

Dynamic Response of Vehicle Roof Structure and ATD Neck Loading During Dolly Rollover Tests

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ABSTRACT

The debate surrounding roof deformation and occupant injury potential has existed in the automotive community for over 30 years. In analysis of real-world rollovers, assessment of roof deformation and occupant compartment space starts with the post-accident roof position. Dynamic movement of the roof structure during a rollover sequence is generally acknowledged but quantification of the dynamic roof displacement has been limited. Previous assessment of dynamic roof deformation has been generally limited to review of the video footage from staged rollover events.

Rollover testing for the evaluation of injury potential has typically been studied utilizing instrumented test dummies, on-board and off-board cameras, and measurements of residual crush. This study introduces an analysis of previously undocumented real-time data to be considered in the evaluation of the roof structure's dynamic behavior during a rollover event. A series of dolly rollover tests (Forester Test Series) were conducted on both concrete and compacted dirt surfaces. The test vehicles, 2003 Subaru Foresters, had a roof strength-to-weight ratio (SWR) of 4.8 (Summers, 2005), among the highest of all vehicles NHTSA has tested to date. The vehicles were instrumented with accelerometers and angular rate sensors to measure the vehicle kinematics and dynamics. The vehicles were also instrumented at the A- and B-pillars with strain gages, accelerometers, and string potentiometers to document the dynamic loading and motion of the pillars at the roof rail junctions. High-speed and real-time video cameras visually documented vehicle motions and roof deformation. The third test in the Forester Test Series, conducted on a dirt surface, included Anthropomorphic Test Devices (ATDs) in the front seating positions to assess the interactions of the ATDs within the occupant space. This paper presents innovative techniques and data analysis that include the dynamic measurement of roof displacement,

acceleration, and strain using polar plots and video synchronized with data.

INTRODUCTION

Passenger vehicle rollover dynamics are known to be chaotic, with dependence on changing external forces throughout the rollover event. Engineering analysis of rollover events is generally based on information collected after the event, including vehicle evidence such as abrasion patterns and residual deformation as well as scene evidence such as tire impacts, pavement and soil gouges, and artifacts such as glass deposit patterns. A reconstruction analysis can provide a detailed understanding of the motion of the vehicle and, possibly, some insight into the order and relative magnitudes of the roof-to-ground impacts. Unfortunately, information regarding the extent of roof structure deformation is typically restricted to measurement of the post-accident roof position.

Assessment of the roof structural deformation history based only on the evaluation of post-accident residual damage gives an incomplete picture of the structural performance of the vehicle and its effect on occupant injury potential. Using a series of dolly rollover tests, this study provides insight into the nature of roof structure performance in the rollover environment; also, data is presented so the reader may develop a better understanding of the relationship between post-accident deformation patterns and the dynamic response of the roof structure. The tests were conducted using an FMVSS 208 (U.S. Department of Transportation 571.208, 2006) dolly with the vehicle oriented with an initial roll angle at 23 degrees. The FMVSS 208 dolly, also defined by SAE J2114, is currently the most commonly used dynamic rollover test device. It is a suitable method for inducing the initial conditions of a lateral rollover, and it provides a controllable translational speed, angular orientation, and vehicle height at launch from the dolly.

Inherent to the chaotic nature of rollovers is the difficulty in predicting the conversion of a vehicle's initial kinetic energy into its various forms. At the beginning of a rollover event, a vehicle possesses primarily translational kinetic energy with minimal amounts of potential energy and rotational kinetic energy. Throughout the rollover sequence, that energy is exchanged back-and-forth between its various forms and is eventually dissipated through damage to the vehicle and its surroundings, movement and compaction of soil, and frictional losses. Some of these energy conversions may be associated with elastic and/or plastic deformation of the roof structure that results in varying deformation patterns after each ground contact.

Orlowski et al. (1985) determined from film analysis of a series of dolly rollover tests on concrete that about half of the kinetic energy of a rolling vehicle is dissipated through ground contacts by the tires/wheels and suspensions, and the remaining energy through ground contacts by the body sheet metal. Orlowski's work further quantified that 20-25% of the overall kinetic energy dissipation was due to roof-to-ground contacts and deformation of the roof structure. Other researchers have studied vehicle kinematics and energy interchange (Cooperrider et al., 1990). More recently, Carter et al. (2008) used video analysis from two dolly rollover tests to determine the translational kinetic energy, and onboard roll rate measurements to determine rotational kinetic energy. Carter's work focused on the general trends seen in the system energy and not on the mechanisms that dissipate that energy.

This research focuses on the evaluation of the dynamic motion of the roof structure for a high strength-to-weight ratio (SWR) sport utility vehicle. The study documents the impacts and resulting roof deformation during a series of dolly rollover events with similar initial conditions. Acceleration and strain measurements of the roof structure were collected, allowing the assessment of force propagation and stress throughout the roof structure assembly. On-board video cameras provided close-up views of the roof structure deformation. Rate measurements, center-of-gravity (CG) accelerations and off-board video were recorded and used to correlate on-board measurements to vehicle orientation during ground contacts.

This research details and evaluates the primary mechanisms of energy absorption and dissipation for a passenger vehicle subjected to rollover conditions on dirt and concrete. A unique contribution of this work is that the vehicles were instrumented to fully record vehicle dynamics and deformation time histories throughout each rollover test. The current study further builds upon the existing body of work by documenting the roof response measured during a rollover; 3-D deformation of the A-pillars, 2-D deformation of the B-pillars, and load distribution of the roof pillars through the rollover. In addition, high-speed video was

recorded to associate on-board measurements to the external forces that influence vehicle dynamics and ultimately dissipate the energy of the rollover event.

The third Forester test analyzed the ATD dynamics and its relationship with vehicle kinematics and ground impacts. Previous studies in the literature have addressed the role of roof-to-ground impacts with roof structure deformation and its relation to occupant injury causation. Because cervical neck fractures are a severe injury potentially found in rollover accidents, the focus on the ATDs in the third test has been to understand that injury mechanism. Studies conducted by General Motors using dolly rollover testing and inverted drop tests known as "Malibu" concluded that compressive neck loading was not caused by roof crush, but by the occupant's head and torso moving toward the roof panel, which was stopped against the ground, thereby generating the compressive neck load (Orlowski et al., 1985 and Bahling et al., 1990). The Malibu test series further concluded that the peak neck loads occur prior to significant roof deformation. Another test series known as the "Crown Victoria Research Project" (CVRP) used the Controlled Rollover Impact System (CRIS) to study the origin of compressive neck loads in matched-pair rollover events where roof strength was the only control variable (Moffat et al., 2003). The CVRP study also concluded that peak compressive neck loads were the result of the roof striking the ground, stopping the occupant's head, while the torso continued to move toward the stopped roof, which resulted in compressive neck loads. Similar to the Malibu study, this research concluded that the neck loads were not a result of roof structure deformation. In 2009 the results from additional tests using the CRIS machine demonstrated the timing of head and neck loading as a result of ATD head contact with a vehicle roof during a far-side ground contact (Raddin et al., 2009). The findings of that study were consistent with the conclusions that roof-to-ground contacts during rollovers produce neck injury due to continued torso motion toward a vertically stopped head.

FORESTER ROLLOVER TEST SERIES - OVERVIEW

The 2003 Subaru Forester was selected for this test series because it represented a sport utility vehicle typical of passenger cars found on American roadways. The Forester's aspect ratio (height divided by width) of 1.06 is consistent with the sport utility vehicle (SUV) class. The Forester also has a relatively high roof SWR of 4.8, providing an opportunity to evaluate the influence of roof strength on dynamic headroom during a rollover event. A SWR of 4.8 is higher than the majority of current vehicles on the road, and above the updated FMVSS 216 required SWR of 3.0 for vehicles with GVWR of 6,000 lbs or less.

