

Finite Element Investigation of Seatbelt Systems for Improving Occupant Protection during Rollover Crashes

Jingwen Hu

University of Michigan Transportation Research Institute

Clifford C. Chou and King H. Yang

Wayne State University

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ABSTRACT

The seatbelt system, originally designed for protecting occupants in frontal crashes, has been reported to be inadequate for preventing occupant head-to-roof contact during rollover crashes. To improve the effectiveness of seatbelt systems in rollovers, in this study, we reviewed previous literature and proposed vertical head excursion corridors during static inversion and dynamic rolling tests for human and Hybrid III dummy. Finite element models of a human and a dummy were integrated with restraint system models and validated against the proposed test corridors. Simulations were then conducted to investigate the effects of varying design factors for a three-point seatbelt on vertical head excursions of the occupant during rollovers. It was found that there were two contributing parts of vertical head excursions during dynamic rolling conditions. Part I was induced by stretching of the seatbelt due to the inertia of the occupant, and part II was induced by the lap belt rotation about its anchor point. Simulation results demonstrated that reducing the initial slack of the seatbelt, adding a pretensioner, and changing the sliding latch plate to cinching latch plate could effectively limit the part I head excursion. Changing the lap belt to a more vertical angle and reducing the clearance between the occupant and seatback could effectively limit the part II head excursion. The effectiveness of some new seatbelt designs in rollovers, such as 3+2-point seatbelt, H-type 4-point seatbelt, and double-lap seatbelt, were also evaluated in this study.

INTRODUCTION

As the most complex type of vehicular crashes, rollover crash has gained much attention over the past three decades. However, occupant protection devices specifically designed for rollovers are not as common as those for frontal and side crashes. To date, the most popular passive safety designs for rollover protection are inflatable devices (e.g. curtain airbag, roof airbag, etc.) and the related sensing systems, as reported by Viano [26]. Although curtain airbags have shown to be very effective in reducing occupant ejections during rollovers, their capability in protecting non-ejected occupants has yet to be established. Furthermore, the seatbelt system was originally designed for protecting occupants in frontal crashes, and many previous studies have reported that the present seatbelt system is inadequate for preventing occupant head-to-roof contact during rollovers, inducing fatal/serious head and neck injuries [2, 12]. Although there is still a debate on whether it is "roof crush" or "occupant diving" that induced occupant injuries during rollovers, previous field data analyses [4, 8, 21, 22], experimental tests [2, 17], and computer simulations [7, 10] have all demonstrated the importance of a more effective seatbelt system in occupant rollover protection. Moffatt and James [19] conducted a literature review of experimental tests related to the quantification of occupant vertical head excursion, which is defined as the vertical head displacement relative to the moving seat, during rollovers. They separated the excursion into four categories: inverted static excursion, rotational excursion, impact excursion, and seatbelt anchor excursion. The seatbelt anchor excursion is actually

accounting for the effect due to the roof crush. Therefore, with reference to occupant excursion without roof crush, the value should be the summation of the first three types of excursions. Some assumed estimates for a typical excursion of a belted occupant presented in that study included: "inverted static excursion" 100 mm, "rotational excursion" 50 mm, and "impact excursion" 50 mm. As a result, the estimated overall vertical head excursion for belted occupants during a rollover is about 200 mm, but it was also reported that the typical vertical headroom for an occupant is about 100 mm. Therefore, typical head excursion in a rollover is almost twice the available headroom, even without any roof crush. Obviously, in order to eliminate or reduce the head-to-roof impacts, new seatbelt designs with optimized design factors are critically needed to limit the occupant excursion during rollovers.

The objectives of this study were: 1) to review previous literature and propose vertical head excursion corridors during static inversion and dynamic rolling tests for human and Hybrid III dummy; 2) to validate a human and a dummy finite element (FE) models against proposed test corridors; and 3) to numerically investigate the effects of changing different design factors for a three-point seatbelt on vertical head excursion of an occupant during a rollover. Other than the three-point seatbelt, some new seatbelt design concepts were also investigated.

