

Head Injuries in Rollover of Military Armoured Vehicle

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Abstract

Rollover crashes in vehicles are disproportionately more dangerous and pose a relatively higher risk of severe injuries and fatality rates compared to other configurations, such as frontal and side crashes. To date, no study has been conducted on injury outcomes of rollover accidents involving military armoured vehicles. This study was conducted to examine the driver's response in the rollover of SIBMAS 6X6 and to evaluate the severity of head injury in the incident using finite element simulation. Hybrid III 50th percentile male dummy was incorporated to represent a driver and was thus configured to simulate a typical seated driving posture. In terms of initial kinetic energy capable of producing two quarter-turns of rolling with vehicle roof landing, rollover intensity was imposed via initial angular velocity applied to the whole vehicle. The dummy's head was observed to make three significant impacts with hull interior structures from the initiation of rollover and until the roof landed on the ground. Head injury severity was evaluated based on the resultant acceleration of the head center of gravity and 15 ms duration Head Injury Criteria (HIC15). The maximum values of these two criteria were 531g and 9098g, respectively. Evaluation of these severity values concerning the associated injury risks and fatality rates as classified in the Abbreviated Injury Scale (AIS) indicated that the head injuries sustained by the driver were mostly fatal.

Keywords: *armoured vehicles; rollover crashes; rollover injuries; rollover simulations; SIBMAS 6X6*



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INTRODUCTION

Rollover crashes occur much less frequently compared to other configurations, such as frontal and side crashes, but in general, they are disproportionately more dangerous and pose a relatively higher risk of severe injuries and fatality rates. For example, of all motor vehicle crashes in 2020 in the US, only about 2% involved a rollover, but it accounted for approximately 30% of all deaths (National Highway Traffic Safety Administration, 2022). In Australia, about 19% of fatal crashes were due to rollover (Rechnitzer and Lane, 1994), while in Europe, it is around 10-20%, depending on the country (Ferguson, 2007). Compared to typical planar collisions, serious and fatal head, neck, and spine injuries are more common in rollover crashes (Yoganandan et al., 1989). For example, the head, brain injury, and hemorrhage accounted for the majority of significant injuries, with the remaining attributed to fractures of the skull (Mattos et al., 2013), whereas most of the major injuries for the spine were fractures (Bambach et al., 2013).

Deadly rollover incidents also occurred for military armoured vehicles. In July 2014, an army sergeant and a corporal died while two other army personnel suffered injuries when the armoured vehicle SIBMAS 6X6 they were in skidded and rammed onto the road divider on the Malaysia North-

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South Expressways before it overturned (ASTRO, 2014). On the other hand, a report from the United States Government Accountability Office (2021) found that 123 soldiers and marines died in 3,753 non-combat tactical vehicle incidents between 2010 and 2019. The report found that despite being responsible for one-quarter of the accidents, rollover crashes accounted for 63% of the deaths reviewed in the study and were by far the deadliest kind of accident.

Given the high fatality rate involved in rollover incidents and different designs of interior structure in armoured vehicles compared to regular passenger-cars, sports-utility vehicles, trucks, etc., the current study was thus initiated with the aim to investigate the driver's head injury due to impacts with hull and to evaluate the severity of the head injuries in an under turn rollover crash using finite element simulation. It is hoped that findings from the study will provide useful input, which is important for designing effective precautions and countermeasures to minimize the related casualties.

LITERATURE REVIEW

The two common criteria for assessing the severity of head injury are the resultant peak acceleration measured at the head's center of gravity and the Head Injury Criterion (HIC) score. HIC measures the likelihood of injury arising from an impact, defined (Kleinberger et al., 1998) as:

$$HIC = \max \left\{ (t_2 - t_1) \cdot \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) dt \right]^{2.5} \right\} \dots \dots \dots (1)$$

where t_1 and t_2 are the initial and final times selected to maximize HIC value, with the acceleration measured in standard gravitational acceleration, gs . The time duration from t_1 to t_2 is usually 15 ms (HIC_{15}) and is limited to a maximum value of 36 ms (HIC_{36}). The HIC_{15} is considered more restrictive as it associates with a higher risk level than the HIC_{36} for the same HIC score (Hodgson and Thomas, 1972; Prasad and Mertz, 1985). Therefore, only the HIC_{15} will be examined in the present study.

