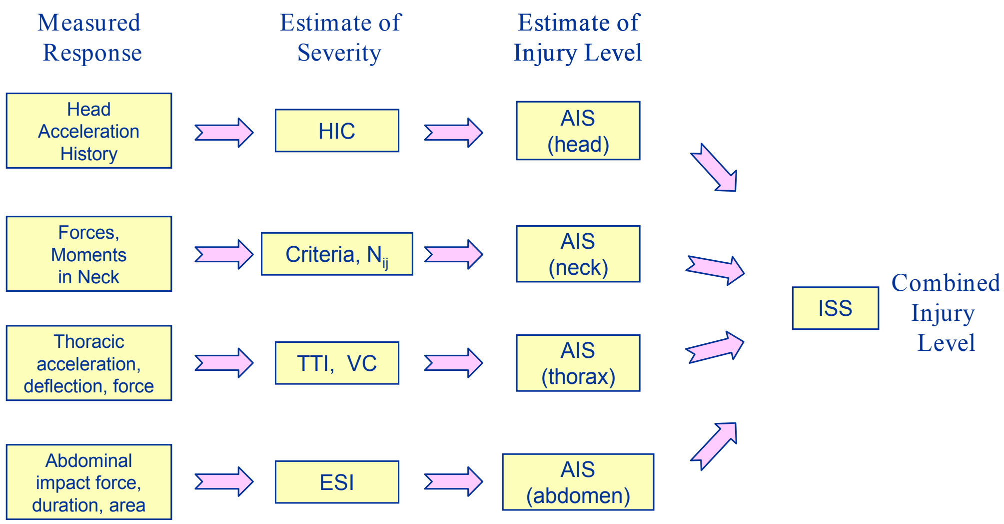


Figure 1. Injury assessment methodology from blunt trauma.

As an example of this methodology, consider the response of the head to blunt impacts. In the test event considered, the dominant injury mechanism was impact of filmed glass sheets to the head. Once an acceleration history is either recorded (by using biofidelic dummies in a test) or calculated (using analytical models), this history may be processed to obtain the Head Injury Criterion (HIC), which is the most widely used criterion for head and brain injuries [3]. The HIC is calculated using the following equation:

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

In the above expression, a is the resultant acceleration expressed in g's and t_1 and t_2 are two arbitrary points in time. In typical automotive safety applications, $t_2 = t_1 + 36$ ms; however, for hard impacts such as those anticipated in blast scenarios, $t_2 = t_1 + 15$ ms is used. Successive trials for t_1 are tested and the value producing the maximum HIC is selected. Federal Motor Vehicle Safety Standards (FMVSS) define the procedures used to measure and calculate the HIC.

Once a HIC value is obtained, it can be correlated to an AIS value using the data in Table 1. In general, a HIC of 1,000 indicates a high probability of moderate brain injury and is to be avoided. Values above 1,500 correspond to a high probability of severe brain injury. Note that the "type of injury" description in the table is associated with each AIS value, and the same description would be applicable to AIS levels obtained from other response metrics (such as thoracic or abdominal injuries). Thus the AIS scale is independent of the location of the injury. Typically, AIS levels of 3 or greater are considered to be serious injuries, while an AIS of 6 is required for a fatality.

Table 1. Correlation between HIC and AIS.

AIS	Severity	Type of Injury	HIC
0	None	None	—
1	Minor	Superficial	< 250
2	Moderate	Recoverable	< 750
3	Serious	Possibly recoverable	< 1,250
4	Severe	Not fully recoverable without care	< 1,750
5	Critical	Not fully recoverable even with care	< 2,500
6	Maximum	Fatal	> 2,500

OVERVIEW OF DIVINE BUFFALO 4 EXPERIMENT

The DIVINE BUFFALO 4 test was conducted in May of 2000. A charge simulating typical terrorist vehicle bombs was detonated outside a simulated four-story office building. A photo of the building's façade (the one facing the charge) is shown in Figure 2. Among the many experiments conducted in this test, the four rooms on the third floor were furnished with realistic office furniture and equipment. A single ATD was also positioned in a chair in each room. Of particular interest in this paper are rooms 3-3 and 3-4, for which detailed analytical calculations were performed. Pretest photos of these rooms are presented in Figures 3 and 4, which illustrate the ATD positions in each room. Test objectives included measurement of ATD response via accelerometers mounted in each head and thorax. Gages were also positioned on the building's exterior and inside the rooms to measure blast pressure histories. Because of the configuration of these test rooms, the focus of the experiment and calculations was on the impact of filmed glass sheets against the head of the ATD, creating high accelerations. And because the glass was filmed, the lethality mechanism was blunt trauma as opposed to penetration, as might occur when the blast produces sharp individual shards of glass.