The Forester Test Series was conducted with a FMVSS 208 dolly rollover fixture that was decelerated from a speed of



approximately 44 mph (71 kph). The test speed was selected based on previous rollover research tests and because it is considered to be representative of overturn speeds of vehicle rollovers that have been investigated by the authors. Each Forester was placed on the dolly with the passenger side leading. Each of the three tests utilized a production 2003 Subaru Forester ballasted to 3,545 lbs (1,609 kg), the curb weight plus two 170 lb (77.2 kg) occupants.

One objective of this study was to assess the effect of terrain interaction on the nature of a rollover event and the resulting roof structure deformation. Therefore, the first two rollover tests (Test #1 and Test #2) were conducted on different rollover surfaces and without ATDs. Test #1 was performed on a 6 inch (15 cm) compacted dirt surface, and Test #2 was performed on a concrete surface. Test #3 was conducted on compacted dirt similar to Test #1, but included instrumented ATDs in the front outboard seating positions.

The vehicles in the first two tests (without ATDs) were instrumented with accelerometers on the roof rails, a pair of triaxial accelerometers and a pair of triaxial angular rate sensors near the vehicle CG, three string potentiometers at the top of each A-pillar junction, two string potentiometers at the top of each B-pillar junction, and sixteen strain gages on roof structure components. The Test #3 Forester did not utilize A-pillar string potentiometers because of the inclusion of ATDs and the potential for string interference during the test. Instead, videogrammetry was used to determine A-pillar displacements. There were no strain gages used in Test #3.

The vehicle roof exterior and interior surfaces were mapped three-dimensionally using ArcSecond's Vulcan System, a laser metrology tool, before and after the tests to define the residual deformations. Orthogonal deformation of the greenhouse at the top of the A- and B-pillars was calculated through coordinate transformation of the real-time string potentiometer data. The deformation data was then synchronized with the test video footage to study the overall roof deformation and timing. Film analysis and roll path evidence mapping was also used in conjunction with onboard vehicle data collection to identify and confirm the complex vehicle motions, deformation characteristics, timing and energy loss with each impact between the vehicle and the ground. Results were compared and contrasted between the three tests.

FORESTER TEST SERIES - VEHICLE SETUP

The test vehicles were drained of all fluids and most of the interior trim was removed. For the first two tests, the front seats were removed to allow installation of instrumentation platforms. The third test included production front seats and restraint systems to position and secure the ATDs. These restraint systems utilized a continuous webbing, single

retractor, three-point belt system with a sliding latch plate and seat-mounted end-release buckle. The retractor incorporated a ball-and-cup style dual-sensitive locking system, an internal torsion-bar energy management feature on the spool, and an electrically-activated pyrotechnic pretensioner. The vehicles were painted flat gray to reduce glare in camera views and to enhance visibility of ground contact abrasion patterns. The vehicle electrical system was not enabled, thus the frontal airbags were disabled for the testing. The Foresters were not equipped with any roll-initiated rollover protection systems so the pretensioner was not deployed.

The vehicle motion during each rollover test was recorded by two high-speed panning cameras, two real-time panning cameras, one elevated high-speed video camera and seven ground-based high-speed video cameras. Six of the ground-based high-speed cameras were positioned with overlapping views of the rollout area; these views were normal to the Forester's initial direction of travel, with three on each side of the roll path at 50-foot (15 m) intervals. In addition, continuous-mode still-camera photographs were taken of each rollover event from various angles. Two high-speed video cameras were also positioned in the rear cargo area of each Forester to record the dynamic deformation of the roof structure. The Forester in Test 3 included four additional cameras positioned along the vehicle centerline, with two mounted between the front seats and two mounted above the instrument panel, to provide additional views of the front roof structure and the dynamic motion of the belted ATDs.

Rigid platforms were installed in each vehicle for the purpose of mounting instrumentation and photographic equipment. A small platform for mounting two triaxial angular rate sensors and two triaxial accelerometer sets was installed near the CG in each test vehicle. The Foresters in Test #1 and #2 also contained a larger platform that was constructed in the front seating area for the purpose of mounting string potentiometers and ballast ([Figure 1](#)). For these vehicles, three string potentiometers were positioned to measure the 3-D movement of each A-pillar roof junction, and two string potentiometers were positioned to measure the 2-D movement of each B-pillar roof junction in the vehicle's vertical plane. The measurement location of each potentiometer was at the top of the roof pillar junctions near the roof rail accelerometer sets.

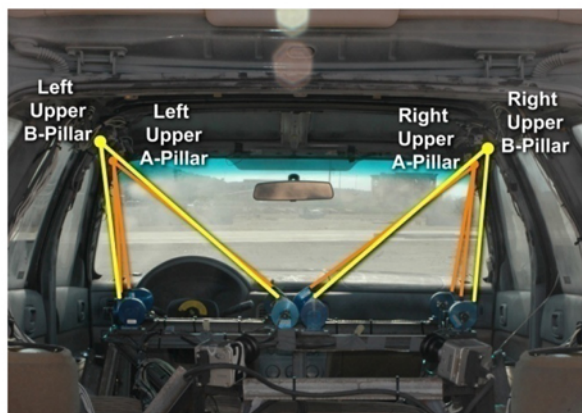


Figure 1. String potentiometer instrumentation installed in Forester Test #1 and #2 to measure dynamic pillar displacements.

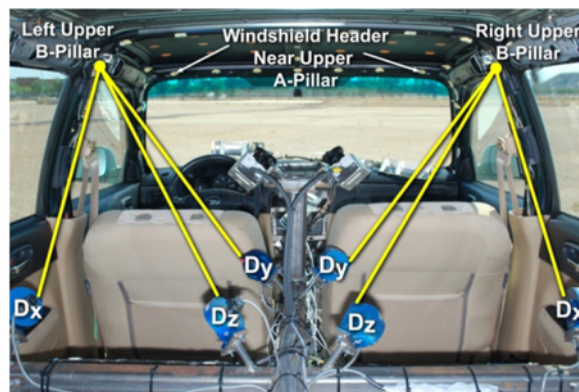


Figure 2. String potentiometer instrumentation and targets on the roof above the front seats in Forester Test #3 to measure dynamic pillar displacements.

Due to geometric constraints within the occupant compartment and the expected dynamic movement of the roof structure, the string potentiometers measuring the A- and B-pillar displacements were not mounted orthogonally in the vehicle-based coordinate system. They were installed to maximize the separation between the transducers and the measurement locations. The orthogonal displacements of the endpoints in the body-fixed coordinate system were calculated post-test using an algorithm that solved for the intersections of the strings at each pillar junction for each point in the time history. The pre-test and post-test endpoints of the string potentiometers were surveyed and served as the beginning and ending boundary conditions within the algorithm.

In Test #3, the larger platform was replaced with a structure that extended from the dashboard to the rear cargo area along the vehicle centerline (Figure 2). A second platform was also installed in the rear of that vehicle for the purpose of mounting cameras. String potentiometers were not used to measure the displacement of the A-pillar junctions during the third test due to the potential for ATD interference with the string potentiometers. In lieu of string potentiometer measurements, three-dimensional video analysis was performed with *EOS Systems PhotoModeler* using the onboard high-speed cameras and a matrix of painted markers on the interior of the roof structure.

