

# Failure mode forensic testing of seat belts

*Seat belts can reveal many clues after an accident*

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## Introduction

Seat belts are the primary occupant restraint system in passenger vehicles. The benefits of seat belt use are many. In the event of a collision, properly designed and manufactured three-point lap and shoulder belts (type 2 seat belts) help to reduce the risk of injury due to impacts with vehicle interior components or ejection. Seat belts provide occupant ride-down by providing restraining forces early in the collision event, thereby decreasing the relative velocity between the vehicle interior and occupant. Seat belts also help distribute restraining forces over sturdy skeletal areas of the body. However, the effectiveness of seat belts cannot be realized unless they are worn.

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Photograph 1



Photograph 2

Oftentimes, a restraint system engineer or traffic safety consultant will be retained to determine whether the seat belt was worn at the time of collision and to evaluate the performance of a seat belt allegedly in use. There may be witness statements or information from the victim's family supporting the allegation of belt use. However, the engineer will seek to identify physical evidence to establish this as fact. The accident vehicle must be preserved, and the seat belt has to be inspected in order to locate physical evidence indicative of use.

Previous studies discuss the identification of witness marks to seat belt components (Moffatt, Moffatt and Weiman, *Diagnosis of Seat Belt Usage in Accidents*, SAE Paper No. 840396, 1984; Gorski, German and Nowak, *Examination and Analysis of Seat Belt Loading Marks*, Journal of Forensic Sciences, JFSCA, Vol. 35, No. 1, January 1990, pp. 69-79; Jacobson and Ziernicki, *Field Investigation of Automotive Seat Belts*, Accident Investigation Quarterly, Winter 1996, pp 16-19; and Jakstis and Brown, *Field Investigation of Airbag, Seat Belt, and Interior Markings*, SAE Airbag Design and Performance TOPTEC, August 1997). These authors provide definitions of component terminology, like retractor, webbing, D-ring, and latch plate, and identify frequently observable artifacts and the mechanisms that produce evidence, such as friction or striation marks, belt stretch and cupping, plastic transfers, and cut webbing. Additionally, one paper illustrates some physical characteristics of seat belt components that are not related to vehicle impact (Bready, Nordhagen and Kent, *Seat Belt Survey: Identification and Assessment of Non-collision Markings*, SAE Paper No. 1999-01-0441, 1999). An expert can use the location, type and severity of physical evidence to determine whether or not the belt was in use at the time of collision or rollover event.

In addition, as a result of crash tests and other forensic testing, the post-accident condition of seat belt assembly components can reveal important information and can be used to quantify the force levels involved. This information, in turn, can be used to assist in accident reconstruction and biomechanical analysis. This article examines three areas where quantification of forces is possible.

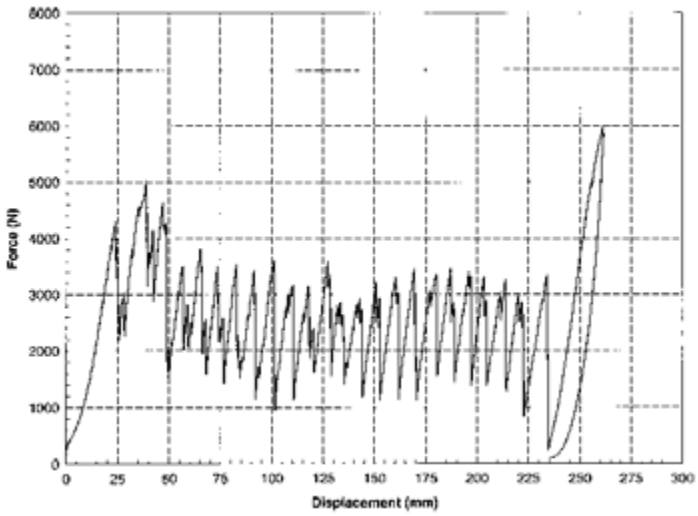
## Expansion loops

In an effort to favorably modify the kinematics of test dummies in barrier impacts, seat belt assembly designs often incorporate expansion loops. An expansion loop introduces additional webbing length when a predetermined level of tension is reached. Expansion loops are composed of webbing that is folded along the short axis and stitched in place by parallel rows of threading. Photographs 1 and 2 show an expansion loop from a 2000 Acura Integra. The thread material and stitch pattern used to make the rows of stitching is designed to tear at predetermined webbing tension levels, for instance around 600 to 700 pounds. When the stitches tear, the webbing fold will partially open thereby introducing additional webbing. Photograph 3 shows the torn stitches of an expansion loop during a test. See *How to Determine if Seatbelts were in Use*, John D. Rowell,