Figure 2. Front face elevation of simulated office building.

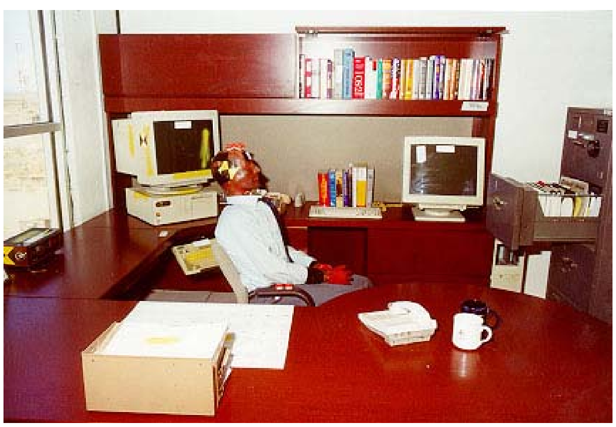


Figure 3. Interior pretest photo of room 3-3.

Figure 4. Interior pretest photo of room 3-4.

A floor plan of room 3-3 is shown in Figure 5; in this figure, the window (and the blast) are towards the bottom. The seated ATD faces away from the window. Once the bomb is detonated, the glass is propelled inward and has an unobstructed path (except for a small clock-radio) to the ATD's head. In this test, the windows consisted of single pane ¼-inch thick thermally tempered glass, to which anti-shatter film had been applied using a daylight technique (i.e., no attachment of the film to the window frame).

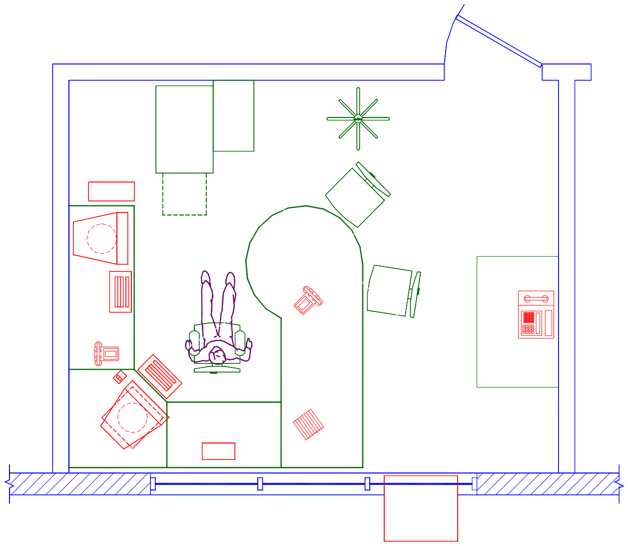


Figure 5. Floor plan of room 3-3.

Comparing Figure 5 to Figure 4, we observe that in room 3-4 (Figure 4), the glass does not have a clear unobstructed path to the ATD. Instead a large computer monitor acts to “shield” the ATD from the glass. While the ATD is not directly in line with the monitor, the majority of the head’s projected area is in line with the monitor. Additionally, a window mullion is immediately adjacent to the monitor, further reducing the amount of glass that would impact the ATD.