Hybrid III 50th percentile male ATDs with pedestrian pelvises were used in Test #3; they were positioned in the front seats and restrained with new service replacement three-point seat belts. Each ATD was instrumented with a triaxial head accelerometer, a six-axis upper neck load cell and a six-axis lower neck load cell. The vehicles were resting on the test dolly at a 23-degree roll angle and the seat belt retractors were locked prior to the beginning of each test due to the initial roll angle. Load cells were installed on the torso belt webbing and lap belt webbing for both seating positions.

To study the dynamic loading of the roof structure with respect to the vehicle CG, a triaxial accelerometer set was mounted at each A-pillar roof junction, and a biaxial accelerometer set (vertical plane) was mounted at each B-pillar roof junction. Temporal loading and the stress state of the pillars and front header, as well as the load paths throughout the roof structure, was analyzed using sixteen uniaxial strain gages (Micro-Measurements Group CEA-06-250UW-350) applied to the interior roof structure. Four gages were mounted to the windshield header, two gages were mounted to each A- and B-pillar, and one gage was mounted to each C- and D-pillar.

All data was acquired at 10 kHz and filtered in accordance with the SAE J211 standard. Data from the ATDs, the roof-mounted accelerometers, and the strain gages were anti-alias filtered at 2,500 Hz to retain the high-frequency content of interest. All other channels were anti-alias filtered at 500 Hz. The measured acceleration and rate data was post-processed to transform the body-fixed acceleration to the global reference frame. With this data, vehicle energy was calculated and plotted as a function of both time and roll revolution.

The curb weight of each test vehicle was approximately 3,205 lbs (1,455 kg). Once the ATDs, instrumentation, and photographic equipment were installed, the test vehicles were

ballasted to a target weight of 3,545 lbs (1,609 kg), representing the received curb weight plus two 170 lb (77.2 kg) occupants. The front and rear axle weight distribution of all tested vehicles remained within 1% of the curb weight distribution. The CG of the unloaded vehicle was measured to be on the longitudinal centerline and 44 inches (112 cm) aft of the front axle and the CG height was calculated to be 22 inches (56 cm) above the ground.

Each test vehicle was placed in a passenger-side leading configuration on an FMVSS 208 rollover dolly as shown in [Figure 3](#). Per the FMVSS 208 test protocol and SAE J2114 recommended practice, the dolly was oriented on the crash rail such that the Forester's longitudinal axis was perpendicular to its velocity vector at the point of release from the dolly. The vehicle was placed on the inclined dolly at a roll angle of 23 degrees measured from horizontal. The vehicles' passenger side tires rested against a 4-inch-tall (10 cm) steel edge that was attached to the dolly platform. For each test, the height of the dolly was adjusted so that the contact surface of the Forester's passenger-side tires was located 9 inches (23 cm) above the rollout surface. The rollover dolly with test vehicle was accelerated to a target speed of 44 mph (71 kph). The dolly struck honeycomb-filled snubber tubes, which decelerated the dolly, but allowed the vehicle to translate and roll onto the test surface.



Figure 3. Subaru Forester on Exponent's FMVSS 208 dolly.

For both dirt tests, the rollout area was prepared by spreading desert soil over a concrete pad. The soil was wheel-compacted to a depth of 6 inches (15 cm), and it was lightly watered to reduce dust. The moisture content of the soil for the first test was measured to be approximately 10 percent. For Test 3, moisture content was not measured, but the soil was conditioned in the same manner and was visibly and tangibly similar. The rollover surface for the second test was the concrete pad surrounding the crash rail, which was a flush-mounted 6-inch (15 cm) wide steel rail with a 6-inch (15 cm) opening on each side. The openings were filled with steel-framed and concrete-filled inserts for the first 100 feet (30.5 m) of the rollout path. The test vehicles and rollout area

were documented with still photographs before and after each test. Additionally, the Vulcan System was used to survey pre- and post-test vehicle geometry, pre- and post-test onboard instrumentation locations, and the post-test debris fields.

FORESTER TEST # 1 - DIRT SURFACE

The first test involved an instrumented Forester rolling passenger side leading on compacted dirt with an initial speed of 44.2 mph (71.1 kph). The Forester's first contact with the ground was with its passenger side tires. The contact resulted in external frictional contact forces on the vehicle that caused a decrease in the translational speed and a moment that increased the vehicle's roll rate. The measured roll rate after the first vehicle-to-ground interaction was in excess of 600 deg/s. The vehicle rolled 5-½ revolutions (22 quarter-turns) over a distance of approximately 129 feet (39.3 m) in approximately 5.7 seconds. The average deceleration of the vehicle from the dolly to rest was calculated to be 0.51 g, which is consistent with the average deceleration of a rolling vehicle found in the rollover reconstruction literature. [Appendix A](#) contains a general description the vehicle motion (focusing on the ground contacts), timing of glazing fracture, and a diagram of the rollout area ([Figure 41](#)) indicating the approximate longitudinal start location for each individual roll and the post-rollover artifacts found in the rollout area.

Composite videos have been generated that include the panning high-speed video and onboard high-speed video synchronized with the instrumentation data that was collected during the rollover tests. An example of the composite video is presented in [Figure 4](#), which includes a panning high-speed view (top left), onboard left and right views (top center and right), CG Y-Z resultant acceleration as a function of roll number (middle), and time, acceleration, roll number, and roll rate displayed at the bottom. The video frame capture in [Figure 4](#) depicts the driver (far-side) roof-rail and A-pillar in contact with the ground at 1.208 seconds and the calculated CG resultant acceleration in the vertical plane of 14.9 g. The frame capture also depicts that the Forester was rolled to the 1.60 roll position with a roll rate of 554 deg/s. This roof-to-ground impact was predominantly in the vertical direction, and as seen in a composite video of the right and left A-pillar ([Figure 5](#)) resulted in the instantaneous displacement at the top of the left A-pillar [8.8" (22 cm) Inboard, 6.9" (18 cm) Down] and at the top of the right A-pillar [2.8" (7.1 cm) Outboard, 0.0" Down]. While the displacement at this roll position corresponded to the maximum A-pillar resultant deformation during the rollover, it was not representative of the residual state of the roof structure at rest.

<[figure 4](#), [5](#) here>

Further analysis of the acceleration data and synchronized video indicates that the vehicle sustained five substantial

impacts to the roof structure: four to the front roof structure that resulted in measureable displacement of the roof and one to the rear roof structure. The Y-Z resultant acceleration in the global reference frame was plotted as a function of roll revolution is shown in [Figure 6](#). Plotting the acceleration against the roll number allows easy identification of the vehicle orientation during ground contact. Four impacts were highlighted in the plot to illustrate the impacts to the front roof structure, which resulted in the dynamic deformation to the roof structure measured by the string potentiometers and observed by the onboard high-speed video cameras. In [Figure 6](#), the accelerations that are adjacent to whole revolutions (i.e. at the start of roll 5 and 6) indicate upright impacts and are associated with body/suspension-to-ground impacts. Accelerations near half revolutions (i.e. 3/8, 1-5/8, 3-3/8, and 5-3/8) correspond to roof-to-ground interaction. During roll 3, the vehicle was pitched nose-up and the front of the roof completely missed the ground, yet the rear of the roof (near side D-pillar) made ground contact. The acceleration levels during roll 3 were relatively small as compared to the roof-to-ground or body-to-ground impacts. If the short duration acceleration spikes measured during the front roof impacts are disregarded, acceleration levels range between approximately 6-8 g's for these four roof-to-ground impacts (blue shaded regions). The durations of these acceleration pulses, as identified in [Figure 6](#), ranged from 126 to 209 ms. By summing the durations of the four distinct frontal roof impacts and dividing by the overall duration of the rollover event, as defined by when the roll rate approached zero, the 4 roof impacts account for 11% of the 5.7 s rollover duration.