PREVIOUS EXPERIMENTS

During the past two decades, numerous researchers have attempted to quantify the occupant head excursion in quasi-static inversion tests or dynamic rolling tests using crash dummies, cadavers, and volunteers. A chronological review of some of these studies is presented below.

Bahling et al. [2] conducted quasi-static inversion tests with three 50th percentile male subjects restrained in a three-point seatbelt. An average vertical head excursion of 99 mm was observed. The safety belt was adjusted on the dummy in the subsequent Malibu II tests to duplicate the average head excursion of these three volunteers.

Arndt et al. [1] conducted static and dynamic inversion tests of volunteers and a 95th percentile Hybrid III dummy. Several test configurations with different values of lap belt angle, pretension force and pre-crash belt slack were used. It was found that the average static head excursion of volunteers was about 80 mm with a 45-degree lap belt angle (defined as the angle formed between the floor of the vehicle and the lap belt line from floor anchor to belt buckle) and a 62-N pretension force, but the same test configuration yielded about 110 mm of excursion for the dummy. During dynamic inversion tests, the dummy was subjected to a 4.25-m/s, -5-Gz impact while restrained in aforementioned restraint configurations. It was found that the dynamic head excursion was about 140 mm more than the static head

excursion of the dummy. Because a 95th percentile dummy was used in a purely vertical impact environment, the dynamic head excursion is possibly higher than the head excursion experienced in a rollover. The results of this study also showed that, in general, less pre-crash belt slack and higher lap belt angles produced significant reductions in occupant head excursions.

Herbst et al. [6] and Friedman et al. [5] conducted several static inversion and slow dynamic (100 deg/s) rolling tests with three volunteers, representing a 5th percentile female, a 50th percentile male, and a 95th percentile male, in a seat that was rotated about the center of gravity of the occupant. Three different production restraint systems were used in those tests. The occupant head excursion observed ranged from 114 to 233 mm in the static inversion tests, and from 93 to 258 mm in the dynamic rolling tests. It was also claimed that simple geometric improvements of seatbelt and the application of pretensioner could dramatically reduce the occupant head excursion during rollovers.

Moffatt et al. [18] conducted extensive static inversion tests with a 50th percentile Hybrid III dummy, cadavers, and volunteers. They reported that the average head excursion of the dummy was about 70 mm. However, it was 165 mm for cadavers, and about 128 mm for volunteers. In addition to the static tests, dynamic rolling tests for near-side occupants with a peak roll rate of 280 deg/s were also performed on the dummy and a cadaver. The average head excursion of dummy with 3-point belt in the dynamic tests was about 80 mm. For the cadaver, it was about 120 mm with 9-N pretension force and about 80 mm with pretension force greater than 200 N. The results also showed that vertically-angled lap belt reduced vertical excursion most effectively. A shoulder belt with its D-ring close to the shoulder provided an additional benefit for vertical restraint to the shoulder. Early application of pretensioner loads could significantly reduce head excursions.

Pywell et al. [23] conducted dynamic rolling tests similar to those by Moffatt et al. [18] with a 50th percentile Hybrid III dummy. A peak roll rate of 240 deg/s was achieved in those tests. An average head vertical excursion of 83 mm was found without pretensioner, and 48 mm with pretensioner. It was also reported that single loop restraints with sliding latch plates provided 30% less vertical head excursion compared to dual loop cinching latch plate restraints.

Rains et al. [24] used a device called the rollover restraints tester (RRT) to simulate rollover conditions and to evaluate the effectiveness of restraints in reducing occupant head excursion. The most important advantage of RRT over other test methods is that RRT combined the inversion, rolling and impact together in an attempt to simulate a real rollover scenario. The results showed that the average vertical head excursion was 133 mm for the 50th percentile Hybrid III dummy with a roll rate of 260 deg/s and an impact at 100 degrees of roll. It was reported that raising the D-ring decreased the

dummy head excursion, which is not consistent with the data reported by Moffatt et al. [18]. It was also found that an inflatable restraint could reduce approximately 60 to 75 percent of the vertical head excursion. Note that because an impact was simulated in each test, the excursion data obtained in this study were greater than those from other tests without simulated impact.