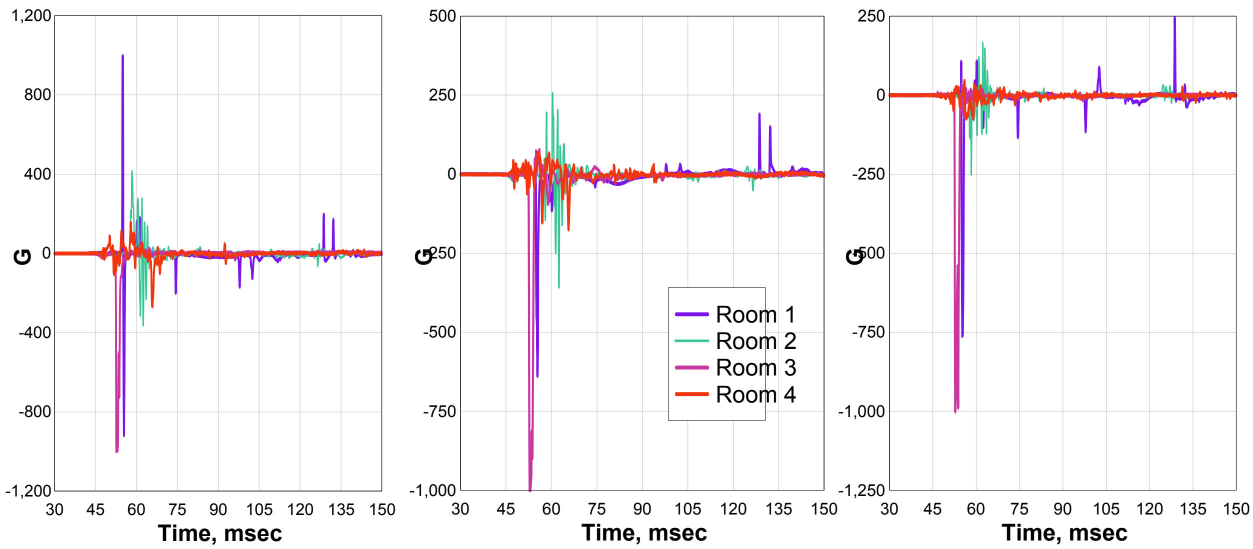
TEST RESULTS

Observation of the third floor rooms after the test indicated that the windows and most of the interior partition walls had been completely destroyed by the blast. Figure 6 illustrates the posttest condition of rooms 3-3 and 3-4 respectively. Most of the furniture was overturned and broken up, and the bookshelves in room 3-3 had fallen over. Debris from ceiling tiles, interior drywall, books, and other materials was strewn about the entire room. In room 3-3, the ATD had been upended and pushed over, while in room 3-4 the ATD was pinned between the credenza and desk.

(a) Room 3-3. (b) Room 3-4.

Figure 6. Posttest views of offices.

A comparison of the acceleration records measured in each of three directions in each of the four ATDs is shown in Figure 7. We note that even though we would expect the highest acceleration peak to occur in the incident direction, given that the glass was traveling in that direction, the peaks in the other directions were comparable in magnitude. The overall level of acceleration was very high, nearly 1,000 g's, but occurring over a duration of only a few milliseconds. What is most noteworthy is that the acceleration for the room 4 ATD (red curve) is consistently much lower than in any of the other three rooms; with comparison to room 3 (purple curve), the room 4 ATD experienced head accelerations that were many times lower.



(a) X-direction (incident). (b) Y-direction (vertical). (c) Z-direction (lateral).

Figure 7. Acceleration histories in head of ATDs in all rooms.

That same observation is confirmed after numerically processing the accelerometer records to obtain HIC and AIS values for each ATD. As shown in Table 2, the results of the analysis indicate that the ATD in room 3-3 suffered fatal injuries due to head impact, while the ATD in room 3-4 only suffered a moderate level of injury. This is presumed to be due to the shielding provided by the monitor in minimizing the amount of glass that hit the dummy's head.

Table 2. HIC analysis and AIS based on measured head accelerations.

Room	Duration of Record Utilized (msec)	HIC	AIS
3-3	50.0 – 140	100,000	6
	59.0 – 140	120	1
3-4	50.0 – 140	850	3

For heuristic purposes, the data for room 3-3 was analyzed in two ways, first by including the entire record (with the very high spike at the beginning which is presumed to be due to glass impact), and again by truncating the early-time portion such that the high spike is omitted. The latter result is shaded in gray. As the table indicates, by omitting the early-time spike, the HIC is reduced by 3 orders of magnitude, and the AIS goes from fatal to light superficial injury. Hence, we can conclude that the impact of the glass was the single event that generated the fatality, assuming the acceleration spike can be demonstrated to correlate to that event. Detailed analysis of film footage from the experiment has shown that the acceleration spike can be closely correlated to the glass impact, as will be demonstrated below.

ANALYTICAL METHODOLOGY

In order to generate a fast-running lethality model, it is necessary to first exercise more intensive analytical models which can predict the response of humans under blast and impact conditions. Within the scope of this paper, the discussion will be limited to models for prediction of blunt trauma injuries; other means can be employed to assess injuries due to crushing (by very heavy but slow moving objects) or penetration (by very small objects which cut the skin).

