PARAMETRIC ANALYSIS OF ROLLOVER OCCUPANT PROTECTION USING A DEFORMABLE OCCUPANT COMPARTMENT TESTING DEVICE

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ABSTRACT

Occupant kinematics during rollover inverted impacts has been the subject of significant research. Controlled experiments have utilized complete vehicles, partial vehicles and seat/restraint systems attached to various platforms. The Deformable Occupant Compartment Impact Tester (DOCIT) was developed to incorporate functions similar to previous methods, but has added a roof capable of deforming under impact. These roof deformation characteristics can be reset without the destruction of a complete vehicle. The DOCIT simulates an occupant compartment (roof, seat, restraint system) in which an ATD is placed and subjected to a repeatable inverted dynamic impact environment. Several test series are reviewed, in which standard of value tests, based upon real-world rollover accidents, are compared with alternate design systems under the same impact environments. 5th and 50th percentile Hybrid III ATD's are utilized to assess neck and head injury criteria. Alternate designs for roof structures and restraint systems are tested to determine the effectiveness of each.

The DOCIT accommodates rapid parametric analysis of occupant injury criteria relative to various occupant, restraint and roof configurations in a dynamic loading environment and enables evaluation of restraint system performance and injury potential under impacts with controlled initial/residual head clearance and repeatable pre-determined roof profiles. Test variations in restraint systems or roof performance can be correlated with other component and full vehicle tests without the need for the destruction of many vehicles.

This research indicates that for reasonably restrained occupants, roof crush preceded head to roof contact and peak neck forces. Reducing roof crush also reduced neck injury measures and therefore neck injury potential. In many cases, reducing roof crush and optimizing restraint designs eliminated interaction with the roof and provided correspondingly negligible injury measures.

INTRODUCTION

In an effort to understand rollover injuries and their relationship to roof crush, many rollover occupant experiments have been conducted with a variety of surrogates, both human and ATDs. Inverted drop tests have been conducted using production and reinforced vehicles utilizing Hybrid III Anthropometric Test Devices (ATD) to examine the relationship between roof crush and neck injury potential. Several inverted drop tests with water-ballast dummies reported additional dynamic occupant excursion during impact. Smaller adjustable test fixtures have also been used to study occupant kinematics and excursion in rollovers and inverted drops.

Arndt studied the effects of belt geometry and slack in a single seat drop cage with Hybrid III ATDs in 91 cm drop tests with 5g decelerations. Herbst developed an adjustable single seat and restraint system buck, capable of being rotated about its roll axis and examined live subject occupant kinematics and excursion. Further studies with this adjustable buck documented production restraint system occupant excursions as well as the effect of alternatively designed restraint systems. Cooper analyzed occupant kinematics under angular roll rates comparable to some rollover crashes with the Head Excursion Test Device. Pywell developed a rollover fixture that was controllable, repeatable and easily modified to study occupant kinematics with various restraint types. The Rollover Restraint Tester (RRT) was developed by the National Highway Traffic Safety Administration (NHTSA) to test restraint effectiveness in rollover conditions and employed a shock tower which simulated roof to ground impacts. Friedman studied the potential for neck injury with Hybrid III dummies and live human subjects in a non-crushable production vehicle compartment dropped from heights up to 91 cm. Several studies investigated the Hybrid III 50th percentile male's response to free fall impacts in drop heights approaching 122 cm.

The Deformable Occupant Compartment Impact Tester (DOCIT) is designed to simulate an occupant compartment including a roof, seat, and restraint system (Figure 1). An ATD is placed normally in the

DOCIT seat and restraint system, which is then inverted and subjected a repeatable impact environment. The roof panel is attached to a series of vertical and lateral pneumatic cylinders, which define the motion of the roof. Adjustable stops and variable pressure relief valves on the pneumatic cylinders can control the extent and resistance to deformation. This configuration allows for controllable roof crush in lateral and vertical directions, and therefore the roof crush is repeatable and defined. The versatility of the DOCIT allows for the examination of the relationship between occupant injury potential and roof crush with a variety of vehicle configurations and occupant protection systems.

Figure 1. Typical DOCIT configuration.