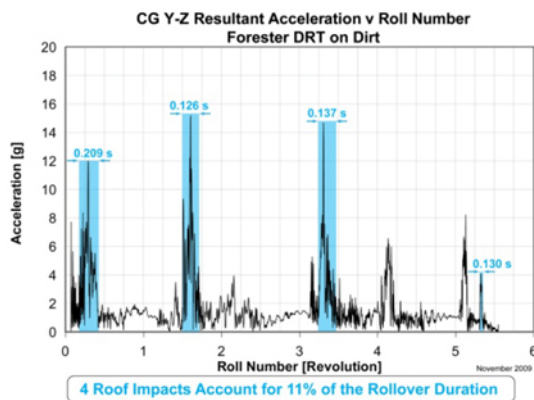


Figure 6. Global CG Y-Z resultant vehicle acceleration during the test on dirt without ATDs.

The pillar displacements of the driver and passenger upper A-pillar junctions were processed and plotted in the body-fixed coordinate system. The passenger (near) side A-pillar displacement is depicted in [Figure 7](#) and the driver (far) side A-pillar displacement is shown in [Figure 8](#). Analysis of the synchronized video and data indicates that during the first roll, while the near side roof (passenger) is being displaced inboard and downward due to contact with the ground, the far

side (driver) roof is being displaced outboard and upward. This can be observed in [Figure 7](#) and [Figure 8](#) by examining the trace from the origin [0",0"] to the end of the first roll, which is designated by the red colored dot. During the first roll, the right side A-pillar was dynamically displaced inboard (left) over 4 inches (10 cm) and downward just under 2 inches (5 cm) during ground contact. Simultaneously, while not in contact with the ground, the left side A-pillar was dynamically displaced outboard 3.5 inches (8.9 cm) and upward approximately 0.5 inches (1.3 cm). The driver (far) side roof structure is being displaced as a result of the load that is transferred through the integrated roof assembly. Two primary observations were made regarding the roof structure during the first roll: 1) the residual deformation was approximately half of the dynamic displacement and 2) the laterally directed load into the roof structure resulted in greater elastic recovery. As seen in [Figure 6](#), the roof contact initiated at the 1/4 roll position and was complete before the 1/2 roll position. The loading orientation during this ground contact directly influenced the nature of the residual deformation at the end of the roll. In the first roll, there was approximately a 50% recovery of the deformation from the first roof-to-ground impact, which was a result of the load being oriented in a mostly lateral direction.

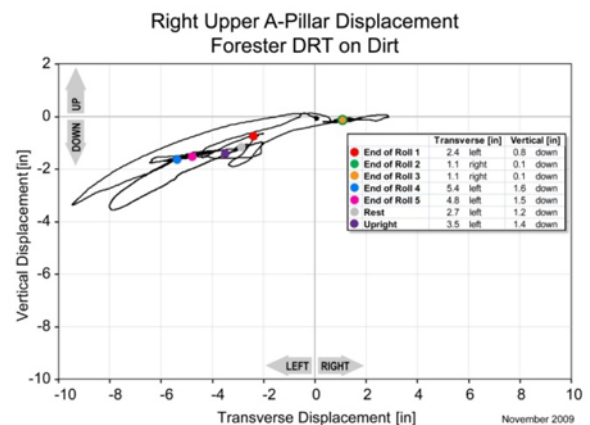


Figure 7. Displacement at the top of the passenger A-pillar during the test on dirt without ATDs.

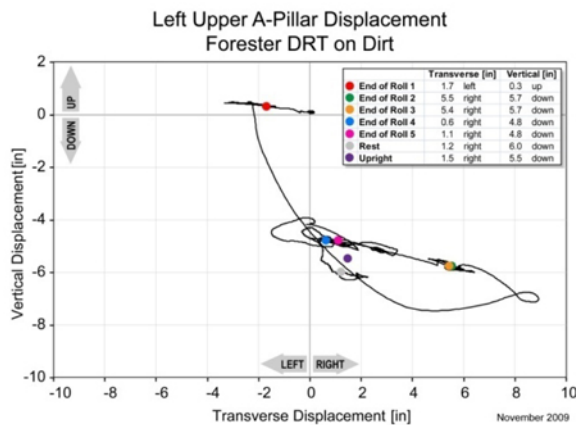


Figure 8. Displacement at the top of the driver A-pillar during the test on dirt without ATDs.

Based on the acceleration profile as a function of roll number, it was expected that there would be displacement during rolls 2 and 4, but not during roll 3. Figure 8 shows that the left A-pillar moved to the right and down during roll 2, ending at the green dot [5.5" (14 cm) Inboard, 5.7" (14 cm) Down]. The orange dot represents the residual displacement of the A-pillar at the end of roll 3, which lies directly on top of the green dot, consistent with the absence of a distinct application of forces to the roof during roll 3. The vehicle orientation during inverted contact for roll 2 was between the 1-1/2 roll to 1-5/8 roll positions, and the deformation measured on the left side A-pillar (far-side impact) was more vertical. Since the impact in roll 2 was an inverted and far-side roof-to-ground impact it is not surprising that the deformation was more vertically oriented. In contrast, the roof-to-ground contact during roll 4 preceded the 3-1/2 roll position, and correspondingly, the displacement data indicated that the additional deformation at the end of roll 4 was more lateral than vertical (see Figure 7 and Figure 8). The instantaneous dynamic data of roof displacement demonstrates the influence that vehicle orientation at impact has on the direction of deformation.

Figure 7 and Figure 8 also demonstrate that the residual deformation of the roof was not representative of progressive damage (a monotonically increasing damage pattern), but rather an incremental accumulation of multi-directional deformations. The dynamic response and subsequent residual displacement of the roof structure was a result of its reaction to impact forces as these forces were distributed throughout the roof assembly. The roof damage in this multi-roll event was the cumulative displacement resulting from multiple roof-to-ground interactions, and its final residual displacement was not representative of the extent of dynamic motion of the roof. For instance, if only the final residual deformation to the left upper A-pillar were considered, the conclusion might be drawn that the A-pillar was displaced mostly vertical with little or no lateral motion. However,

Figure 5 and Figure 8 show that the left upper A-pillar dynamic motion was 8.8" (3.5 cm) in the lateral direction and about 7.5" (3.0 cm) in the vertical direction.

To further evaluate the distribution of the load throughout the roof structure, various portions of the greenhouse were instrumented with uniaxial strain gages. As shown in Figure 9, two strain gages were located on the driver A-pillar; the upper gage was 9.4 inches (24 cm) from the accelerometer block at the A-pillar junction, and the lower gage was 5.8 inches (15 cm) from the upper gage.

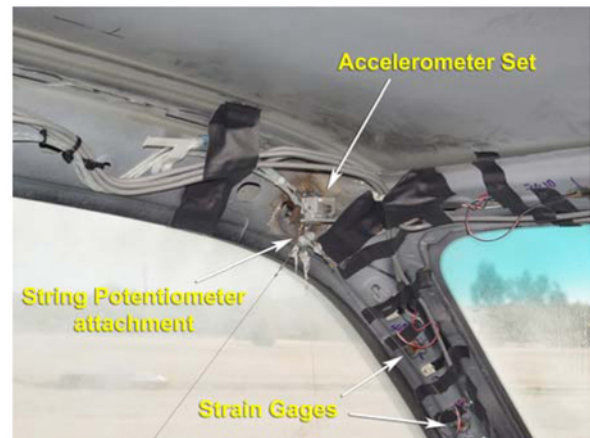


Figure 9. Strain gages, accelerometer set, and string pot attachment locations on the left A-pillar.