The most widely used code for predicting biodynamic kinematic response is MADYMO [4, 5]. Developed by TNO in the Netherlands, MADYMO (Mathematical Dynamic Models) is a general purpose engineering software package that can be used to simulate the complex dynamic response of humans and mechanical systems subjected to impact loading. It has special features for analyzing the motion of the human body and its interaction with the surrounding environment in an event such as a vehicle crash or a fall. MADYMO has fully integrated multi-body and finite element capabilities. MADYMO is used world-wide in the automotive industry, design offices, research laboratories, universities, and the accident reconstruction industry. It is a mathematical tool used by manufacturers and designers to study, improve, and predict the performance of their products and has proven itself in numerous applications, often supported by verification studies using experimental test data. MADYMO offers a unique library of crash dummy and component databases that are validated for a range of applications.

A typical MADYMO model of a human is shown in Figure 8. Human and mechanical systems can be characterized by a combination of essentially rigid and deformable parts connected by joints. Each part is treated as a lumped mass having 6 degrees of freedom (3 translation, 3 rotation). The mass of the individual parts and the stiffness properties of the joints are biofidelic, that is, they represent the kinematic properties of human bodies under acceleration and impact loads. To model contact between the human and other bodies, each part is represented by an ellipsoidal surface. Contact between the ellipsoidal surface and any other body is defined in terms of force-penetration relationships that are available for a range of materials (e.g., glass, wooden furniture, etc.).

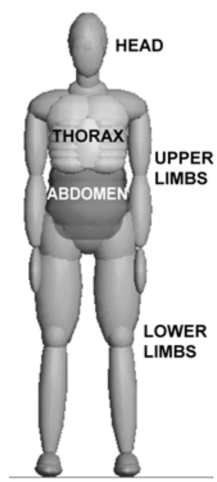


Figure 8. Typical MADYMO representation of a human.

One of the key features of this test was the interaction of the glass sheet with the ATD head. To represent this, a model was developed to represent a sheet of filmed glass which, though cracked into pieces and separated from the window frame, was still held together by the film. The glass was modeled using a mesh consisting of square elements (to represent the glass pieces) connected by rotational joints and linear springs (to represent the film). Each individual element has a mass and inertia concentrated at its center of gravity and an ellipsoid to represent the contact surface. The joint and spring properties were selected such that they had minimal strength to allow for flexibility and tearing in high speed impacts, but they provide enough strength to keep the glass together during travel in the air. The model thus assumes that the glass will either tear when impacting a hard edge, or will shatter and tear further allowing to pass through the hard round objects such as the head. This model is therefore tailored for the conditions in this test. For general applications a more generic glass model needs to be developed.

The interaction between glass and the ATD head is represented in MADYMO by a force-displacement curve. Figure 9 shows one such curve for low-speed impact against a windshield, which is based on automobile windshield impact tests. Also shown for reference is the curve representing very slow impact against a rigid object. When impacting the laminated windshield, the load increases until the glass cracks, at which point the load drops to a lower level but continues over large displacements until the inner laminate is torn. Impact on a rigid object generates a continuously increasing force, by comparison. The curve for shattered, filmed glass at high speed impact is also shown. The initial trial for this model was obtained by maintaining constant energy relative to the first spike in the windshield curve (about 30 ft-lb), but making adjustments for the effects of high-speed motion. High-speed impacts produce a much sharper rise in the force, but unlike the low-speed impact against the windshield, the film is unable to deform over large displacements and shatters or tears quickly. Hence, the spike is very narrow. Some iterations were made in the height and width of the spike (while maintaining constant energy under the spike) until the calculated acceleration history in the head provided a reasonable match with the test data (see Figure 14 below). The glass impact model also includes damping and friction between the head and the glass.