Photograph 3

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Graph 1

*Advocate*, July 2004 for more information on expansion loops and other evidence of belt loading.

When examining a seat belt assembly for physical evidence consistent with belt use at the time of collision, the expansion loop may offer excellent confirmation if partial or complete tearing of the stitches result from occupant loading. Expansion loops are most often found adjacent to the lap belt lower outboard anchor, and usually concealed by a plastic sleeve or rubber-like escutcheon (examples can be observed in Honda, Nissan, Mazda, Mitsubishi, Toyota and General Motors vehicles). However, some systems incorporate an expansion loop in the shoulder belt (Mitsubishi Eclipse and sister vehicles), or in the D-ring anchor (Dodge Ram van). The left front and right front expansion loop designs may be dissimilar in number of stitching rows and total webbing payout. Furthermore, expansion loops may be present in the right front passenger's seat belt assembly, yet no similar device is used in the driver's seat belt assembly. A warning label, commonly stating "REPLACE BELT," is often visible after the stitches are torn.

Expansion loop design parameters vary with vehicle make, model and even model year, by virtue of the fold and stitch patterns, number of stitching rows and webbing payout. When inspecting the restraint system, if the plastic sleeve can be moved to allow observation of the expansion loop without disturbing evidence, the amount of webbing payout can be estimated. Forensic testing can determine the amount of force required to break the stitches and the webbing payout. Knowing the unique force-displacement characteristics of the expansion loop will help quantify the corresponding occupant restraining forces.

Testing includes new samples and used assemblies removed from salvage vehicles. Efforts are taken to maintain the in-vehicle condition when securing the sample to the test fixture by using the original attachment hardware and plastic sleeve. Tension is applied to the specimen by pulling on the other end of the webbing held by a split drum grip as specified under FMVSS 209. The split-drum grip ensures that the fixture does not cut the webbing during the test. Tension in the webbing increases and



Photograph 4



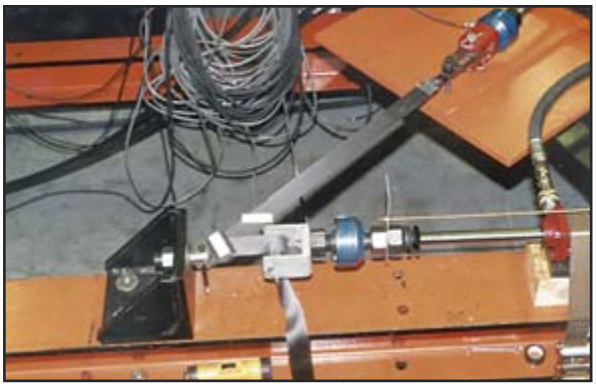
Photograph 5



Photograph 6

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Photograph 7



Photograph 8

continues until all stitching rows are broken. The tensile force in the webbing is measured with a load cell. The displacement of the webbing is measured by the crosshead of the tension machine. The test data produces a sawtooth-like force versus displacement curve that is commensurate with the fold pattern and number of rows of stitches (see graph 1 on Previous Page).

Forensic testing has determined that the expansion loops in the front lap belts of 1996 and 1997 model year Honda Accords contain 24 parallel rows of stitching. Interestingly, the first three rows of stitching tear at about 1200 pounds while the remaining 21 rows break at about 700 to 800 pounds. When all rows of stitches are torn, about 9.5 inches of webbing is added to the restraint system.

