DYNAMIC ROOF CRUSH INTRUSION IN INVERTED DROP TESTING

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ABSTRACT
Inverted drop testing of vehicles is a destructive determination of roof strength used by industry, government organizations and independent engineers to determine vehicle safety with respect to rollover collision. In this paper, the results of numerous inverted drop tests are summarized and analyzed, giving both the amount of permanent and temporary roof crush that occurs during impact. Only unmodified production vehicles with sound roofs were tested. The amount of dynamic roof crush varied from a low of 0 to a maximum of 7.0 cm, the relationship between elastic and plastic roof crush was not found to be statistically significant, and prediction intervals for A and B-pillar crush were developed.

INTRODUCTION

Many engineers believe that strong roofs provide significant protection to occupants during rollover collisions. As of this writing, the American National Highway Traffic Safety Administration (NHTSA) has opened docket #5572 regarding review of the technical methodology for certifying the roof strength of passenger vehicles. In this docket can be found arguments in support of, and counter-arguments dismissive of, the assertion that stronger roofs (beyond a certain minimal point) are safer roofs. This paper addresses the lack of solid data regarding impact-generated dynamic intrusion into the occupant space.

There is currently a lack of information regarding the dynamic intrusion of the roof structure into the occupant capsule as a result of rollover. This information has not been tabulated as a result of Family of Motor Vehicle Safety Standards (FMVSS) 216 tests, and cannot be reliably measured from actual rollover collisions. In some cases, evidence of dynamic intrusion is present due to witness marks on headrests and other components during rollovers, but the actual intrusion distance still must be estimated rather than measured.

STATIC ROOF CRUSH TESTING

Roof strength is regulated in the United States by the FMVSS 216 standard, *Roof Crush Resistance – Passenger Cars*, and was adopted on September 1, 1973. General Motors developed the procedure at their research laboratories. One reason that it was adopted was for its repeatability, a desirable attribute for expensive, time-consuming tests.

The pre-amble of the FMVSS-216 standard states, "The purpose of this amendment…is to add a new Motor Vehicle Safety Standard…that sets minimum strength requirements for a passenger car roof <u>to reduce the likelihood of roof collapse in a rollover accident</u>" (emphasis added). As was alluded to in the introduction, there is significant, ongoing controversy regarding roof crush as it relates to occupant injury. Certainly, if roof crush is an issue in occupant safety, it is immaterial as to whether or not the intrusion that may or may not have injured the occupant was temporary or permanent.

DYNAMIC ROOF CRUSH TESTING

The quasi-static roof crush test mandated by the FMVSS 216 subjects the vehicle to a maximum force significantly less severe than would be applied to the vehicle during a multiple rollover. The Society of Automotive Engineers (SAE) recommended practice J996, *Inverted Drop Test*, is also a test of rollover crashworthiness, and was developed by SAE in the late 1960s. Since it is a more severe test, numerous engineers prefer it to the quasi-static FMVSS 216 test.

The SAE J996 test was designed, "…to obtain as closely as possible deformation of a vehicle roof or roll bar structure which occurs in a vehicle roll-over." In this test, the subject vehicle is inverted, given a roll angle, pitch angle, and drop height that are representative of the assumed loading at rollover. The angles present ensure that the majority of potential energy is transferred directly to the A-pillar structure. This standard does not specify any crush measurement methodology, permanent or dynamic.

DEVICE DESIGN AND TEST PROCEDURE

A reusable telescoping rod assembly was designed and constructed to document dynamic crush. The two rods are made of cold-rolled 4130 steel, approximately 56 cm in length, with a 2 cm nominal inner diameter of the thin-wall hollow (female) upper rod, and a 2 cm nominal exterior diameter of the solid (male) lower rod. The rods are not spring loaded, but free to move axially in extension and compression. The rod ends are capped with machined gimbals that fit into bases to allow rapid re-orientation of the rod ends during testing thus preventing binding. The orientation of the rod assembly inside of the vehicle is such that it is perpendicular to the test pad as the vehicle is inverted and ready to be dropped. The driver's seat is removed or modified as necessary to accommodate rod mounting. The top base is riveted into place at the root of the pillar / roof rail interface, and the bottom base is welded to the floor or seat structure.