The strain gages were applied directly to the sheet steel and were balanced to measure zero strain at the installed location; any residual strain (stress) on the surface of the sheet steel due to the stamping of the part or vehicle assembly could not be decoupled. The strain measurements of the stamped steel parts yield an indication of the stress state at that location for a given loading condition. The strain indicates how the magnitude of the stress, through Young's Modulus, changes for a given vehicle-to-ground impact. Figure 10 shows the strains measured at the left upper A-pillar. As a reference value, low carbon automotive steels (yield stress in the region of 30 ksi (210 MPa)) exhibit plastic behavior at approximately 1,000 microstrain.

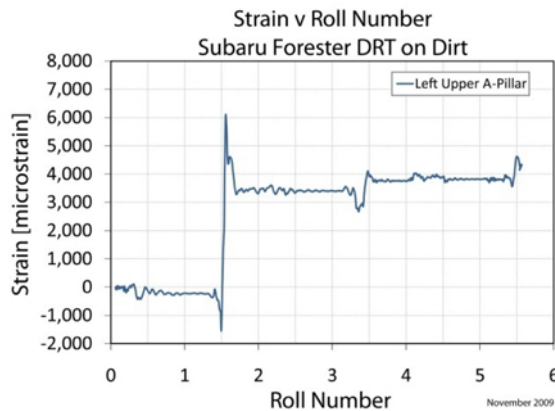


Figure 10. Upper left A-pillar strain during the test on dirt without ATDs.

The strain gage at the left upper A-pillar measured the surface strain of the beam in a uniaxial direction. The measurement itself does not indicate the combined loading condition; that is, interpretation of the data trace alone does not permit one to distinguish between uniaxial tensile loading or bending of the pillar, but it does address the change in the stress state of the surface to which it is attached. Given the location of the gage and considering the A-pillar as a beam in bending, a positive strain (tensile) value indicated that the inner upper surface of the A-pillar was loaded such that it was in tension after roll 1-1/2. Figure 11, a photograph of the Forester at the 2-1/2 roll position, depicts the A-pillar deformation due to contact during the first two rolls (the front of the roof did not contact the ground during the third roll). The deformation to the A-pillar was consistent with the measured tensile strain on the inner upper left A-pillar surface as shown in Figure 10. The strain gage recorded a dynamic strain of over 6,000 microstrain that settled to a value of approximately 3,500 microstrain at the end of roll 2. These peak and residual strain values are representative of plastic strain for low carbon automotive steels, though they may be in the elastic region for some high strength automotive steels. Knowledge of the material properties, and thus the stress-strain curve, permits the assessment of the strain magnitude at which the component exhibits plastic behavior. Despite the change in A-pillar displacement during roll 4 (see Figure 6 and Figure 8), the residual strain on the left inner upper A-pillar surface underwent only a 1,000 microstrain variation, indicating that the A-pillar junction shifted without deformation at the gage location.

<figure 11 here>

Each B-pillar was instrumented with two surface mounted strain gages; 1) the upper gage was located 5.3 inches (13 cm) from the center of the accelerometer block and 2) the lower gage was located 6.9 inches (18 cm) from the upper strain gage. The lower strain gage (Figure 12) was

deliberately placed where a plastic hinge in the B-pillar was anticipated to, and did, form. The vehicle captured mid-air in Figure 11 (still photograph during the test at the 2-1/2 roll position) illustrates an outward bending of the left B-pillar between the side roof rail and the beltline. Observing the visible outward deflection of the pillar, an observer would be inclined to conclude that compressive strain (stress) exists at the midspan of the inner B-pillar between the roof side rail and the beltline. The post-test photo of the left B-pillar, Figure 13, confirms the bending of the pillar remaining in the residual state, and the location of the plastic hinge at the lower strain gage. The strain gage data collected on the left B-pillar can be used to confirm the changing stress imposed on the inner surface of the B-pillar from the roof-to-ground impacts.

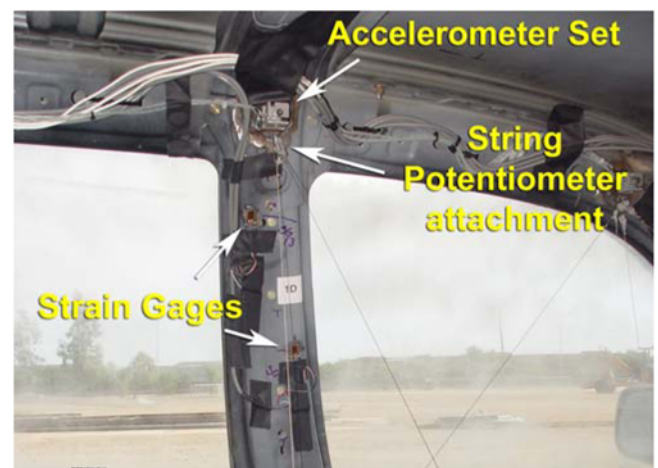


Figure 12. Strain gages, accelerometer set, and string pot attachment locations on left B-pillar pre-test.



Figure 13. Interior of left B-pillar post-test on dirt without ATDs.

The left B-pillar's lower inner surface strain is shown in Figure 14 and it indicates that the surface is still in the plastic

region (less than 1,000 microstrain) during roll 1. The string potentiometer measurements at the top of the left B-pillar show that it was deformed during roll 2 (Figure 15) to [3.1" (8 cm) Inboard, 4.0" (10 cm) Down], which was confirmed by the strain gage measurements. For reference purposes, the Analog/Digital (A/D) full-scale strain reading was set to be 10,000 microstrain in the data acquisition system. Any reading above 10,000 microstrain is indicative of a saturated strain measurement by the recording device and would be substantially beyond the linear region of the stress-strain curve for low carbon automotive steels. The strain measured on the left lower B-pillar was -10,000 microstrain and then settled to approximately -7,000 microstrain at the conclusion of the roof-to-ground impact in roll 2. The next notable change in the left lower B-pillar strain that occurred in roll 4 was associated with a roof-to-ground impact on the passenger side roof rail. The loading into the passenger B-pillar caused an accumulation of the plastic hinge deformation at the gage location, which resulted in the strain gage failure and saturation of the electrical signal from the gage. The strain data appeared to record tensile strain before it saturated the A/D board in the data acquisition system, but that was not the case; the electrical continuity within the strain gage failed. The only significance of the strain data during roll 4 is associated with the timing of its transition from the residual strain after roll 2, which places the vehicle at roll position 3-3/8. This passenger side roof rail ground contact deformed the right roof rail inboard and down (as shown in Figure 16), distributing the load through the roof assembly. This caused the left roof rail at the B-pillar to deform laterally to a residual state of [3.0" (8 cm) Outboard, 2.9" (7 cm) Down] at the end of roll 4 (as shown in Figure 15).