METHODOLOGY

DOCIT testing is often performed as part of a thorough rollover accident analysis. A detailed accident reconstruction analysis is conducted in order to understand the kinematics of the vehicle throughout a rollover, including the various impacts along its trajectory. Structural analysis is then employed to quantify the forces and energy imparted to the vehicle's roof structure during the rollover impacts as well as the orientations of the vehicle at the time these impacts occurred. Physical testing, such as inverted drop testing or tip-over testing, can be used as part of the structural analysis to quantify impact conditions required to induce damage consistent with an accident vehicle. The vehicle impact conditions ascertained from analysis and testing can then be utilized to establish the appropriate orientation and drop height (Figure 2) for the DOCIT tests. The DOCIT ties together elements of the accident reconstruction, structural analysis and biomechanical analysis while allowing for testing of the key components that influence occupant protection in rollovers, specifically occupant survival space, occupant restraint and roof crush.

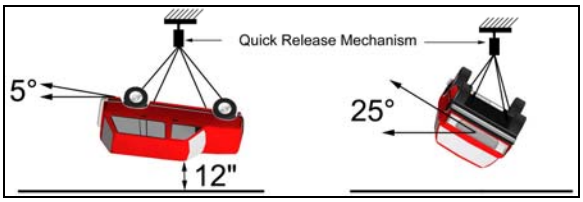

Figure 2. Typical inverted drop test configuration.

The occupant compartment geometry, including the locations of the seat, restraints and roof, can be documented with a survey tool for both the accident vehicle and an exemplar. These digitized measurements are then used as a template for the locations of the various DOCIT components. The D-ring anchor for the retractor system is attached to the roof rail of the system, and therefore would move in conjunction with the roof system when it displaced or crushed under impact, as would be the as case in a real-world rollover accident. The motion of the D-ring during roof crush has the effect of inducing slack into the restraint system and limits its ability to contain the occupant. This effect is important to understand the effects of roof crush on occupant kinematics and injury measures.

In each DOCIT test series, a baseline test is conducted to establish the test conditions under which the comparisons are to be made. The baseline test impact conditions are set based upon the reconstruction, structural and biomechanical analyses and result in injury measures, which are consistent with the occupant injuries. Once the configuration for baseline test has been established, the test device can quickly be reset between tests by righting the device, recharging the pneumatic cylinders and replacing the roof panel. Once it has been reset, a single test parameter change, such as variations in roof crush or alternate restraint system characteristic, can be made. The biomechanical effects of these parametric changes to the test setup are then easily analyzed by comparing the resulting ATD injury measures.

Hybrid III ATDs can be used as occupant surrogates, which can be tailored with spacers and ballast to more accurately represent occupants of various sizes. The ATD is instrumented to record head acceleration, upper neck forces and moments. The DOCIT fixture is instrumented to record roof crush displacement data and occupant excursion through displacement transducers, as well as lap belt loads and compartment accelerations. The ATD is placed within the DOCIT fixture seat and the restraints are normally applied. The restraint system can also be pretensioned at this point, depending on the nature of

the experiment. Pre-test head-to-roof clearance and restraint measurements are made prior to inversion. Once the ATD is in place and restrained, the DOCIT is raised from the ground via a floor lift. The fixture is inverted by a set of internal pivots and attached to a quick-release mechanism from its underside. Once the test height is set, post inversion measurements are made which indicate the static excursion of the ATD within the restraint system relative to the compartment roof and other interior components. The fixture is then released and allowed to impact the floor. High speed and real-time video document the impact. Data is collected and filtered according to SAE J211 from the ATD and test fixture at a rate of 10,000Hz.

TEST RESULTS

Four test series using this DOCIT fixture and methodology are reviewed in this paper.

TEST A Results

Test series A was based on a model year 2000 domestic SUV rollover accident in which the driver suffered a cervical neck fracture resulting in quadriplegia. The DOCIT was assembled to approximate the restraint and seating systems of this accident vehicle as well as the approximate shape and extent of roof crush experienced.

The roof panel in the DOCIT was specifically constructed to allow for the formation of a longitudinal buckle by placing two hinge points at the perimeter of the roof panel support frame (Figure 3). A piece of undeformed sheet metal was placed within this hinged frame. At impact, the downward and inward motion of the impacting corner created a longitudinal buckle over the occupant.

A Hybrid III 50th percentile ATD was used during Test series A, which had the lumbar spine replaced with a lighter and shorter assembly. This modification adjusted the Hybrid III ATD to approximate a 71 kg occupant that had a seated height of 83.8 cm and would stand approximately 162.6 cm tall. The DOCIT had a pre-impact configuration of 20 degrees of roll from inverted, 0 degrees of pitch and a drop height of 30.5 cm.