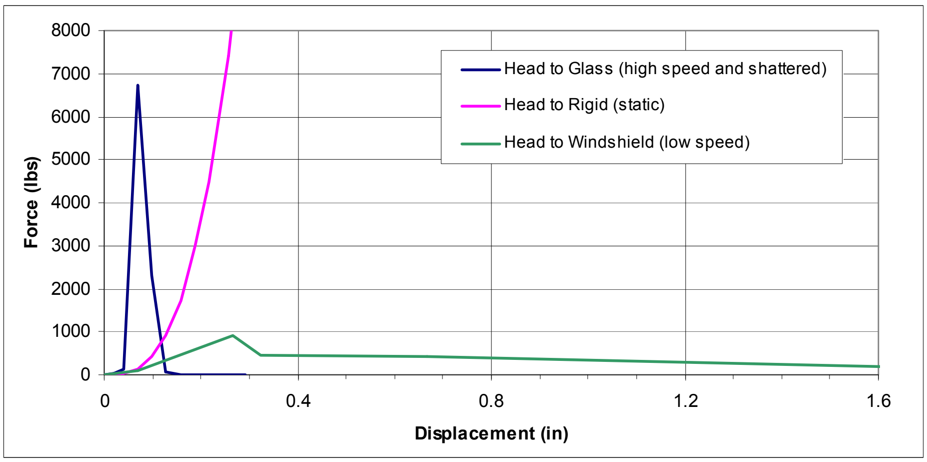


Figure 9. Force-displacement relationships for objects striking the head.

To drive the MADYMO model, a history of acceleration is needed for each object. Using the mass of the object, the code converts the acceleration to a force which is then applied, in conjunction with all the other forces due to impacts and joints, to the body. These inputs were obtained by taking pressure records measured on the exterior of the building, multiplying by the exposed or projected area of each object to obtain force, then dividing by the mass to obtain acceleration histories. For objects inside the room (such as the chair in which the ATD is seated), pressures measured inside the room were utilized in the same fashion. However, the pressures in the room were of less consequence since the primary aspect of the test was impact against the head of window glass, which is loaded by the exterior pressure.

ANALYTICAL RESULTS: ROOM 3-3

Figure 10 shows the MADYMO model used to calculate room 3-3. The model omits all the furniture and equipment that are irrelevant to the primary response of interest, and focuses instead on representing the ATD, the chair, the desk, the window, and the clock radio which lies directly between the window and the ATD.

A series of snapshots from high-speed film taken during the test is presented in Figure 11. In the initial photo, the blast has just hit the windows and the glass has begun traveling inward; the glass motion is much more evident in the second snapshot. In the final snapshot, the individual glass panes are visible having gone roughly halfway across the room. The lower glass pane has hit the ATD's head and has passed through after the splitting the anti-shatter film.

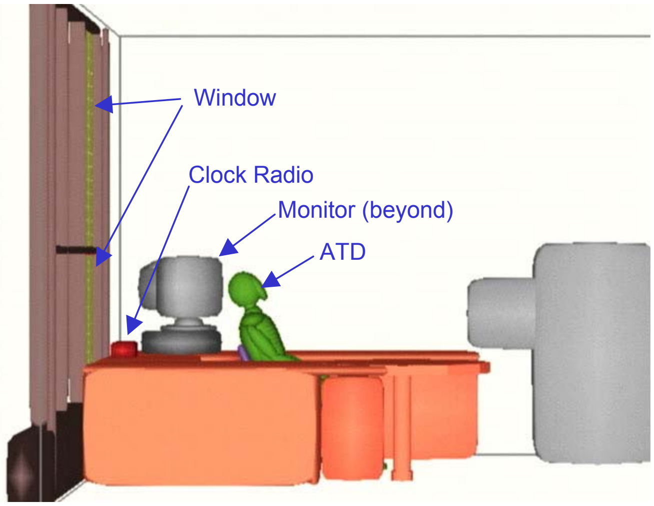


Figure 10. MADYMO model used for room 3-3.

Figure 11. Snapshots from room 3-3 test film.

Snapshots at similar times in the analytical simulation are shown in Figure 12. We see here many of the same features observable in the test film: the sweeping of the clock radio by the glass sheet as it goes by, and the glass traveling past the ATD head relatively unhindered or unaffected by the impact. We can also see the clock hitting the back of the chair, and the ATD head being snapped forward by the impact of the glass, features which are not visible in the test film due to the lack of clarity and abundance of visual obstructions.

