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Evaluation of SUV Roof Crush Analysis using Alternative Non-Linear Structural Analysis Solver

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Abstract – *Accidents involving rollover in countries although low in numbers, recorded the highest Killed & Severed Injury (KSI) index and highest fatality index. The roof Crush Resistance test has been found to be one of the relevant tests to anticipate the impact of rollover incidents. However, a very limited number of research has been done on roof crush analysis using non-linear RADIOSS solver. Therefore, the aim of this study is to develop an FE model for roof crush analysis using RADIOSS and to validate and compare the RADIOSS model to LS-DYNA. An SUV is selected, and its finite element (FE) model obtained from CCSA is converted from LS-DYNA to RADIOSS with equivalent element type, element properties, material, and damage modelling adjustment. The analysis is performed according to FMVSS 216 standard and the result of deformation and SWR plot is compared to the NHTSA report. From the result, it has been shown that RADIOSS is a good alternative to run highly non-linear analysis such as roof crush analysis.*

Keywords: Roof crush analysis, FMVSS 216, RADIOSS

1.0 INTRODUCTION

Road vehicles are the main mode of transport for land mobility and have become one of the basic needs for people whether for personal use or commercial. It is very common for every household to have at least one motor vehicle and thus adding to the number of vehicles on the road. ASEAN Automotive Federation (AAF, 2020) reported that there are 3,458,482 units of motor vehicles (excluding motorcycles & Scooters) were sold in 2019 in all ASEAN countries (excluding Cambodia & Laos). From these figures, about 65% are passenger vehicles, and 35% are from commercial vehicles. In addition to that, ASEAN top 10 best-selling cars in 2019 were dominated by pickup trucks, SUVs, and MPVs (Focus2Move, 2020). These types of vehicles have become popular these days mainly due to their practicality, durability, affordability, and many other advantages. Nevertheless, despite all these advantages, there is also a drawback to these types of vehicles that associate its center of gravity (CG), which is higher compared to sedan or hatchback. Therefore, a higher center of gravity causes the static stability factor (SSF) for the vehicle to be lowered and the chances for rollover to occur are very high (Marie, 2005).

Rollover is a type of major road vehicle crash that can cause fatal injuries. Even though accidents involving rollover across the countries are considerably low in numbers, it has recorded a high Killed & Severely Injured (KSI) index. Therefore, it is significant to investigate various aspects that induce rollover crashes and their effect on the severity of driver's injury (Cong, 2016; Santosa et al., 2018). Rollover crashes happened through interaction between the driver, the vehicle, and the environment (Office of the Federal Register, 2010). However, this research will be focusing on the vehicle factor.

A rollover crash is very complex, as it associates with multi-directional dynamic behavior and involves numerous impacts. Any small changes that occur will significantly affect the rollover outcomes. Rollover test is one of the ways to mimic the real rollover condition, but it is very expensive (Robert, 2019). Therefore, computer simulation is the best option to replicate the rollover at the early stage. In a rollover crash, the roof of the vehicle is the most important structure that will be the ultimate protection for vehicle occupants. It needs to be strong enough to withstand the impact of a rollover crash. The roof Crush Resistance test is one of the relevant tests to anticipate the impact to the vehicle structure as it is correlated to the rollover incidents. There are a few options simulation software that can be used to simulate Roof Crush Resistance including LS-DYNA and RADIOSS. The most used explicit simulation program that can simulate the response of the material to short periods of severe loading is the Ansys LS-DYNA.

Anandkumar (2016), for instance, has used Ansys LS-DYNA to conduct a roof crush test to evaluate an alternative material for the roof (Docol 1000dp) by comparing it to the baseline material (Steel). The roof crush test was performed according to FMVSS 216 standard and the same standard was also use for the rigid plate that is used to crush the car. For the mesh and boundary condition setup, Hypermesh software was used. IIHS (Insurance Institute of Highway Safety) on the other hand was used to determine the orientation between the car and the rigid plate. The result shows that Docol 1000dp have more strength to weight ratio (SWR), hence more crashworthy compared to the baseline material. Wook et al. (2017) have proposed the Enforced Displacement Method for roof structural optimization, which is a novel method for nonlinear dynamic response. They use LS-DYNA for nonlinear dynamic response to perform roof crush analysis in their study to optimize the roof structure. Whereby, the structural optimization for a linear static response was solved by NASTRAN software. The variances between a nonlinear dynamic analysis response and a linear static analysis response were compensating by using a correction factor with enforced displacement. Cezary et al. (2011) also used LS-DYNA to perform explicit FE simulation roof strength assessment for paratransit buses to compare results from two different rollover test standards which are the ECE-R66 and FMVSS 220. The two tests that have been conducted are the dynamic rollover test (ECE-R66) and the quasi-static roof crush resistance test (FMVSS 220). They found that the result from the standards has some differences. Anders et al. (2019) on the other hand used the implicit solver to analyze the roof crush for Volvo XC40, also by using the LS-DYNA software. They point out that for Volvo cars, usually the roof crush analysis was done by using explicit solver in LS-DYNA. The finite element models that were used are the same model for the side impact load case. Therefore, to perform implicit analysis, a minor modification was done to the finite element models that initially prepared for explicit analysis. They also suggested the LS-DYNA implicit solver be used for large-scale analysis, as the results show good agreement with the explicit analysis.