HIC scores are correlated with the likelihood of different severities of head injury that are classified in the Abbreviated Injury Scale (AIS) (Association for the Advancement of Automotive Medicine, 2015). The relationship between the HIC and the probability of injury was presented by Prasad and Mertz (1985) as a group of sigmoidal curves. These curves can be described using the following exponential model, with the coefficients corresponding to each of the AIS levels as summarised in Table 1:

$$p(AIS) = 1 - \exp(-a \cdot HIC^b) \dots \dots \dots (2)$$

Table 1. Coefficients values of the exponential model of equation (2)

AIS Scale	a	b
Minor (AIS 1)	8.79×10^{-06}	1.94
Moderate (AIS 2)	4.18×10^{-07}	2.24
Serious (AIS 3)	9.00×10^{-09}	2.64
Severe (AIS 4)	2.34×10^{-09}	2.69
Critical (AIS 5)	2.23×10^{-19}	5.66
Usually fatal (AIS 6)	4.76×10^{-31}	9.03

In addition to classifying the injury severity into a six-division ordinal scale, as shown in Table 1, each of the AIS scales is indeed associated with risks of threat to life, or fatality rate, as summarised in Table 2 (Hayes et al., 2007). This relationship was reported in AIS 2005 (Association for the Advancement of Automotive Medicine, 2016) in a nearly perfect nonlinear correlation, i.e., with a coefficient determination (R^2) of 0.9934.

Table 2. AIS levels and the corresponding fatality rates

Severity scale	Injury severity	Fatality rate
1	Minor	0.0
2	Moderate	0.1-0.4
3	Serious	0.8-2.1
4	Severe	7.9-10.6
5	Critical	53.1-58.4
6	Maximum (untreatable)	-

RESEARCH METHOD

The reference armoured vehicle used in the present study to simulate rollover crashes is SIBMAS 6X6 AFSV-90, which measures 7.32 m in length, 2.5 m in width, 2.24 m in height to hull top, and 2.77 m to turret top. The wheelbase measured 2.8 m for the mid-row wheels and 4.2 m for the rear ones. The finite element (FE) model of the SIBMAS was created based on the CAD model created using photogrammetric techniques. The meshed FE model of partially opened SIBMAS in Figure 2 shows the general compartment layout of the vehicle interior. The SIBMAS body is generally made from high-strength steel, of which deformations are negligible during the rollover. Thus the detailed material input data is not crucial as it can be modeled as an assemblage of rigid parts.