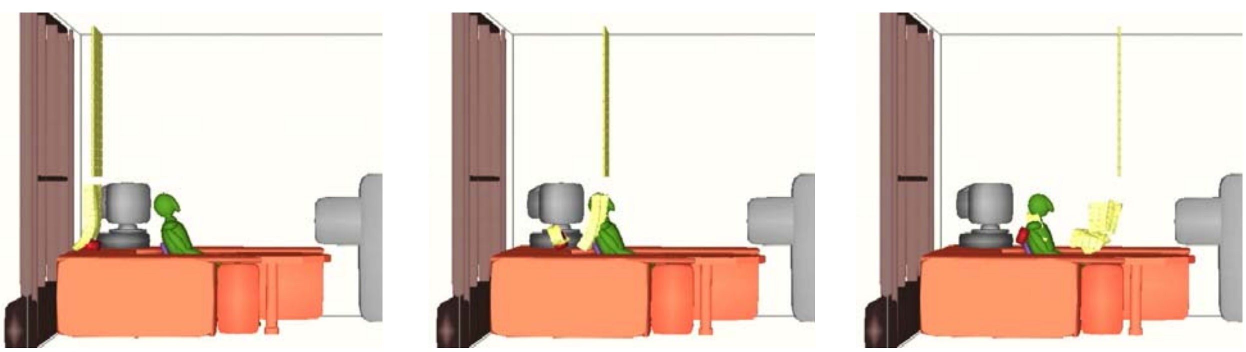


Figure 12. Snapshots from room 3-3 analysis.

Based on the comparison of these snapshots, the analysis replicates the primary features of the experimentally observed response with good fidelity. The timing of the impacts is reasonably close, and the glass velocity appears to agree well. The latter is confirmed by comparing the displacement of the glass at various times as indicated in

Figure 13. The blue data come from frame-by-frame analysis of the test films. The green points represent the input to the model which is directly taken from the pressure history measurements. The red points show the outcome of the simulation which, until the time of impact, is identical to the input; following impact, the interaction slows down the glass somewhat.

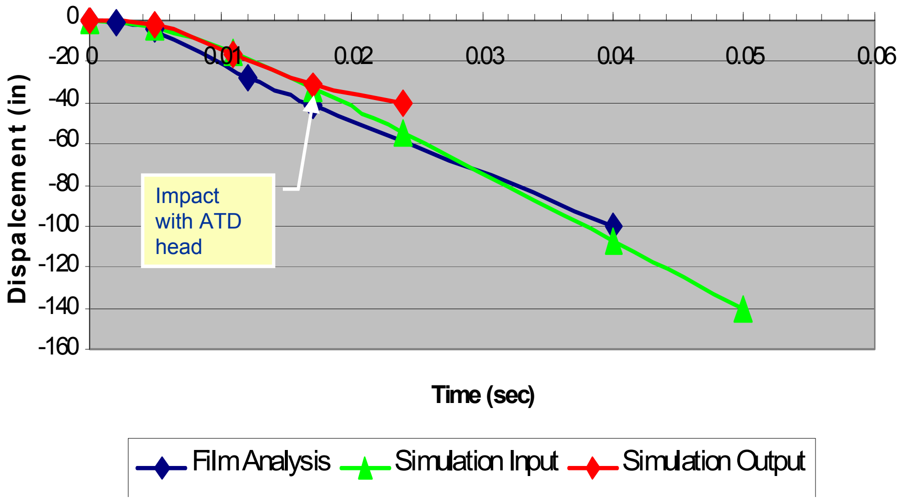


Figure 13. Comparison of glass displacement histories.

As a measure of the response of the ATD, we can also compare the measured and calculated acceleration histories, as done in Figure 14. It was with a view towards improving this comparison that the glass-head interface model (shown earlier in Figure 9) was refined. As the graph indicates, the comparison is quite good, resulting in a very similar peak value and duration for the main pulse. Note that what is plotted is the resultant acceleration which was obtained by combining all three components (x, y, and z) by taking the square root of the sum of the squares, hence the absence of any negative values.

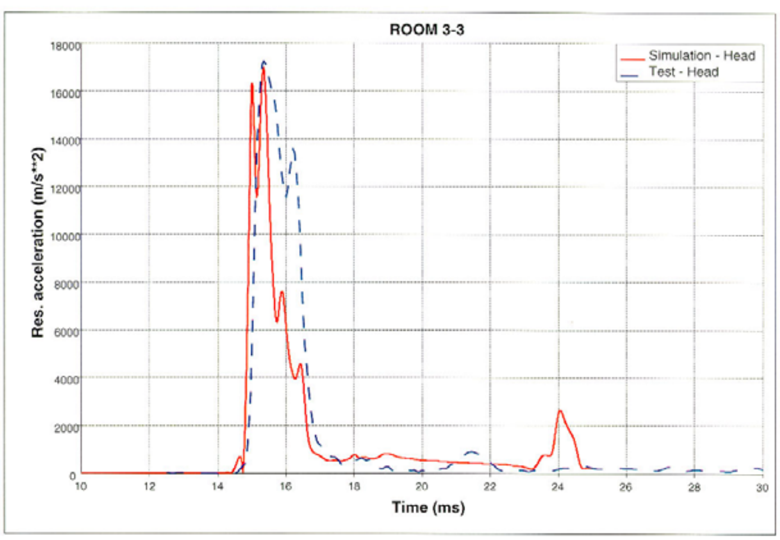


Figure 14. Comparison of ATD head acceleration histories in room 3-3.