From all this literature, most of the researchers tend to use LS-DYNA for rollover or roof crush analysis. Nevertheless, a limited number of research on roof crush analysis using non-linear RADIOSS solver are found. For that reason, this study aims to develop an FE model for SUV roof crush analysis using RADIOSS according to FMVSS 216 standard and to validate and compare the RADIOSS model to LS-DYNA.

2.0 METHODOLOGY

This section describes the assessment of Roof Crush Analysis using RADIOSS Solver against LS-DYNA. The description begins with two main parts: the FE model development, which was developed based on the LS-DYNA model. After that, Roof Resistance Test Rating for both solvers against actual physical test is examined.

2.1 Roof Resistance Test Rating

In FMVSS 216 test, the vehicle roof is crushed by an angled metal plate to a minimum displacement of 127 mm at a slow but constant speed. The force required to crush the roof is recorded along with the angled metal plate travel. The recorded force is then divided with measured vehicle curb weight to calculate the SWR value. The formula is as shown in Equation 1. Peak SWR value is a vital factor in assessing the roof strength resistance of a vehicle. It can be assessed by IIHS roof strength rating boundaries as shown in Table 1. The SWR formula is as demonstrated in Equation 1 below:

$$SWR = \frac{Peak\ Force\ (N)}{Vehicle\ Curb\ Weight\ (N)} \tag{1}$$

Table 1: IIHS roof strength rating boundaries

SWR	Rating
≥ 4.00	Good
≥ 3.25 to < 4.00	Acceptable
≥ 2.50 to < 3.25	Marginal
< 2.50	Poor

Curb weight and force are rounded to the nearest Newton value, prior to the calculation and the resulting SWR is rounded to the nearest hundredths. IIHS roof strength rating boundaries shown in Table 1 could be displayed graphically in chart form of SWR against plate displacement as depicted in Figure 1. The chart area on the y-axis is divided into good, acceptable, marginal, and poor ratings based on the corresponding SWR value. Vehicle A in Figure 1 is considered as good because the maximum SWR falls in the good rating region in green color, whereas Vehicle B is rated poor due to its peak SWR value is located in the red color region.

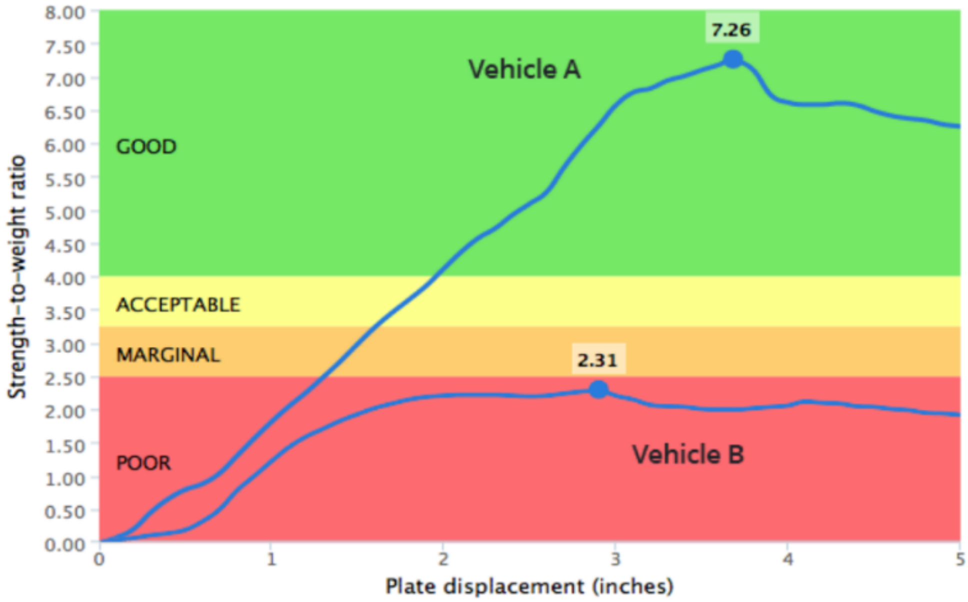

Figure 1: IIHS roof strength rating boundaries

Table 2: Specification of Chevrolet Silverado 1500 MY2015 (Crew Cab)

Specification	Details
Body style	Large pickup (Crew Cab)
Engine	Longitudinal 5.3-liter V8
Transmission	6-speed automatic, Rear-wheel drive (RWD)
Weight	23,000 N

The vehicle has undergone IIHS Roof Strength Test Protocol, Version 2 and conforms to Large Pickups equipment & trim levels specified in the protocol as detailed in Table 2 (Insurance Institute for Highway Safety, 2016).