The baseline test resulted in significant interaction between the occupant and the intruding roof. The injury measures resulting from the baseline test conditions (Table 1) are consistent with the injuries to the real world occupant. In the baseline test, the ATD registered 7527 N of neck compression when it impacted the intruding roof.

Table 1.
Results from test series A

	Restraints	Roof Crush (cm)	Belt Load (N)	Nij	Neck Force Z (N)
Baseline	Production	18.7	1143	1.37	-7527
Alt. 1	Production	0.6	2334	0.14	-176
Alt. 2	Pretension	0.9	2200	0.25	-291

The neck injury criteria, Nij, used by the National Highway Safety Administration, is a linear combination of tension-compression and flexion-extension moments which are normalized by the critical limits established for each ATD type. A Nij value of greater than 1.0 is generally viewed as a critical threshold. The baseline test measures resulted

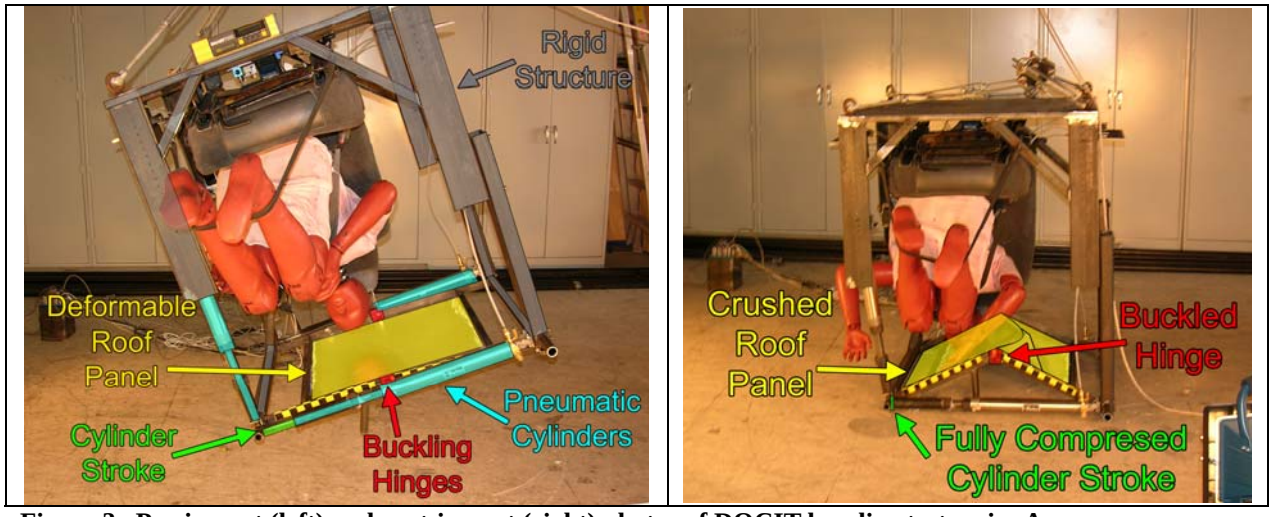

Figure 3. Pre-impact (left) and post-impact (right) photos of DOCIT baseline test series A.

in a Nij of 1.37 (based upon 50th percentile male criteria).

Two tests were conducted for comparison to this baseline test. Alternate system 1 is a parametric test comparison in which the influence of reducing roof crush is analyzed relative to the ATD injury measures. In this test, the pneumatic roof cylinders were locked out allowing only minimal dynamic flex in the roof system. Under these conditions, the occupant interaction is greatly attenuated, with the occupant only slightly touching the roof during impact. The critical neck injury measures are reduced by more than 90%, with a resultant Nij of 0.14 and a compression load of 176 N.

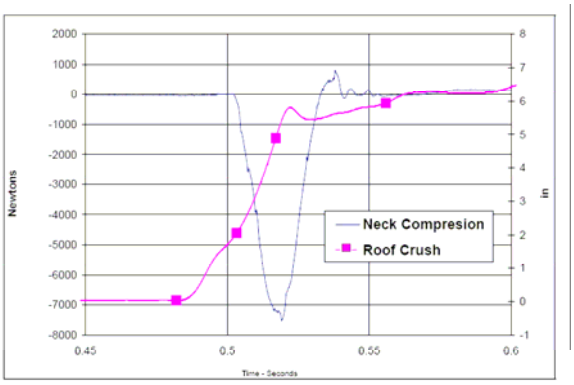

Figure 4. Roof crush vs. neck compression for baseline test series A.

