Seatbelt submarining injury and its prevention countermeasures: How a cantilever seat pan structure exacerbate submarining

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Abstract

The purpose of this study and a case report was to demonstrate seat belt webbing induced injury due to seatbelt submarining during the frontal motor vehicle crash. Submarining is an undesired phenomenon during a frontal crash scenario and is dependent on design features of the seat pan and seatbelt system. The lack of adequate anti-submarining features at any seating position with three-point restraint can cause abdominal solid and hollow organ injuries. This paper reports a case of submarining and factors that exacerbated this phenomenon leading to critical occupant abdominal injury. This case report and the following injury causation analysis demonstrate the shortcomings of a cantilever seat pan design in context to the occupant safety. The inadequate seat pan anti-submarining feature in association with lack of seatbelt load-limiter and Pretensioner reduces the level of occupant protection offered by the seat belt system in the rear seat. This case report shows the dangers of cantilever seat pan design and its association with increased risk of submarining causing severe abdominal injuries.

Keywords: Contoured seat pan, liver, load-limiter, pretensioner, submarining

Introduction

The seatbelt is the most important safety device in the vehicle protecting an occupant in every crash scenario. The National Highway Traffic Safety Administration report shows the effectiveness of seat belts in saving lives similar to many other reports and studies. However, many have reported seat belt induced injuries in the past. The level of protection offered by the seatbelt is reduced if the load transfers to relatively soft anatomical regions such as abdomen and chest wall. This phenomenon is called submarining. The classical definition of submarining is “the lap belt sliding over the iliac crest with lap belt forces affecting the internal abdominal organs during the forward displacement of the lower torso.”

Case Report

The 61-year-old Hispanic male sustained critical abdominal and thorax injuries in the frontal crash. Figure 1 shows the crash location and vehicle orientation postcrash. He was seated in the right rear seat position of the pickup (a small truck with an enclosed cab and open back). The seat at this location featured a cantilever type seat pan structurally unsupported at the front end as shown in Figure 2. Figure 3 shows the pickup frontal damage. He was complaining, “my stomach and chest hurts” at the crash scene based on the emergency medical service responders report. This report also indicates the presence of positive lap and shoulder belt bruising on the occupant. The computed tomography (CT) scan study at the hospital revealed grade 5 liver laceration with small bowel perforation and left first, second, third and fourth rib fractures with pneumothorax as shown in Figure 4. He also sustained associated right C7 transverse process fracture with no cerebrovascular injuries. Head and neck CT studies were unremarkable. Table 1 shows his injury severity as per the Abbreviated Injury Scale (AIS) scale, and Table 2 shows several operative procedures conducted on him in the hospital. He expired after 20 days of treatments and operations in the hospital. He developed septic shock and progression of his liver failure.

Discussion

During impact, he moved forward at the initial vehicle speed due to inertia until acted upon by the lap and shoulder belt

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restraining force. The left multiple rib fracture pattern with abrasion and bruising on the left chest occurred due to shoulder belt loading. The fracture pattern of the ribs is consistent with excessive anterior chest compression on the left side. The Toyota Central R and D Labs Research,\textsuperscript{10} based on computational model, showed lateral rib fracture along the path of the diagonal belt similar to a 30 mph frontal crash scenario. Figure 3 shows the zoomed rib fracture pattern and its location. This fracture pattern supports the fact that the shoulder belt load was more directed to the chest instead of on stronger anatomical regions such as clavicle and his right shoulder. The absence of a load-limiter likely subjected his chest to higher load and increased the severity of his chest injury. Foret-Bruno \textit{et al.}, 1998\textsuperscript{11} showed more than 50% probability of AIS 3+ thorax injury for a 60-year-old occupant with shoulder belt load \( \geq 5000 \) N (Newton). The associated right C7 transverse process fracture and absence of sternum fracture verify the shoulder belt load path, consistent with his submarining. Arndt 1975\textsuperscript{12} reports of C7 and T1 transverse process fracture for drivers on the left-hand side due to shoulder belt contact. The absence of a load-limiter and pelvis forward and downward motion most likely caused the shoulder to lag the pelvis. This motion positioned his upper torso in a more reclined configuration as shown in Figure 5 by the unfavorable kinematics image. In the past, researchers\textsuperscript{8,13,14} have shown the effect of these kinematics to cause the lap belt to ride over anterior superior iliac spine. This riding over cause severe loading of the abdomen, causing solid and hollow organ injuries.\textsuperscript{13,14} The lap belt riding on the abdomen due to his submarining is the source of injury to his abdominal solid and hollow organs. The force exerted by the lap belt caused bruising on the lower and mid abdomen along with all of his internal injuries.