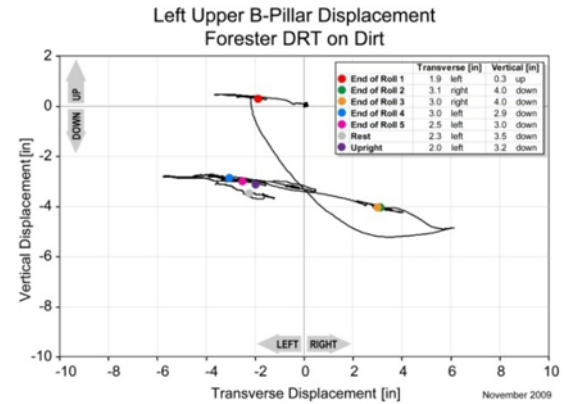


Figure 15. Displacement at the top of the left B-pillar during the test on dirt without ATDs.

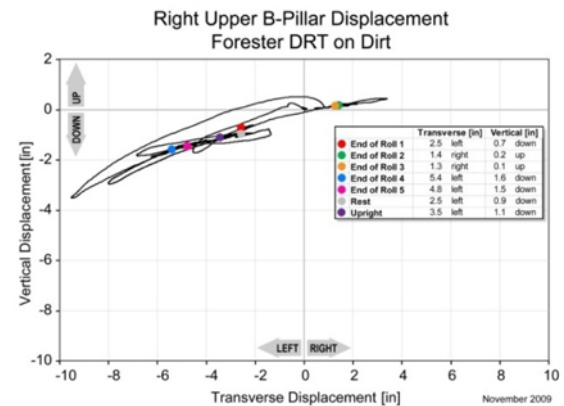


Figure 16. Displacement at the top of the right B-pillar during the test on dirt without ATDs.

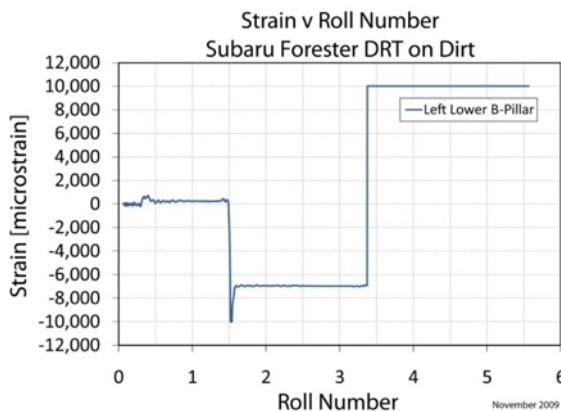


Figure 14. Lower left B-pillar strain during the test on dirt without ATDs.

FORESTER TEST # 2 - CONCRETE SURFACE

The second test, involving an instrumented Forester rolling passenger side leading on a concrete surface was conducted with an initial speed of 44.0 mph (70.8 kph). Initial ground contact was similar in orientation to the first test, but the difference in terrain and the interaction between the vehicle and ground resulted in significant variation in subsequent vehicle dynamics. The Forester rolled twice (8 quarter-turns) over a distance of 160 feet (48.8 m) in 4 s and then transitioned to rolling forward on all four tires for another 5.5 s. During the rollover portion of the test, the vehicle experienced peak roll rates exceeding 380 deg/s, and the average deceleration of the vehicle was calculated to be 0.40 g. Overall, the Forester rollover on concrete exhibited lower roll rates and a fewer number of vehicle revolutions than the Forester rollovers on dirt.

The primary differences in vehicle dynamics were associated with two phenomena: 1) the vehicle response following the

initial contact forces and 2) the fracture of the near-side rear suspension at the completion of roll 2. During the rollovers on dirt, the moment produced by large tangential frictional forces on the vehicle gave rise to increased angular acceleration. During the initial vehicle-to-concrete interaction, these frictional forces were lower in magnitude and resulted in a smaller conversion of translational energy to rotational energy. After completing the second roll, the Forester impacted the concrete test surface on the right rear corner and fractured the right rear suspension. The impact forces, oriented generally vertical in relation to both the world and vehicle coordinates, arrested the vehicle's remaining roll velocity and induced clockwise yaw. The rear suspension impact generated enough counter-moment to reduce the roll rate from nearly 300 deg/s to zero in less than 1/8 of a roll. [Appendix A](#) contains a general description the vehicle motion, timing of glazing fracture, and a diagram of the rollout area ([Figure 43](#)) indicating the approximate longitudinal start location for each individual roll and the post-rollover artifacts found in the rollout area.

Examination of the acceleration data in [Figure 17](#), and the synchronized video, reveals that the vehicle's roof structure experienced the same number of roof-to-ground contacts (four), as the first test vehicle, yet the impacts were generally lower in magnitude and shorter in duration than the roof impacts in the dirt test. The CG accelerations during the front roof contacts (blue shaded regions on [Figure 17](#)) yielded magnitudes that range between approximately 2-5 g's (not including the short duration spikes), and have durations that ranged from 56 to 134 ms. By summing the durations of the four distinct frontal roof impacts and dividing by the overall duration of the rollover event, as defined by when the roll rate approached zero, the 4 roof impacts account for 9% of the 4 s rollover duration.

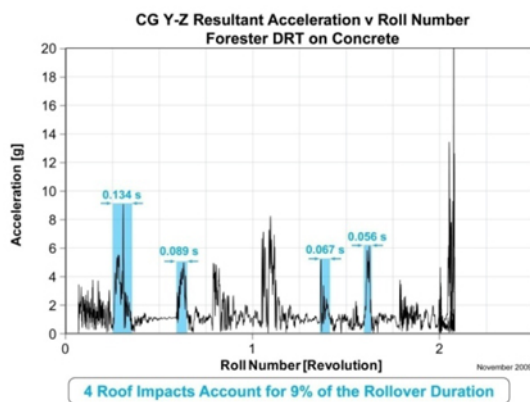


Figure 17. Global CG Y-Z resultant vehicle acceleration during the test on concrete.

Shorter duration impacts were expected since the concrete surface was less compliant than the compacted dirt. While different terrain surfaces can generate variations in vehicle

dynamics, in general, terrain surface type should not be considered the sole variable in determining roof impact severity. The vehicle dynamics and resulting lower severity roof impacts experienced during the concrete rollover is also demonstrative of the random nature of rollovers despite similar initial conditions.

This paper introduces an innovative approach to analyzing vehicle dynamics during rollovers using polar plots. Polar plots are particularly useful given the cyclic nature of the vehicle roll position during a rollover event. For the test on concrete, the CG resultant acceleration in the vertical plane (Y-Z components) was plotted as a function of roll angle and is depicted in [Figure 18](#). The acceleration is plotted radially outward, spaced at 5 g/division with the zero degree vehicle roll angle (upright) at the 12 o'clock position. To enhance the readability of the polar plot, a profile of a Forester is depicted at each 45 degree position in the CCW direction. The data measured during each revolution is color coded and defined in the graph legend on the lower right corner; red is roll 1, green is roll 2, and blue is the rear suspension strike after the completion of roll 2. This spatial representation allows an analyst to quickly ascertain the accelerations associated with roof-to-ground impacts versus body/suspension-to-ground impacts. The roof-to-ground impacts are represented by acceleration peaks on the lower half of the polar plot in [Figure 18](#), whereas the body/suspension-to-ground contacts appear on the upper half of the plot. More specifically, the near-side roof-to-ground impacts appear in the region between the 8 o'clock and 6 o'clock positions, and the far-side roof-to-ground impacts appear between the 6 o'clock and 4 o'clock positions.