A second alternate design is test in which the roof is set as in alternate design 1, but the restraints are pretensioned to 355- 375 N prior to testing. Under these circumstances, the Hybrid III ATD did not contact the roof during impact, and the resulting injury measures are below all the critical criteria. During analysis of the test data and video, it was clear that the roof crush occurred prior to the ATD's interaction with the roof and prior to the peak neck loading (Figure 4).

Both alternate systems demonstrate the potential to significantly reduced ATD injury measures and even eliminate contact. Both of these alternate systems can be compared to current production designs or designs which are technologically feasible. Pretensioners, including rollover activated pretensioners, are available in many production vehicles on the road today.

TEST B Results

Test series B involved the rollover of a 1990's small four door sedan. The injured occupant was a small female located in the driver's seat at the time of the accident, who suffered a neck fracture with resulting quadriplegia. A 5th percentile female ATD was used as the surrogate in these DOCIT tests. A 2.54 cm steel spacer was placed at the top of the lumbar spine and 11.3 kg lead ballast was attached to the ATD's legs and torso. This ATD configuration approximated a small female weighing 56.6 kg, with a seated height of 81.3 cm in. and would stand approximately 154.9 cm tall. The DOCIT had a pre-impact configuration of 20 degrees of roll from inverted, 0 degrees of pitch and a drop height of 30.5 cm.

The roof panel in the DOCIT was specifically constructed to allow for the formation of a longitudinal buckle as in Test series A. (Figure 5) The DOCIT had a pre-impact configuration of 19 degrees of roll from inverted, 0 degrees of pitch and a drop height of 45.7 cm.

Figure 5. Roof buckle formations in accident vehicle and DOCIT fixture.

The baseline test in series B, the ATD registered 5820 N of neck compression and a Nij measurement of 2.0 (based upon 5th percentile female criteria) (Table 2). Three tests were conducted for comparison to this baseline test. Alternate system 1 is a parametric test comparison in which the influence of reducing roof crush is analyzed relative to the ATD injury measures. In this test, the pneumatic roof cylinders were locked out allowing only minimal dynamic flex in the roof system. Under these conditions, the occupant interaction is greatly attenuated, with the occupant only minor contact with the roof during impact. The critical neck injury measures are reduced by approximately 85%, with a resultant Nij of 0.3 and a compression load of 839 N.

A second alternate design was tested in which the roof is set as in alternate design 1, but the restraints are pretensioned to 311 N prior to testing. Under these circumstances, the Hybrid III ATD did not contact the roof during impact, and the resulting injury measures are below all the critical criteria.

Table 2.
Results from test Series B

	Restraints	Roof Crush (cm)	Belt Load (N)	Nij	Neck Force Z (N)
Baseline	Production	19.6	891	2.0	-5820
Alt. 1	Production	4.1	3201	0.3	-839
Alt. 2	Pretension	4.7	2701	0.2	-121
Alt 3	BIS/ABTS	3.1	2596	0.12	-359

The third alternate design was tested in which the roof was set as in alternate design 1 and the seat and restraint were replaced with a production belt-in-seat or all-belts-to-seat design. Under these conditions, the occupant made light contact with the roof during impact. The critical neck injury measures are reduced by approximately 85%, with a resultant Nij of 0.12 and a compression load of 359 N. As in the previous test series, it was clear that the roof crush occurred prior to the ATD's interaction with the roof and prior to the peak neck loading (Figure 6).