The right front lap belt of the 2000 Mitsubishi Montero Sport has an expansion loop with 31 parallel rows of stitching. Each row breaks at about 450 pounds, and a total of about 10.5 inches of webbing is added when all rows are torn. Curiously, if one were to purchase a replacement seat belt assembly from a certified new car dealer, and then remove the plastic sleeve, there would be 18 rows of stitches in what appears to be a revised expansion loop design. The force to break the rows in the revised loop is about 600 pounds, but it adds only 8.5 inches to the seat belt assembly.

The right front lap belt of the 1988 Chevrolet Corsica contains an expansion loop with only one row of stitching. Remarkably, this single row of stitches tears at less than 300 pounds, and provides six inches of webbing. Another single row expansion loop is incorporated in the lap belt of the 2001 Chevrolet Sonoma truck. Testing reveals this row of stitching tears at about 450 pounds and only two inches of webbing is added to the seat belt assembly.

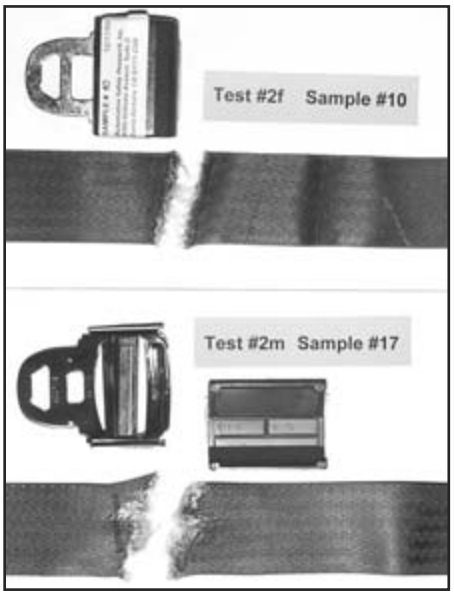
General Motors (GM) uses the term "energy management loop" for their expansion loop. However, as an energy-absorbing device, the loop is often ineffective. The forces and corresponding displacements do not constitute significant energy absorption when compared to the occupant's kinetic energy, especially in the case of the Corsica and Sonoma. Once the expansion loop fully opens, the additional webbing length can increase occupant excursion, which can result in increased lower limb impact severity and injury risk. By modifying the occupant's kinematics, the opening of the loop is intended to reduce the likelihood of head impacts with interior components, but at the expense of increased risk of lower limb injury as well as other injuries associated with the modified kinematics. By incorporating this type of load-limiter, seat belt assemblies with expansion loops are exempt from the webbing elongation requirements under Federal Motor Vehicle Safety Standard (hereinafter FMVSS) 209. The reduction in occupant restraint can also lead to increased risk of occupant ejection in rollover collisions. As such, the effects of expansion loops often run counter to effective restraint and occupant containment, and introduce detrimental slack to the seat belt assembly.

## Seat belt anchors

Frequently restraint system engineers first look to the latch plate and D-ring for physical evidence of use. The plastic coating on these components often exhibit artifacts consistent with occupant loading. However, D-rings and latch plates may be chrome-plated, or the plastic coating so hard that load marks may not be detected. In the instances where the load surface of these components do not reveal occupant witness marks, the attachment hardware and surrounding area should be examined. Seat-integrated belts and passive safety belts will be ignored for this discussion, because these systems generally contain unique component hardware.

Seat belt attachments are points where the occupant restraining forces are transferred from the seat belt assembly to the vehicle structure. If the webbing does not terminate at a retractor, then the webbing end is anchored to the

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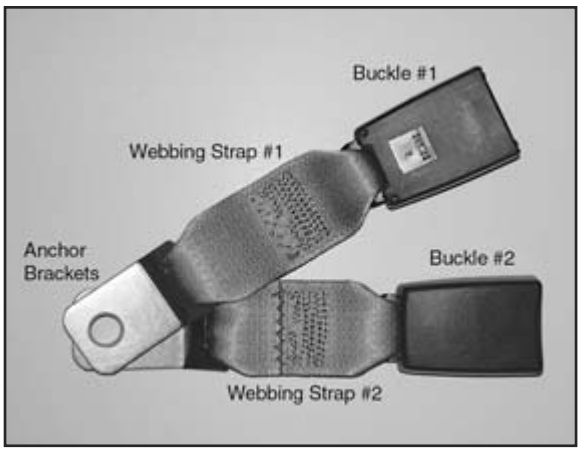



Photograph 9

vehicle. The end of the webbing is typically folded, looped through and stitched to a slot in a metal bracket. The edge of the slot is coated, dipped or otherwise protected so the webbing is not cut by its periphery. The bracket is securely bolted to the vehicle structure. Depending on the force level applied to the anchor point, deformation or failure of the surrounding vehicle structure may be observed.