Once the device is in place, its installed length is measured, and a rubber o-ring is positioned at the exterior mating rim of the female rod. As the rod compresses during impact, the o-ring is displaced by the female rod. As the roof rebounds, the o-ring remains in place. By measuring the distance between the o-ring and the female rod, the amount of dynamic roof crush is determined. In some configurations of this dynamic roof crush measurement device, an ink marker is affixed to the female rod and the tip bears against the male rod in order to provide further visual documentation of relative rod travel. These two measurements were always found to be in agreement. Thus, this simple device documents both permanent (plastic) and dynamic (elastic) deformation of the roof. The rod is examined for free travel before and after testing to ensure no binding has occurred.

RESULTS AND STATISTICAL ANALYSIS

A compilation of the drop testing results is given in Table 1, given in Appendix I. Measurements were made to the nearest sixteenth of an inch, but have been given in SI units to the nearest millimeter. The amount of plastic intrusion for the A pillar varied from a low of 8.3 cm to a high of 42.5 cm, while the elastic varied from 0 - 6.4 cm. The amount of plastic intrusion for the B pillar varied from a low of 3.2 cm to a high of 40.6 cm, while the elastic varied from 1.3 - 7.0 cm. The average dynamic roof crush for both pillars was found to be approximately 4.4 cm.
Figure 1 shows the plastic roof crush plotted against the drop height for both the A and B pillars. As can be seen, the amount of plastic roof crush is not strongly correlated with drop height. These figures show the effect of differing roof strengths across different vehicle designs.

Figure 2 shows two graphs of elastic versus plastic roof crush for both the A and B-pillars. Importantly, there is no apparent trend linking the two different crush types. If least-squares regression lines were added to the plots, they each would show only a very modest positive slope. Calculations reveal that the confidence intervals on these two slope magnitudes includes zero, meaning that there is no statistically significant relationship between the two types of crush.

Figure 3 shows that A & B pillar plastic crush are strongly correlated. As expected, as the A pillar plastic crush increases, the B pillar residual crush also increases. The A-pillar plastic crush was always measured to be greater than that of the B-pillar plastic crush, although sometimes the two values differ only slightly. The average difference between the measurement sites was found to be 5.0 cm. The regression of the B pillar crush on to A-pillar crush is:

$$\hat{B} = 1.13A - 3.06 \qquad (1)$$

where $\hat{B}$ is the predicted residual B-Pillar crush, and A is the measured A-pillar plastic crush. The regression yields an $R^2 = 0.958$. This equation shows that there is an approximate 3 cm crush threshold for the A pillar to induce crush at the B pillar.

As was shown in Fig. 2, the elastic and plastic crush intrusions are not strongly correlated. It is, however, worthwhile to construct a prediction interval for the amount of elastic intrusion that is independent of the plastic crush. That is, *if another drop test were performed for a randomly selected FMVSS-216 compliant vehicle, what interval of elastic intrusion values would bracket the next measured value with a 90% success rate*? Thus, if it is sensible to model crush measurements from the population of FMVSS-216 compliant vehicles as normally distributed, one may use the sample means and sample standard deviations from Table 1 to state such intervals predicting next measured values. Figure 4 shows Q-Q plots for the A and B pillar dynamic crush measurements. The data appears sufficiently "well behaved" to use a standard prediction limit interval analysis. A 90% prediction interval on the elastic intrusion is made as follows [Vardeman and Jobe, 2001]:

$$\bar{x} \pm t_{\nu, 1-\frac{\alpha}{2}} s \sqrt{1 + \frac{1}{n}} \qquad (2)$$

where ν = n-1, n = sample size, and α= 0.90. This yields two prediction intervals for the dynamic A-Pillar (3) and dynamic B-Pillar intrusion crush:

$$0 \text{ cm} \langle A_{0.90} \langle 8.4 \text{ cm} \qquad (3)$$

$$1.3 \text{ cm} \langle B_{0.90} \langle 8.1 \text{ cm} \qquad (4)$$

The A-pillar dynamic intrusion is of greater consequence, as the front seats are more likely to be occupied, and the plastic intrusion of the A-pillar is usually greater than that of the B-pillar in rollover collisions. The FMVSS-216 requires that the vehicle does not exceed 12.7 cm plastic intrusion during quasi-static testing. An 8.4 cm dynamic intrusion into the occupant survival space is a significant fraction of this allowable plastic deformation level.