<[figure 18](#) here>

Analysis of the polar plot in [Figure 18](#) reveals two impacts to the near (passenger) side roof rail and two impacts to the far (driver) side roof rail. These are the same impacts that are highlighted in the shaded regions of [Figure 17](#), but their vehicle orientation is much more readily identified in the polar plot. During the first roll, roof-to-ground impacts can be identified just after the 1/4 roll position (8 o'clock) and at the 5/8 roll position (4:30 clock position) by red peaks. The red peaks on the upper right quadrant are associated with left side wheel contact (just after the 3/4 roll position at 2 o'clock). The blue peaks in the upper left quadrant are associated with the right side wheel impact (just before the 1-1/8 roll position at 11 o'clock). Two distinct roof-to-ground interactions occurred during the second roll at the 1-3/8 (7:30 clock position) and 1-5/8 (4:30 clock position) roll positions (green peaks). Finally, the largest impact in the concrete test occurred just prior to the 2-1/8 roll position (11 o'clock and blue peaks), which arrested the roll momentum and ended the roll portion of the test. It is interesting to note that the final impact that fractured the right rear suspension was the most severe acceleration measured by the vehicle CG throughout

the entire rollover test. If an impact of this magnitude had occurred when the vehicle was near the inverted orientation (6 o'clock on the polar plot), similar magnitudes of roof deformation to those seen in the rollovers on dirt would be expected.

The post-test condition of the vehicle's roof after the concrete test was similar in appearance to the undeformed vehicle roof, despite having undergone a series of impacts and corresponding lateral deformations (Figure 19). There was however enough roof deformation to fracture the windshield and tear the PVB layer from the perimeter at the roof header. The real-time measurements of the roof structure at the top of the A- and B-pillars (Figure 20) indicated that there was minimal residual deformation at the completion of the overall roll sequence. The vertical and transverse displacements measured during the concrete test exhibited a similar trend when compared to the deformation during the first roll in the dirt test. The deformation to the near-side roof rail (passenger) followed a path from upper right to lower left and the deformation to the far-side roof rail shifted from upper left to lower right. The absence of plastic vertical permanent deformation in the roof structure is attributed to the random nature of a rollover resulting in no significant impact events near the inverted roll position (6 o'clock position in Figure 18). Rather, the loading to the roof structure occurred while the vehicle was oriented more on its side and thus the vehicle was not exposed to forces in a vertical direction that would tend to cause plastic deformation to the roof structure.



Figure 19. Roof deformation to Subaru Forester after the test on concrete.

<figure 20 here>

The integrated construction of the vehicle roof structure is clearly illustrated by the overall deformation patterns of the A- and B-pillars. Despite roof loading from varying directions, the load was distributed and the roof structure was displaced on the non-contact side due to loading on the

contact side, indicating that the roof structure shifted as an assembly. Repeated impacts to the roof assembly, whether directed from the left or right side of the vehicle and at varying orientations, caused the roof structure to follow nearly symmetric and predictable patterns. Recognizing that roof structures behave as an assembly provides valuable insight into the nature of roof deformation during ground impacts within a rollover.

FORESTER TEST # 3 - DIRT SURFACE

The third test involved an instrumented Forester rolling passenger side leading on compacted dirt with an initial speed of 43.4 mph (69.8 kph); nearly identical initial conditions to the test on dirt without ATDs. The Forester's first contact with the ground was with its passenger side structure, missing the right side tires. The first ground contact resulted in an external frictional force to the near side body that converted some of the translational energy to rotational energy, increasing the roll rate to near 600 deg/s. The vehicle rolled 5-3/4 revolutions (23 quarter-turns) over a distance of approximately 138 feet (42.1 m) in 5.7 s. The average deceleration of the vehicle during this event was calculated to be 0.46 g. Appendix A contains a general description the vehicle motion (focusing on the ground contacts), timing of glazing fracture, and a diagram of the rollout area (Figure 45) indicating the approximate longitudinal start location for each individual roll and the post-rollover artifacts found in the rollout area.

Analysis of the acceleration data indicates that the vehicle sustained three substantial impacts to the front roof structure that resulted in measureable displacement of the roof. The resultant (YZ) acceleration in the global reference frame was plotted as a function of roll revolution, as shown in Figure 21. Three impacts during rolls 1, 3, and 5 were highlighted in the plot to illustrate the contact to the front roof structure, which resulted in the dynamic deformation to the roof structure measured by the on-board string potentiometers and observed by the onboard high-speed video cameras. The durations of these three acceleration pulses identified in Figure 6 ranged from 84 to 135 ms. By summing the durations of the three distinct frontal roof impacts and dividing by the overall duration of the rollover, the 3 roof impacts account for 6% of the 5.7 s rollover duration. The significant portion of these three roof-to-ground acceleration pulses occurs at levels of approximately 6-10 g's (blue shaded regions). The body-to-ground impacts during rolls 2 and 4 measured higher acceleration levels than the roof-to-ground impacts.

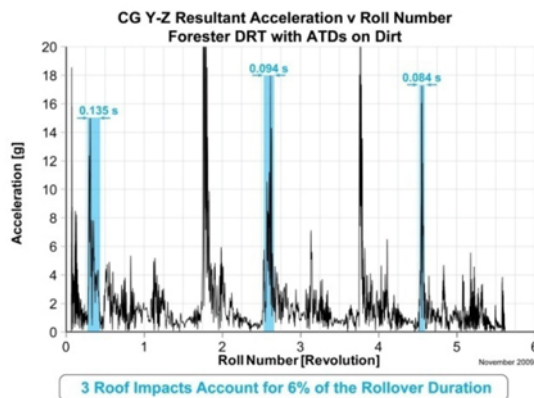


Figure 21. Global CG Y-Z resultant vehicle acceleration during the test on dirt with ATDs.

For this dirt test with ATDs, the resultant acceleration in the vertical plane (Y-Z components) is presented as a function of roll angle in [Figure 22](#). The three roof-to-ground impacts are easily identified on the bottom half of the polar plot. The first roof impact is observed near the 8 o'clock position in roll 1 (red), the second impact occurred at the 4:30 clock position on roll 3 (cyan), and the third roof impact occurred at the 5 o'clock position on roll 5 (magenta). In terms of magnitude, the largest accelerations were not the three roof-to-ground impacts but left side body/tire impacts between the 2 and 3 o'clock positions during rolls 2 and 4. Furthermore, the polar plot graphically illustrates the magnitude and direction of the variable for a series of discrete impacts that occurred in the rollover test.

<[figure 22](#) here>

The dynamic pillar displacement on the driver and passenger upper A and B-pillar junctions were analyzed in the body-fixed coordinate system. The driver (far) side A-pillar displacement is depicted in [Figure 23](#) and the driver side B-pillar displacement is shown in [Figure 24](#). In the first roll, the left A-pillar is shifted during near side contact to the right roof rail and then immediately displaced again from direct contact between the ground and left roof rail. After being displaced nearly 4 inches (10 cm) due to these ground impacts, the left A-pillar returned to a residual state near the as-designed position. This dynamic deformation in the first roll demonstrates two characteristics; 1) vehicle impacts with a lateral orientation can result in elastic deformation to the roof structure and 2) displacement of the non-contact side of the roof structure occurs because the roof structure behaves as an integrated assembly. The other remarkable impacts occurred during rolls 3 and 5 with the vehicle closer to an inverted orientation and exhibited a similar characteristic to what was observed in the first dirt test; the vehicle, when it was near the inverted orientation and in ground contact, sustained plastic deformation to the roof structure. Comparing the left A-pillar and B-pillar polar plots, the left

B-pillar was displaced about 1/3 as much as the A-pillar. This difference in deformation was due to the vehicle orientation at ground contact (nose down) when the load was distributed through the roof structure. The final observation seen in both polar plots is that during roll 2, while the vehicle impacts the ground on the left side body (2 o'clock position), the roof structure was displaced approximately 2 inches (5 cm) at the B-pillar (green loop) due to inertial loads, which was subsequently recovered (elastic return). This inertial loading event was a result of the CG acceleration of nearly 30 g on the driver side and tires/wheels ([Figure 22](#)).