ANALYTICAL RESULTS: ROOM 3-4

Figure 15 shows the MADYMO model used to calculate room 3-4. As with the other room, the model is limited to the key objects relevant to the calculation: the ATD, the glass, and the monitor directly behind the ATD. In this model, since the monitor was so close to the window, it was assumed that the exterior pressure load (which was applied to the window) was also acting on the monitor.

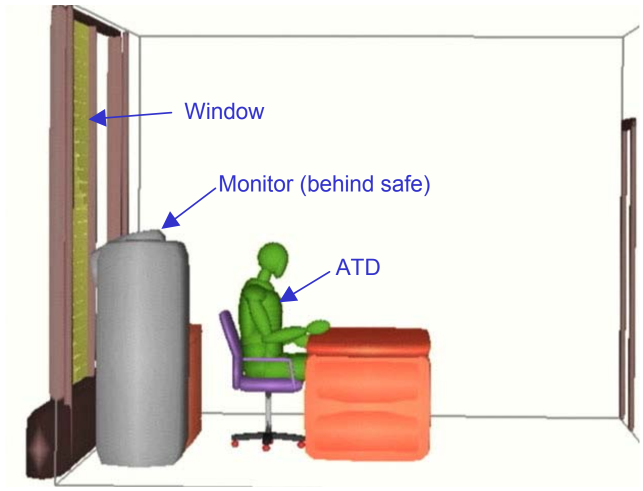


Figure 15. MADYMO model used for room 3-4.

A series of snapshots from high-speed film taken during the test is presented in Figure 16. In the first snapshot, the shielding effect of the computer monitor is evident as the window glass is propelled inward all around the monitor. By the time of the second snapshot, the glass is roughly at the plane of the ATD. In the third view, we observe that at this late time, when the glass has already reached the back of the room, the monitor is still visible atop the credenza, long after the main response of the dummy is over.

Figure 16. Snapshots from room 3-4 test film.

Snapshots at similar times in the analytical simulation are shown in Figure 17. Very little glass interacts with the ATD head, because of the monitor shielding. We observe that in the simulation the monitor strikes the dummy somewhat obliquely, partially in the shoulder and partially in the head, then rolls over and past the dummy. This occurs at much earlier times than the test film would suggest.

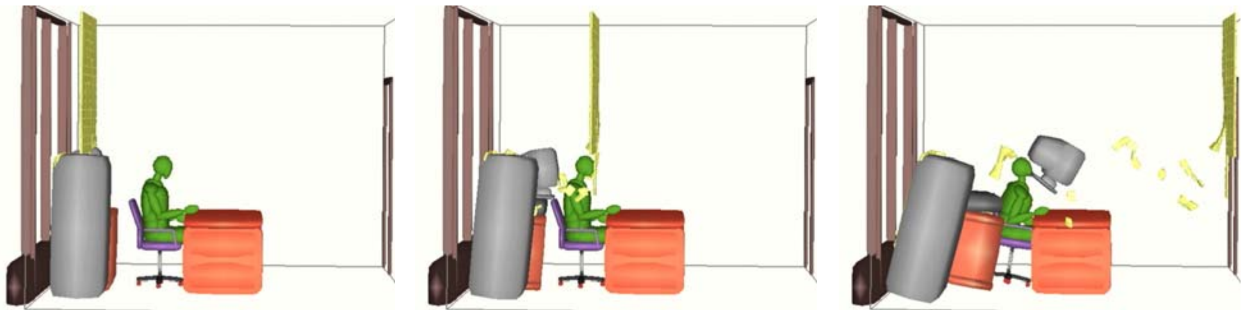


Figure 17. Snapshots from room 3-4 analysis.