Examining the seat belt attachments may require the removal of the upholstery, trim panel or seat cushion. However in the case of pending or anticipated litigation, removal of any component that may irreversibly alter or degrade evidence should be conducted during a joint inspection. Comparison with the corresponding component of the adjacent passenger location or exemplar vehicle is a useful technique.

Quantifying the force required to produce the deformation to the anchor bracket in the accident vehicle is useful in understanding the forces applied to the occupant. The identification of the type and location of occupant injuries can be supported by testing of the restraint system anchors and knowledge of human tolerance to impact injury. An example is a case of a rear-seat passenger wearing a lap belt at the time of a frontal collision. This particular occupant suffered significant internal injuries, which is a frequently-observed injury pattern when no shoulder belt is installed. The physical evidence confirming seat belt use was significant deformation and tearing of the vehicle floor structure surrounding the lap belt anchors (see photograph 4 on Page 3).




Photograph 10

Subsequent testing was conducted to quantify the amount of force required to deform and tear the vehicle structure. An exemplar vehicle was used. The test setup included removing unnecessary interior components and securing the vehicle to a test fixture. A hydraulic cylinder was used to pull on the seat belt anchors in a direction consistent with occupant restraining forces. Photograph 5 (Page 3) shows the test setup. The force applied to the lap belt anchor was measured with a load cell, and the displacement of the structure was measured with a linear variable displacement transducer. When the floor structure of the exemplar vehicle was deformed to an extent similar to the accident vehicle, the test was stopped (see photograph 6 on Page 3). In this case, the force necessary to produce similar deformation at two lap belt anchor points was 2600 and 3300 pounds, and was found to be consistent with seat belt loading that would result in the internal injuries suffered by the crash victim.

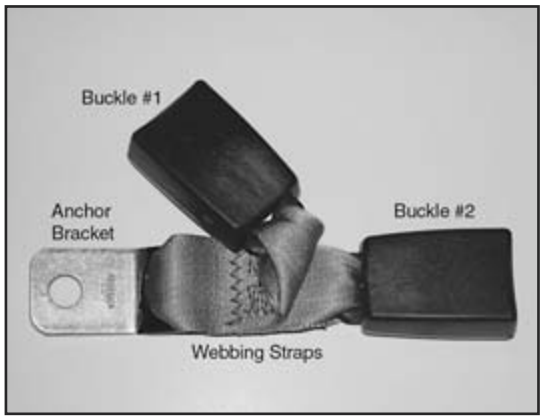
## Seat belt separation/failure

*Seat belt hardware design:*

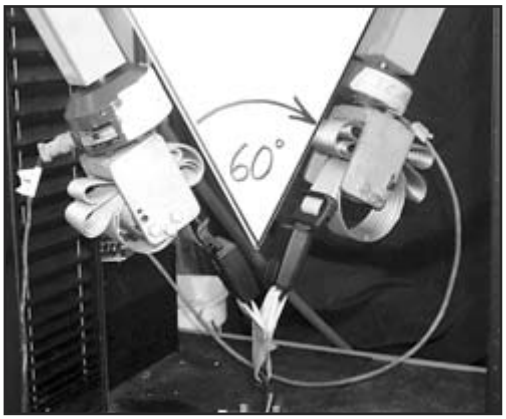
Before the installation in a production vehicle, seat belt assemblies must be certified to conform to all applicable federal safety standards. However, the testing procedures required by FMVSS 209 are not tailored to adequately test for the many potential failure modes observed in seat belt assemblies. FMVSS specifies that any webbing cut by assembly hardware during compliance testing shall have a breaking strength of not less than 3500 pounds for the lap belt and not less than 2800 pounds for the shoulder belt. In real-world crashes, it has been observed that some assembly hardware can reduce the breaking strength of the webbing to levels below those specified in FMVSS 209.