CONCLUSIONS

During rollover collisions, energy is dissipated at a relatively low rate, making these events much less severe from the point of view of the vehicle than are other types of collision such as frontal impact. Franchini [1969] discussed the "crash survival space" which needs to be maintained for occupant survival. The volume of interior space enveloping the occupant represents the survival space, and takes into account the size, posture and position of the occupant. It is of principal importance in designing a vehicle for crashworthiness. An analysis of the testing presented in this paper sheds new insight into the integrity of the occupant survival space during rollover collisions. It has been shown for the sample set presented that the measured crush at the A pillar exceed that at the B pillar, that the dynamic crush averaged approximately 4.4 cm, and that the amount of plastic and elastic crush are not strongly enough correlated for the relationship to be statistically significant for our sample size. Further, a 90% prediction interval for the elastic intrusion of FMVSS-216 compliant vehicles encompasses 0 – 8.4 cm at the A-pillar, and 0 – 8.1 cm at the B-pillar.

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APPENDIX I – DATA

TABLE I: Plastic and dynamic roof crush measurements.

Make	Model	Year	Roll (°)	Pitch (°)	Drop Height (cm)	Plastic Crush (cm)	Dynamic Crush (cm)	Total Crush (cm)	Location
Ford	Aerostar	1993	25	5	30.5	19.7	5.1	24.8	A Pillar
Ford	Aerostar	1993	25	5	30.5	11.7	5.1	16.8	B Pillar
Ford	Bronco II	1984	25	5	30.5	32.4	6.4	38.7	A Pillar
Ford	Bronco II	1984	25	5	30.5	27.5	5.4	32.9	B Pillar
Ford	F-150	1986	25	5	30.5	42.5	6.0	48.6	A Pillar
Ford	F-150	1986	25	5	30.5	40.6	6.4	47.0	B Pillar
Honda	Accord	1988	25	5	45.7	21.3	4.4	25.7	A Pillar
Honda	Accord	1988	25	5	45.7	10.8	4.1	14.9	B Pillar
Hyundai	Excel	1991	25	5	30.5	21.9	4.8	26.7	A Pillar
Hyundai	Excel	1991	25	5	30.5	17.8	5.1	22.9	B Pillar
Isuzu	Rodeo	1994	25	5	30.5	12.4	1.7	14.1	A Pillar
Isuzu	Rodeo	1994	25	5	30.5	8.9	5.4	14.3	B Pillar
Nissan	Pickup	1985	25	5	30.5	34.6	0.0	34.6	A Pillar
Nissan	Pickup	1985	25	5	30.5	34.5	2.5	37.0	B Pillar
Plymouth	Laser	1992	25	5	30.5	10.2	6.4	16.5	A Pillar
Plymouth	Laser	1992	25	5	30.5	3.2	7.0	10.2	B Pillar
Pontiac	Fiero	1986	25	5	45.7	8.3	3.2	11.4	A Pillar
Pontiac	Fiero	1986	25	5	45.7	3.8	3.2	7.0	B Pillar
Subaru	Loyale	1993	25	5	30.5	17.8	1.3	19.1	A Pillar
Subaru	Loyale	1993	25	5	30.5	11.4	1.3	12.7	B Pillar
Suzuki	Samurai	1988	45	0	91.4	22.9	6.4	29.2	A Pillar
Suzuki	Samurai	1988	45	0	91.4	19.1	6.7	25.7	B Pillar
					$\bar{x}$	**22.2**	**4.1**	**26.3**	**A Pillar**
					s	**10.2**	**2.2**	**10.4**	
					$\bar{x}$	**17.2**	**4.7**	**21.2**	**B Pillar**
					s	**11.7**	**1.7**	**11.8**	