<[figure 23, 24](#) here>

In this study, the third Forester test builds upon the existing body of research through the use of belted and instrumented driver and passenger ATDs that can be used to evaluate the relationship between vehicle kinematics, roof-to-ground impacts, roof deformation, and occupant kinematics and injury. The potentially injurious compressive neck load events in the ATDs, in a high strength-to-weight ratio vehicle, were consistent and supportive of conclusions from previous studies that compressive neck loads occurred prior to roof deformation. The neck loading mechanism was consistent with torso augmentation. The synchronized video and data generated from this test provides an understanding of the vehicle dynamics together with the neck loading events to the driver and passenger ATDs. For additional discussion of the data analysis, occupant kinematics, and injury mechanism for the driver and passenger ATD throughout the entire rollover event, see [Heller et al. 2010](#).

There was one axial compressive loading event from the passenger ATD (near side) and two events from the driver ATD (near and far side contact) during the first roll that will be presented and discussed. To provide a reference to the key vehicle positions of interest during this first roll, the kinematics and roof deformation of the vehicle, as well as the associated upper neck load cell measurements from the ATDs are summarized in [Table 1](#). Vehicle positions 1,2, and 5 are used to describe the passenger ATD near side event, vehicle positions 3 and 4 are used to describe the driver ATD near side event. Vehicle positions 6-9 are used to describe the driver far side roof-to-ground impact event. Accompanying this table is a frame capture from the synchronized data and video for each vehicle position. The composite graphics include video frame captures showing a vehicle interior view, and panning exterior view for the respective ATD of interest. In addition, the composite graphic displays the synchronized data showing the ATD axial neck load versus time and Y versus Z displacement at the top of the adjacent B-pillars.

<[table 1](#) here>

The vehicle left the dolly with its roof in an undeformed state and made first contact with the ground on its passenger side.

The first ATD neck loading event to be discussed is the passenger ATD near side roof-to-ground impact. Vehicle position 1 (see [Figure 25](#), top) represents the beginning segment of a compressive neck loading event to the passenger ATD during a near-side impact. At 460 ms the vehicle was traveling at 39 mph (62 kph), was rolled to the 0.29 roll position, and had an instantaneous roll rate of 232 deg/s. The passenger ATD moved upward and outboard due to centrifugal forces, positioning its head near the right roof rail. The 123 N (28 lbf) tensile force in the upper neck results from centrifugal forces acting on the head mass, and confirmed the head was not in contact with the roof at 460 ms. At roll position 2 (see [Figure 25](#), bottom), which is 28 ms later, a peak compressive neck load of 6,328 N (1,423 lbf) was measured from the passenger ATD.

<[figure 25](#) here>

Over the 28 ms from vehicle position 1 to vehicle position 2, the vehicle horizontal speed decreased by 5 mph (7 kph) to 34 mph (55 kph), rolled an additional 9 degrees, and its roll rate increased from 232 deg/s to 429 deg/s. During the same time frame, the B-pillar adjacent to the passenger ATD head was displaced to [1.6" (4.1 cm) Inboard, 0.8" (1.9 cm) Down] from its undeformed state. This first vehicle-to-ground contact resulted in additional movement of the passenger ATD up and out until the head made contact with the adjacent right roof rail, the ATD head stopped, and the torso continued towards the head, resulting in a compressive upper neck load of 6,328 N (1,423 lbf) due to torso augmentation. The area of vehicle where the head of the passenger ATD made contact, a stamped steel bracket for mounting the grab handle, was dented as a result of the ATD loading. The peak compressive load in the passenger ATD was reached before any significant roof deformation occurred, and while the roof was deforming inboard and downward the ATD neck load changed from a maximum compressive load of 6,328 N (1,423 lbf) to a 514 N (116 lbf) tensile force. The maximum right B-pillar deformation during roll 1 occurred at 552 ms, 64 ms after the peak compressive neck load (see [Figure 26](#)).

<[figure 26](#) here>

The first driver ATD event discussed occurred during the first near side roof-to-ground impact. Vehicle position 3 (see [Figure 27](#), top) represents the beginning of the compressive neck loading event, defined near the point of load transition from tension to compression. The vehicle was traveling at 32 mph (52 kph), rolled to the 0.36 roll position and had an instantaneous roll rate of 509 deg/s. At vehicle position 3 the near side roof rail of the vehicle was in contact with the ground and there was separation between the roof bow and the roof panel. The left B-pillar adjacent to the driver ATD was deformed to [3.6" (9.1 cm) Outboard, 0.6" (1.5 cm) Down] relative to the undeformed position. The driver ATD moved upward and outboard from the near side impact due to

centrifugal forces and the vehicle deceleration. The 308 N (69 lbf) of tension in the upper neck load cell was again demonstrative of centrifugal forces acting on the head mass, and confirmed the head was not in contact with the roof at vehicle position 3. At vehicle position 4 ([Figure 27](#), bottom), 19 ms later, a peak compressive neck load of 2,406 N (541 lbf) was measured on the driver ATD.

During the 19 ms from vehicle position 3 to position 4, the vehicle horizontal speed decreased by about 1 mph (2 kph), rolled an additional 10 degrees, and the roll rate increased 27 deg/s to 536 deg/s. During this near-side contact, the loading to the passenger roof rail caused both the right and left B-pillars to matchbox left. The B-pillar adjacent to the driver ATD head moved 0.4" (1.0 cm) inboard and 0.2" (0.5 cm) up from vehicle position 3 to vehicle position 4. The vehicle dynamics and its orientation during the near side roof-to-ground contact resulted in additional excursion of the driver ATD up and out such that the head made contact with the adjacent left roof rail. As the ATD head was being stopped against the roof rail (while also deforming the grab handle attachment bracket), the compressive neck load was increased to 2,406 N (541 lbf). This neck load event occurred without the driver ATD's adjacent roof rail in contact with the ground.

<[figure 27](#) here>

The second neck loading event on the driver ATD occurred while the vehicle was transitioning from a near side to a far side roof-to-ground contact. Vehicle position 6 (see [Figure 28](#)) represents the composite video for the driver ATD at the beginning segment of the second compressive neck loading event. At this instant in time, the vehicle was traveling at 30 mph (48 kph), was rolled to the 0.45 roll position, and had a roll rate of 594 deg/s. With the vehicle near the inverted position, the roof panel was in contact with the ground; and comparison of the roof panels ([Figure 28](#) to [Figure 27](#)) indicates that the roof panel and roof bow has straightened due to ground contact. The left B-pillar adjacent to the driver ATD was displaced to [4.0" (10 cm) Outboard, 0.1" (0.3 cm) Down]. The driver ATD was still upward and outboard due to centrifugal forces and vehicle decelerations, positioning the head in contact with the left roof rail. The 117 N (26 lbf) compressive force in the upper neck load cell was clearly from centrifugal forces acting on the torso loading the neck after the side roof rail stopped moving laterally outboard.

<[figure 28](#) here>

At vehicle position 7 (see [Figure 29](#), top) 20 ms later, the compressive neck load was 3,195 N (718 lbf) and was also the start of a very short duration plateau in the neck load. Over this 20 ms interval, the vehicle's horizontal speed remained constant, it rolled an additional 12 degrees, and its roll rate decreased to 558 deg/s. The displacement at the left B-pillar adjacent to the driver ATD head moved inboard by