Latch plates may have pass-through designs that allow them to shift position on the webbing of a three-point lap and shoulder belt. Alternately, the webbing ends may be stitched to the latch plate thereby fixing its position on the seat belt assembly (GM vehicles). Pass-through latch plates can be free-sliding designs that allow unrestricted movement along the webbing length, or cinch-bar types that bind down on the webbing when the seat belt webbing is in tension. However, some cinch-bar latch plates have been observed to cut webbing under occupant loading conditions. When the webbing is cut by assembly hardware, the occupant is rendered unrestrained, a condition that increases the risk of injury and ejection.

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Photograph 11




Photograph 12

One case in study involved a two-vehicle collision with a seat belt-restrained driver that was ejected and killed. Use of the three-point lap and shoulder belt by the driver was certain. Post-crash photographs of the vehicle interior show the latch plate remained fastened in the buckle. The seat belt webbing was found severed into two at the approximate location of the latch plate when the seat belt assembly is worn. A portion of the webbing was jammed in the D-ring slot. Each side of the belt demonstrated a non-linear cut end with frayed webbing fibers. Under magnification, the ends of the fibers showed a ball tip associated with heat. This physical evidence is unlike a seat belt cut with a sharp blade during occupant extrication. The localized strain associated with the sharp edge of the latch plate frame cut the webbing not unlike the edge of a ruler cutting a piece of paper.

Testing was performed to evaluate the effect of this assembly hardware on the breaking strength of seat belt webbing under reasonably anticipated forces due to occupant loading. Samples of exemplar seat belt assemblies were removed from salvage vehicles and new samples were purchased from a new car dealer. Tension tests were conducted first to evaluate the breaking strength of the webbing, without the effect of the latch plate. The breaking force measurements were between 4200 and 4900 pounds, which are approaching but below the 5000 pound requirement for lap belt webbing specified by FMVSS 209. The performance of the webbing samples was then contrasted with the test setup that included the latch plate.

The in-vehicle geometry was maintained by using three-point anchoring. Photograph 7 (Page 4) shows the test setup. One end of the webbing was secured to a hydraulic cylinder using the OEM bracket to which the webbing was sewn. The webbing was then routed through the cinch-bar latch plate secured to the test fixture. The other end of the webbing was held by a split drum grip attached to a second hydraulic cylinder. The included angle between the lap belt and shoulder belt webbing was approximately 45 degrees (see photograph 8 on Page 4 for a close-up). The force in the webbing was measured with a load cell, and displacement of the shoulder belt grip was measured with a linear variable displacement transducer. Initial conditions applied a 500 or 1000 pound preload to the lap belt side of the restraint system. Tension was applied to the shoulder belt and increased until the webbing failed. The test results showed that each webbing sample was cut by the sharp edge of the latch plate similar to the condition of the accident vehicle. Photograph 9 (Page 5) illustrates the cut webbing. Measurements revealed the webbing was cut at forces between 1800 and 2200 pounds tension for the in-service webbing samples, and about 2400 pounds tension for new samples.

These results show the ultimate breaking strength of the webbing was reduced by the latch plate to the extent that the seat belt assembly failed to pass the intent of FMVSS 209, which unfortunately does not specify that seat belt assemblies be tested in conditions similar to when they are worn. Only through using realistic anchor geometries was the failure mode exposed.