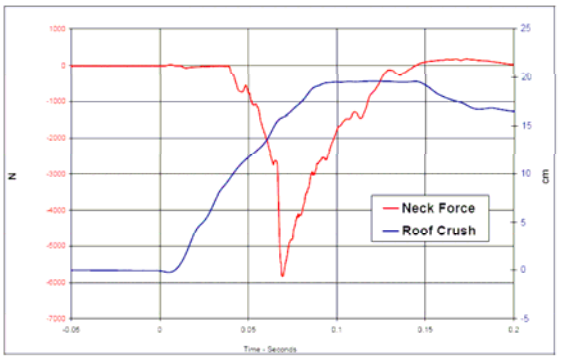

Figure 6- Roof Crush vs. Neck Compression for Baseline Test Series B

TEST C Results

Test C tests examine the injury potential of a Hybrid III 5th Female ATD restrained in the DOCIT configured to approximate the driver's seat location of a 1992 sedan in a 30.5 cm drop. The DOCIT fixture had no roll or pitch angles and the roof crush was allowed to intrude uniformly in the vertical direction. The roof was decelerated by crushable foam blocks rather than the pneumatic valves of Tests A and B. Reductions in roof crush and pretensioned production restraints are separately assessed to identify their ability to reduce injury potential.

Table 3.
Results from test Series C

	Restraints	Roof Crush (cm)	Belt Load (N)	Nij	Neck Force Z (N)
Baseline	Production	15.8	1152	1.77	-6260
Alt. 1	Production	2.3	2242	0.25	-876
Alt. 2	Pretension	15.8	1027	1.19	-4263

The 30.5 cm inverted drop resulted in 15.7 cm of roof crush and 5.9 cm of occupant excursion. With only 7.5 cm of pre-impact headroom, the extent of roof crush and occupant excursion resulted in an occupant impact with the roof. The baseline test had neck injury measures of 6260 N of neck compression and a Nij of 1.77. Alternate test 1 had the same test parameters as the baseline test except for a reduction in roof crush from 15.8 cm to 2.3 cm. This roof crush reduction lowered peak neck compression by 86% to 876 N and lowered Nij 86 % to 0.25. Alternate test 2 had the same test parameters as Test 1 except that the belt was pretensioned to 356 N prior to static inversion. The pre-impact headroom was increased to 17.1 cm and dynamic occupant excursion was reduced to 1 cm. This lowered peak neck compression 32% to 4262 N and lowered Nij 32% to 1.19, when compared to the baseline test.

TEST D Results

Test C tests examine the injury potential of a Hybrid III 50th Male ATD restrained in the DOCIT configured to approximate the driver's seat location of a 2003 pickup in a 30.5 cm drop. A 2.54 cm steel spacer was placed above the ATD's lumbar spine to bring the overall seated height up to 91 cm. The DOCIT fixture had 10 degrees of roll and no pitch angles. The roof crush was allowed crush vertically and laterally in a planar manner without any roof buckles. The roof was controlled by pneumatic cylinders as in Tests A and B. Reductions in occupant excursion through restraint improvements are assessed to identify its ability to reduce injury potential.

Table 4.
Results from test Series D

	Restraints	Roof Crush (cm)	Belt Load (N)	Nij	Neck Force Z (N)
Baseline	Production	8.6	1287	1.46	-8368
Alt. 1	Pretension ABTS	7.7	4092	0.16	+676

The 30.5 cm inverted drop resulted in 8.6 cm of roof crush and 10.2 cm of occupant excursion. With only 2.0 cm of pre-impact headroom, the extent of roof crush and occupant excursion resulted in an occupant impact with the roof. The baseline test had neck injury measures of 8368 N of neck compression and a Nij of 1.46. Alternate test 1 had the same test parameters as the baseline test except for the seat was replaced with an ABTS (all belts to seat or integrated seat belt) with the belts pretensioned to 280 N. This improved restraint performance resulted in pre-impact headroom increasing to 13.3 cm and dynamic occupant excursion was reduced to 2.7 cm. The ATD did not contact the roof at all during impact, thereby eliminating any neck compression due to head to roof contact.

DISCUSSION

The DOCIT fixture allows for rapid parametric analyses of various occupant, restraint and roof systems. The test variations in restraint systems or roof performance can be correlated with other component or full vehicle tests without the need for the complete destruction of many vehicles to achieve the same result.

In the four test series performed, the following conclusions were drawn:

- Roof crush preceded head to roof contact as well as peak neck forces.
- Reducing roof crush correspondingly reduced neck injury measures and therefore neck injury potential.
- In many cases, reducing roof crush and pre-tensioning restraints or ABTS to a reasonable level eliminated interaction with the roof and with correspondingly negligible injury measures.
- Feasible roof and restraint design alternatives can significantly reduce the likelihood of neck injury in inverted impacts such as rollovers.

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