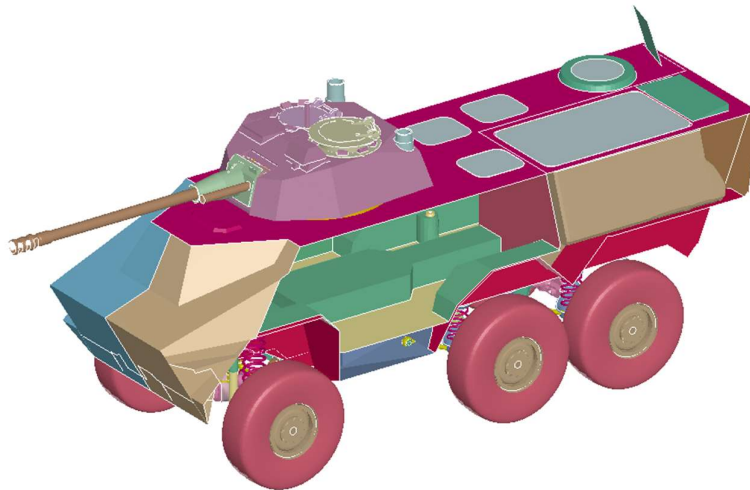


Figure 1. Created finite element model of SIBMAS AFSV

For this exploratory study, with the main focus on the driver's head impact-contact points with the vehicle interior during a rollover incident, a more efficient dummy model, i.e., LSTC Hybrid III Fast Dummy 50th percentile male, was used in the current simulations to represent the driver. The dummy model consists of 119 parts, 2566 deformable elements, 1712 rigid elements, and 7074 nodes. Detailed specifications, calibration data, and pre- and post-processing procedures of this model for quantitative analysis are documented in (Guha et al., 2011). The dummy was positioned and orientated to simulate a driver posture, as shown in Figure 3, where it was adjusted to sit on the driver seat, with the buttocks fine-tuned to merely touching the seat surface. The initial seat deformation due to the sinking of the dummy into the seat under gravity was neglected since the chair surface is horizontal, and the buttock would not be sliding but leaving the seat immediately once the rolling initiated. The upper and lower legs were adjusted such that the heels of the shoes were just resting on the cabin floor. The hands were adjusted to merely touching the steering wheel.

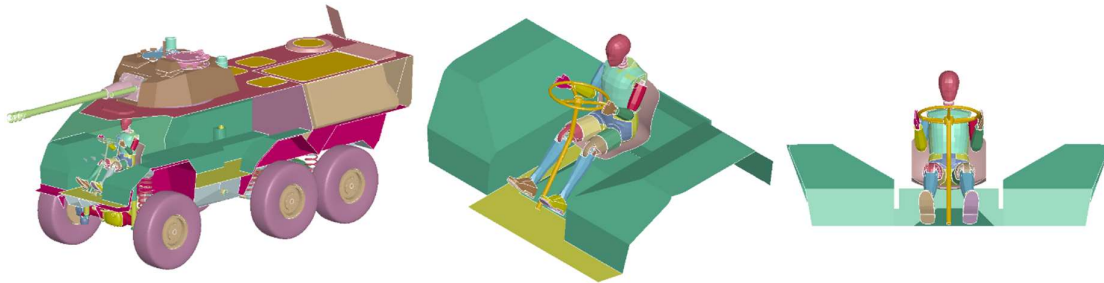


Figure 2. The dummy is positioned and orientated on the driver's seat.

For the dummy to experience some diving/falling motions during the rollover, an approximate initial angular velocity sufficient to produce at least two quarter-turns (180°) at landing was imposed on the entire vehicle, of which the final magnitude was set as 1.9765 rad/s . With the roll mass moment of inertial of $7.492 \times 10^4 \text{ kgm}^2$ concerning the rolling axis, the resulting initial kinetic energy was $1.457 \times 10^5 \text{ J}$. As it would be impractically long to simulate the rollover event until the vehicle came to a complete stop, the simulation was terminated when less than 5% of the kinetic energy was left in the system.

FINDINGS AND DISCUSSION

The time histories curve of the head resultant acceleration presented in Figure 3 signifies the three key instants when the head impacts occurred, i.e., at the time 0.22, 1.22, and 1.29 s, and the corresponding peak magnitudes of the head resultant acceleration are $139g$, $531g$, and $144g$, respectively. The computed HIC_{15} scores were found to follow the magnitude order of the head resultant acceleration, which was 9098, corresponding to the second impact, followed by 3456 and 2086 of the third and first impacts, respectively.