Meyer et al. [15] conducted dynamic rolling tests with volunteers in a test setup similar to that used by Herbst et al. [6] and Friedman et al. [5]. It was reported that the average vertical head excursion without a pretensioner was 138 mm, and it reduced to 31 mm when a pretensioner was used. Although the pretensioner has been proven to be very effective in reducing the head excursion during dynamic rolling tests, the results with pretensioner from this study were still much lower than those reported by other studies.

Ward et al. [27] conducted quasi-static inversion tests using a 50th percentile Hybrid III dummy and volunteers in an alert position (i.e. sitting more upright prior to the roll). The vertical head excursion of the dummy with cinching latch plate was 48 mm, and it was 66 mm with a sliding latch plate. The average vertical head excursion for volunteers with a cinching latch plate was 115 mm, and it was 249 mm with sliding latch plate. It was concluded that the cinching latch plate provided better neck protection during rollovers than the sliding latch plate. However, their sliding latch plate tests showed that the vertical head excursions were more than twice those measured in the cinching latch plate tests, which is not consistent with findings from other researchers. One of the reasons for this contradictory result may be due to the fact that the volunteers in this test were in an alert position, which is different from other tests.

Moffatt et al. [16] conducted static inversion tests and extensive dynamic rolling tests under different roll rates (180 – 360 deg/s) with a 5th and a 50th percentile Hybrid III dummy (with seated or pedestrian pelvis) and volunteers. If we combined the data of different rolling side and different sizes of occupant together, the average vertical head excursion of dummies was about 110 mm in a static inversion test, and about 140 mm in a dynamic inversion test with a 220 deg/s roll rate. For volunteers, the average vertical head excursion was 127 mm in a static inversion test, and 138 mm in a dynamic rolling test with a 220 deg/s roll rate. During the tests, most of the dummies were instrumented with a pedestrian pelvis, which may generate greater excursion data. Far-side rollovers caused the test subjects to have about 50% greater head excursion than near-side rollovers. It is interesting to note that the head excursion data from dummy and volunteers were very similar in this study.

In summary, in all the previous studies that were reviewed, the average vertical head excursions of dummies ranged from 48 to 110 mm in static inversion tests and from 80 to 140 mm in dynamic rolling tests. For volunteers, the range of the average vertical head excursions was from 80 to 249 mm in static inversion tests and from 120 to 220 mm in dynamic rolling tests.

VALIDATION CORRIDOR

In order to validate the restraint system, dummy, and human FE models, results from quasi-static inversion tests and dynamic rolling tests could be used. However, different test configurations were applied in the previous tests. Consequently, the combined results showed a large test to test variation. For this reason, in our current study, the aforementioned test data under similar test conditions were selected for validating the FE models based on the following criteria.

For the restraint system, only three-point seatbelts without pretensioner or with small pretension forces (< 70 N) were selected. Tests with lap belt angle of 90-degree were eliminated because no current production seatbelt is designed that way. Only seatbelts with sliding latch plate were selected, since the cinching latch plate is not used in current seatbelt systems. In addition, only tests using a Hybrid III dummy with seated pelvis were selected, because our current dummy model has a seated pelvis. During static inversion tests, the test configuration did not change very much, so all the data from static inversion tests were selected. However, for dynamic rolling tests, the test configurations used were very different, thus only tests with rolling rates greater than 180 deg/s were selected. In Rains' study [24], there is an extra impact to the system, which consistently generated about 50 mm extra vertical head excursion. Therefore, the vertical head excursion data from Rains' study minus 50 mm was chosen to validate our models. In Ward's study [27], the volunteer head excursion data under static inversion test was much greater than other tests, so it was eliminated from our validation dataset. In Bahling's study [2], an average of 99 mm head excursion of three volunteers was reported in a static inversion test. Since they did not report the results on a case by case basis, three 99 mm were assumed in the validation dataset.

The selected validation dataset is shown in Table 1. In static inversion tests, the average head excursion for the dummy was 73.8±19.5 mm, and it was 124.8±30.8 mm for the human. In dynamic rolling tests, the average head excursion for the dummy was 89.6±22.9 mm and 116.1±30.5 mm for the human.