When we compare the measured and calculated acceleration histories, as done in Figure 18, we observe again close correlation between measured and calculated results. The highest peak in the test record matches well with the peak of the simulation in magnitude and duration. However, in the simulation, this peak was caused by impact of the monitor against the head, while the test films indicate that this could not have occurred at such an early time. Consequently, we can only hypothesize regarding the cause of that spike in the test record. It could have been due to glass impact, in which case it needs to be compared to the first, smaller spike in the simulation. It could have been caused by other debris which is not visible in the test film. Or, it might be an anomaly of the gage and the recording apparatus but not directly reflective of any physical contact.

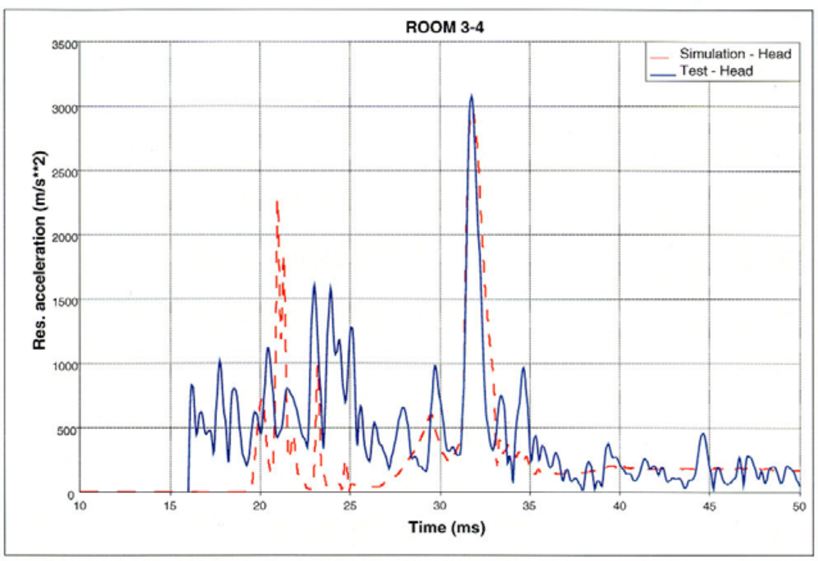


Figure 18. Comparison of ATD head acceleration histories in room 3-4.

CONCLUSIONS

Table 3 compares the calculated and measured accelerations, HIC, and AIS values for the two ATDs discussed above. The peak accelerations compare extremely well. The HIC values are also in very good agreement; the factor of two difference for room 3-3 is inconsequential as both test and analysis have values that are several orders of magnitude beyond the upper end of the HIC spectrum (refer to Table 1). Consequently, the AIS values are all in agreement. In the case of room 3-3, this comparison is valid and credible and indicates that the model is able to accurately represent the response of the glass and its interaction with the dummy. It is also able to correctly predict a fatal injury. In the case of room 3-4, the comparisons are equally close, but the physics behind the comparison appears suspect. The motion of the monitor was not properly represented in the model, and the loading assumption used to drive the monitor is suspect. In spite of its frangibility, the window may have significantly reduced the total load on the monitor by reflecting back (if even for a few microseconds) the peak incident pressure. But aside from this, the MADYMO model's ability to properly account for the interaction between a high-velocity sheet of filmed glass and a human head has been adequately validated, at least in this regime of response.

Table 3. Summary of ATD head response.

Room		Peak Resultant Accel. (g's)	HIC	AIS
3-3	Test	1,760	105,000	6
	Analysis	1,730	51,000	6
3-4	Test	313	850	3
	Analysis	302	1120	3

Future tests and further research are needed to better understand the physics that controlled the behavior in room 3-4. A better understanding of the pressure loads acting on objects in the room is essential before lethality predictions can have much reliability. Nevertheless, where the debris field with which the human occupant of an office must interact is dominated by filmed glass, MADYMO models have been demonstrated to provide reliable estimates of response and lethality.

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REFERENCES

1. Pike, J. A., 1990, "Injury Scaling," Automotive Safety, Anatomy, Injury, Testing and Regulation, Published by Society of Automotive Engineers, Inc.

2. Abbreviated Injury Scale, 1990 Revision, Association for the Advancement of Automotive Medicine, Des Moines, Iowa, 1990.

3. Backaitis, S. H., 1981, "The Head Injury Criterion," Head and Neck Injury Criteria, A Consensus Workshop, published by U.S. Department of Transportation, NHTSA.

4. MADYMO User's Manual 3D, Version 5.4, May 1999.

5. MADYMO Database Manual, Version 5.4, May 1999.