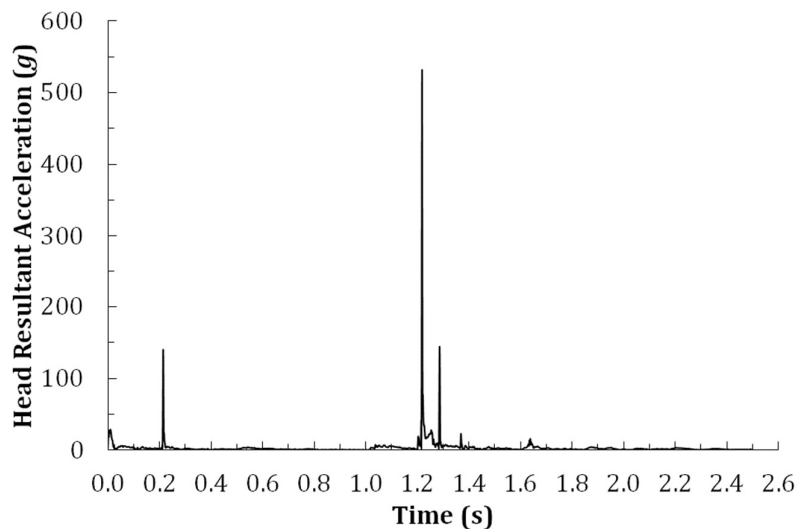


Figure 3. Time history of head resultant acceleration in the rollover

The severity of the head injury suffered by the dummy in the simulated rollover was significantly higher than the head's corresponding injury assessment reference values (IARVs). The

IARVs are the limits of severity a dummy can sustain for less than a 5% chance of the injury occurring. The IARV for the midsize adult male based on peak resultant acceleration is 180g, which corresponds to a 5% risk of skull fracture (Mertz et al., 1997), while the limit for HIC₁₅ is 700, which corresponds to a 5% risk of skull fracture and 5% risk of AIS_{≥4} brain injury (Mertz et al., 2003). However, in cases of serious crashes in which injuries are primarily serious, severe, or even critical, the IARVs are not so helpful in assessing severity since the values would mostly be exceeded, and the focus then often on chances of survivability, such as the threat to life ranking based on AIS scale (Table 2).

For the peak resultant acceleration, the value at about 410g would cause a 99.9 % chance of skull fracture, according to the report of Mertz et al. (1996). In the current simulated rollover outcomes with the peak value of 531g, the skull fracture thus for sure occurred. The injury risks associated with HIC₁₅ scores for the three head impacts in the rollover, calculated based on Equation 2, are summarised in Table 4. It can be that the resulted in HIC₁₅ scores of 9098 (second impact) and 3456 (first impact) are extremely high such that even at AIS 6 level, the associated probability is 100%, i.e., the definite fatal head injuries.

Table 4: Injury risk associated with head injury based on HIC₁₅ scores

HIC ₁₅	$p(\text{AIS} \geq 2)$	$p(\text{AIS} \geq 3)$	$p(\text{AIS} \geq 4)$	$p(\text{AIS} \geq 5)$	$p(\text{AIS} \geq 6)$
9098	1	1	1	1	1
3456	1	1	1	1	1
2086	1	0.99	0.86	0.75	0.36

The first impact was predominated by axial loading exerted on the vertex of the head, which would result in basilar skull fractures without concomitant vault fractures. It would also involve fracturing of the occipital condyles without concomitant brain injury (Bambach et al., 2014). Brain injury is always a primary concern in any head impact. Skull fractures with severe brain damage tend to occur at AIS_{≥4} (Benetton et al., 2017). The dummy in the simulated rollover condition was undoubtedly not survivable with critical brain damage, as indicated by 100% AIS 6 injury level in Table 4.

CONCLUSION

The study identifies the severity of head and neck injuries and the associated injury risks and fatality rates experienced by the 50th percentile male dummy in the rollover of the SIBMAS 6X6 armoured vehicle. The study also identifies the potential locations of the head and the vehicle interior where the impacts would most likely occur throughout the rollover. Even at the rollover intensity of two quarter-turns, it could result in absolute fatality. The causes of death are mainly due to severe skull fractures, brain injuries, and neck fractures. It is recommended that some cushioning elements be placed at the potential impact locations in the driver compartment to minimize the severity of injuries. Also, the driver should always apply at least a lap belt to prevent being ejected from the seat and subsequently sustaining multiple impacts in this section.

LIMITATION & FURTHER RESEARCH

In future research, initial velocities with combinations of linear and rotational components shall be imposed for more realistic simulation conditions and parametric studies with various rollover intensities shall be conducted to obtain more generalized dummy responses in rollovers.

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