APPENDIX II – Statistical Analysis Graphs

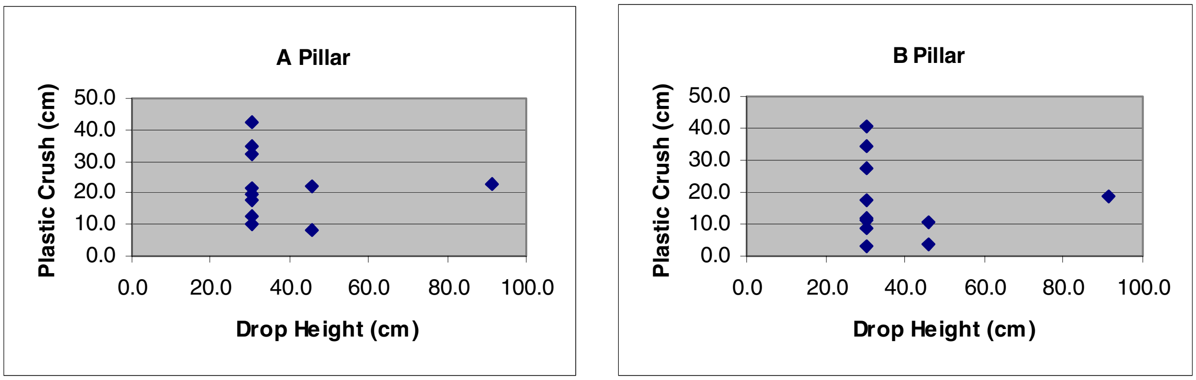

Figure 1. Plastic crush versus drop height for the A-Pillar.

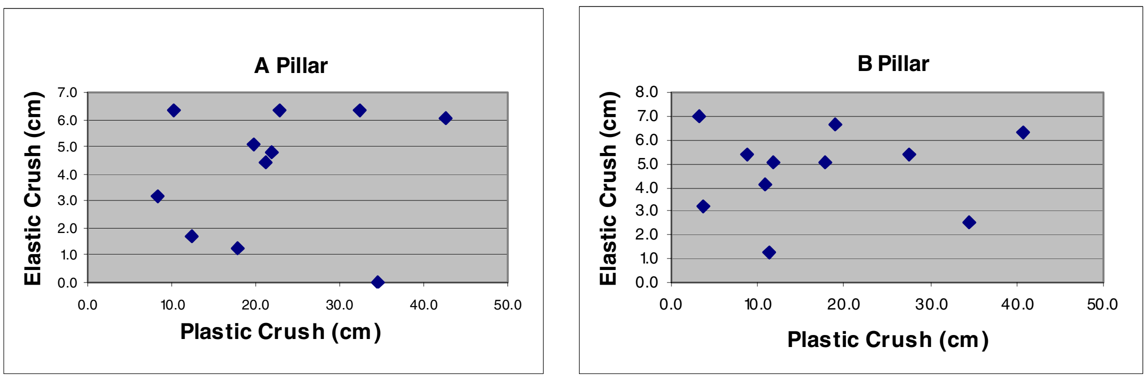

Figure 2. Elastic vs. plastic crush measurements.

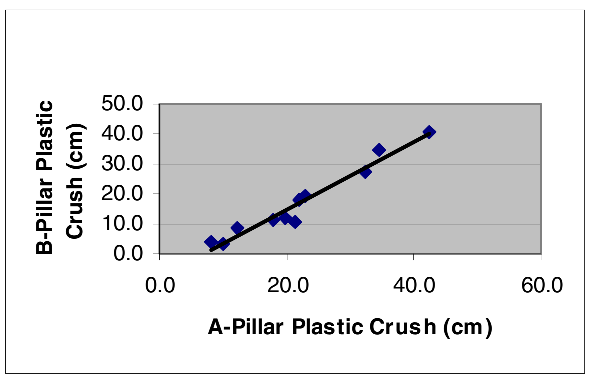

Figure 3. B vs. A pillar plastic crush.

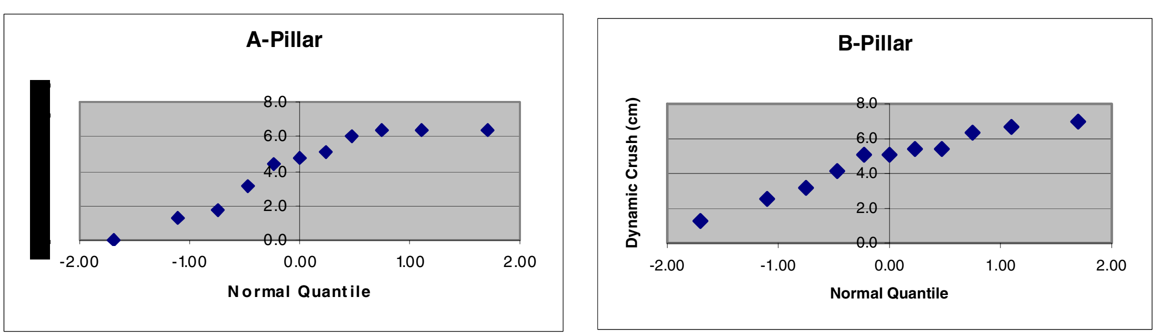

Figure 4. Q-Q Plots – A & B pillars.