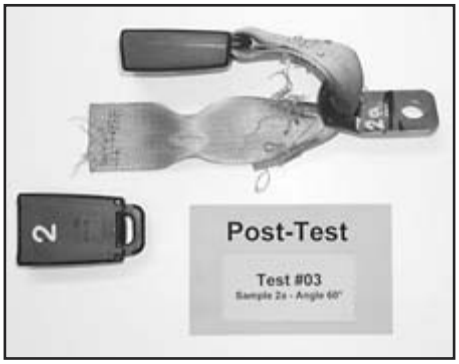
*Shared-anchor seat belt components:*

A shared-anchor seat belt assembly is one that uses a common anchor bolt or attachment hardware to transfer restraining forces of two adjacent occupants to a single point on the vehicle structure. The common practice is to provide side by side seat belt anchors for two seating positions. By attaching seat belt assemblies to a common anchor point, cost and assembly time can be reduced. However, when modification of a seat belt assembly component is implemented based on economic decisions, without due consideration of performance issues, troubling system performance may arise.

A case in point involved the rollover collision of a seven-passenger mini-van. Two rear seat passengers were ejected and seriously injured. Inspection of the

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Photograph 13

seat belt assemblies revealed physical evidence that these rear occupants were wearing their three-point lap and shoulder belts at the time of collision. It was determined that both seat belt buckles were designed to be secured to the seat cushion frame by a single webbing strap passing through an anchor bracket. Unfortunately, the stitches used to assemble the component failed, releasing the buckles from their anchorage. The two buckles were found still attached to their respective latch plates.

Examining previous model year vehicles revealed that there was a design change during the model run. The former component design used identical buckles, each of which was attached to separate anchor brackets each with its own independent webbing strap (see photograph 10 on Page 5). The anchor brackets of two adjacent buckle components were then secured to the vehicle through a single anchor bolt. The redesigned buckle component that appeared later in production utilized one piece of webbing to attach both buckles to one anchor bracket which was then secured to the vehicle with a single anchor bolt (see photograph 11 on Previous Page). The component redesign may save production costs; however, the ultimate strength of the newer component is decreased by virtue of the stitching configuration used to assemble the component.

A series of tests was conducted using a rigid beam fixture on new and used samples to evaluate the effect of loading angles on the failure strength of the shared webbing designs. The loading angle is defined as the included angle between the force vectors directed along the webbing straps of the adjacent seat belts. The loading angles used were 60, 90, 120 and 180 degrees. The applied forces were measured with load cells, and the displacement was determined by the crosshead of the tension machine. Photograph 12 (on Previous Page) shows the test setup.

At loading angles of 60, 90 and 120 degrees, the previous design which utilized independent anchor straps did not fail. However, at a loading angle of 60 degrees, the redesigned component utilizing one webbing strap to hold both buckles failed at an average force of about 2700 pounds. Failure occurred when the stitching used to assemble the component tore. Photograph 13 illustrates this failure mode. At 90 degrees, the redesigned component failed at an average force of about 1500 pounds. Again, the stitches used to assemble this component tore, releasing the buckle. At 120 degrees, the stitches failed at an average force of about 1000 pounds.

Lastly, at a loading angle of 180 degrees, the previous design also failed but at about 5000 pounds, and only after one strap was cut at its attachment to the buckle. Conversely, at this angle, the redesigned component failed at an average force of about 500 pounds.

The results of this testing are remarkable. They demonstrate that restraint failure can occur when a shared-anchor component of adjacent seat belt assemblies is simultaneously loaded with reasonably expected forces. But why wasn't the inadequate strength of the redesigned component recognized before installation in thousands of passenger vehicles? The truth may stem from the testing methodology of FMVSS 210, as this standard does not require simultaneous testing of adjacent seat belt assemblies. Only through forensic testing designed to more closely duplicate occupant loading in a real-world collision scenario was the deficiency of the redesigned component revealed.

## Conclusion

Thorough analysis of seat belt assemblies and forensic testing of their components will aid the restraint engineer's analysis of a particular accident vehicle. Sometimes, physical evidence consistent with seat belt loading is difficult to identify on the surfaces of the most frequently inspected seat belt assembly components. Careful observation of expansion loops and attachment hardware may isolate additional physical artifacts that confirm seat belt use for an occupant in a motor vehicle collision. When catastrophic failure of seat belt assemblies occurs, forensic testing has been shown to be useful to quantify force and failure modes. Adequate latch plate designs and independent anchor components are necessary to provide sufficient occupant restraint.

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Weiss

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