Car manufactures have shown the efficacy of a fixed stiff contoured seat pan structure at a rear seat location in the

| Injury                                      | AIS 2005          |
|---------------------------------------------|-------------------|
| Liver laceration level 4-5                  | 541828.5 (critical)|
| Mesenteric avulsion                         | 542026.4 (severe) |
| Perforation of small bowel                  | 541424.3 (serious)|
| Necrotic omentum                            | 542299.2 (moderate)|
| Left chest wall (rib fractures)             | 450203.3 (serious)|
| C7 transverse process fracture-right        | 650620.2 (moderate)|

AIS: Abbreviated injury scale
frontal crash in the past. This design has been shown to produce favorable occupant kinematics by preventing the pelvis from moving forward and downward reducing the risk of submarining.\cite{17,18} High cushion thickness at the front end of the seat pan has been linked to worsening the submarining.\cite{19} Any counter measure that ensures the upward motion of the H-point (pelvis) and the reduction of upper torso angle (getting more acute) during the forward motion of the pelvis is capable of eliminating or reducing submarining. Several United States seat pan patents demonstrate different ways of achieving this favorable pelvis kinematics.\cite{20‑22} The analysis of a seat pan structure of a similar vehicle is shown in Figure 6. The seat pan is a smooth plane stamped surface with a nonrate sensitive cushion on top of it and features a 13–14° upslope. All the features along with its overhanging structure make it less desirable for anti-submarining performance. A seatbelt equipped with a pretensioner and a load-limiter further improves the occupant kinematics by allowing forward rotation of the upper torso with adequate pelvis restraint.\cite{23,24} William Haddon matrix, as shown in Table 3, provides an opportunity to understand the various factors influencing the outcome of a crash in different phases. This systematic approach to injury prevention is crucial to Indian conditions.\cite{25} In the case study discussed, the vehicles cantilever rear seat design, reduced the level of occupant protection by making it unreasonably dangerous in a frontal crash scenario. During the impact phase, vehicles crashworthy performance is the single most important factor that prevents or reduces the severity of injuries to the occupants. The weather conditions during the crash were good with dry road surface and good light conditions. The posted speed limit at the crash site was 55 mph (88 kph).

**Recommendation**

A stiff fixed contoured anti-submarining seat pan with a seat belt equipped with load-limiter and pretensioner is the best countermeasure to tackle occupant submarining and subsequent abdominal injuries. The stiffer fixed, properly supported seat pan, instead of a cantilever seat pan would have prevented the downward deflection of the pan while the forward excursion of the pelvis. This downward dynamic deflection worsened the lap belt riding on the abdomen. This knowledge will assist Indian automotive design

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**Table 2: Operative procedures conducted on the occupant**

| Day after crash | Operative procedures |
|-----------------|---------------------|
| Day of crash    | Insertion of left 32-French chest tube-Left pneumothorax |
|                 | Exploratory laparotomy for trauma |
|                 | Small bowel resection × 4 |
|                 | Hepatorrhaphy × 2 |
|                 | Packing of liver |
|                 | Placement of wound VAC |
| Next day        | Second-look laparotomy - Traumatic shock |
|                 | Small bowel resection |
|                 | Repacking of liver laceration |
|                 | Suture of 4+ cm liver laceration |
|                 | Repacking of liver with multiple pads |
|                 | Placement of ABThera with open abdomen |
| 3 days after crash | Exploratory laparotomy |
|                 | Cholecystectomy |
|                 | Hepatorrhaphy with wrapping of liver with Vicryl mesh |
|                 | Resection of segment of small bowel |
|                 | ABThera placement |
| 4 days after crash | Exploratory laparotomy with removal of lap packs from around liver |
|                 | Small right colon resection with ileocolonic stapled anastomosis |
|                 | Small bowel-to-small bowel anastomosis |
|                 | Placement of ABThera for open abdomen |
| 6 days after crash | Exploratory laparotomy with abdomen washout |
|                 | Closure of abdominal wound with ABThera |
| 8 days after crash | Exploratory laparotomy |
|                 | Partial omentectomy |
|                 | Negative pressure therapy 20 cm × 30 cm |
| 10 days after crash | Bronchoscopy with bronchial washing - Severe acute respiratory failure |
| 11 days after crash | Exploratory laparotomy |
|                 | Abdominal washout |
|                 | Rectus advancement flap, right, and left |
|                 | Negative pressure therapy 20 cm by 30 cm |
| 14 days after crash | Bronchoscopic guided percutaneous tracheostomy-Respiratory failure |
| 15 days after crash | Central line placement |

VAC: Vacuum-assisted closure
Thorbole: Seatbelt submarining injury

| Phase   | Goal                      | Human                  | Vehicle                | Environment                      |
|---------|---------------------------|------------------------|------------------------|----------------------------------|
| Preimpact| Accident prevention       | Education/enforcement | Accident prevention technologies | Road design, weather conditions, road surface condition (dry/wet) |
| Impact  | Injury prevention         | Using available safety system | Crashworthiness, occupant protection features | Roadside barriers |
| Postimpact | Life support             | EMS, fire, aid         | No fire risk           | Quick rescue facility            |

EMC: Emergency medical service

engineers to develop a more effective injury prevention scheme for rear seat passengers. Emergency medical responders will also benefit from this study by identifying and understanding the submarining and suspecting serious underlying abdominal injuries. This knowledge facilitates in prompt diagnosis and treatment of injuries.

Conclusion

The downward dynamic deflection of the rear seat pan and the unavailability of advanced seat belt features such as load-limiter and pretensioner are the fatal injuries producing cause in the crash investigated. The study explains the injury mechanism and countermeasures to prevent such injuries. The occupant died due to his abdominal injuries after 20 days in the hospital.

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