2.2 FE Model Development

The description of the procedures of this research is illustrated in Figure 2. Initially, the Chevrolet Silverado 2014 model was selected because of its large pickup body style and its SSF rating of 1.19 according to National Highway Traffic Safety Administration (NHTSA) report. The rating which is considered as poor holds a 28 to 30 percent possibility of a rollover (Scotti, 2018). In this research, the vehicle was modelled to be loaded with an angle-positioned impactor plate normal to the roof which is demonstrated in Figure 3. In this standard, the impactor contact to the roof was located at 254mm to the end of the windshield. This simulation is in accordance with FMVSS 216 standard, Roof Crush Resistance. The Finite Element (FE) model was developed based on the LS-DYNA model from the Center for Collision Safety and Analysis (CCSA). The baseline model is in LS-DYNA format and then changed to RADIOSS format. During this conversion, RADIOSS automatically carries over the mesh size and structure from the original model. Basic FE parameters such as material model, connectors, contact modelling and element formulations among other things are set to the equivalent RADIOSS parameters using Hypercrash, as the pre-processor for the RADIOSS solver.

Although Hypercrash was able to automatically convert them, revision of the FE model and its parameters was required as some of them were not set up correctly. In case of no equivalent parameter exists in RADIOSS, a new parameter needs to be defined to suit the RADIOSS solver requirement. This is the case for the contact modelling in RADIOSS, whereby TYPE 7 RADIOSS contact model was created to model the contact between the vehicle with the impactor as well as the contact between the vehicle component itself.

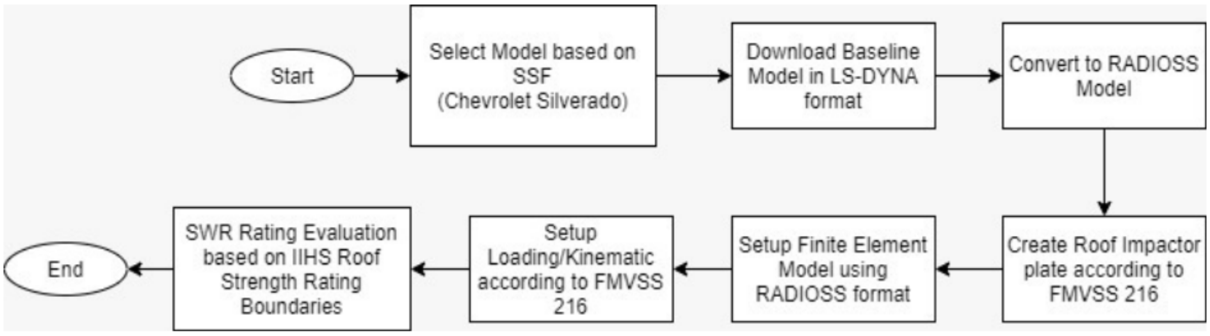

Figure 2: Flowchart of the research

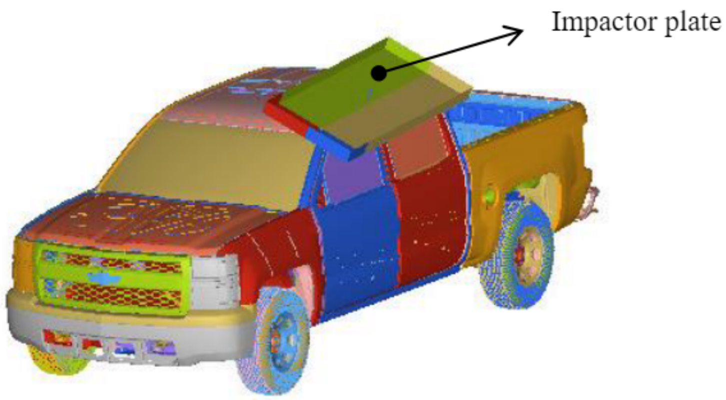

Figure 3: Impacted plate position in roof resistance test setting

Based on the research flowchart in Figure 2, in this case, the model is imported from LS-DYNA. In RADIOSS solver, Solid Hexahedron Elements (HEPH) formulation & Quadrilateral ElastoPlastic Physical Hourglass Control (QEPH) shell element formulation were applied to avoid high hourglass energy. QEPH shells are more precise for this type of simulation where elastoplastic loads and quasi-static loading types are involved (Goelke et. al, 2015). Then, the model was exported to the RADIOSS file (.rad). In this case, the initial velocity was removed because the initial model was developed for frontal crash analysis. After that, an impactor plate needs to be created for the purpose of roof crush analysis. The impactor size and dimension are designed according to FMVSS 216 standard. Finally, the FE model was set up and run. In the FE model, material model, connection model, section properties, element formulation retained as close as possible with the LS-DYNA model. The result from RADIOSS analysis was then compared and validated with the result from LS-DYNA analysis.

3.0 RESULTS AND DISCUSSION

The graph in Figure 4 depicted force against plate displacement of model-simulated using LS-DYNA, RADIOSS as well as the actual test result. The key discovery that could be acquired from the simulation is the peak force measured within 127 mm plate displacement. Based on this graph, the peak force is summarized in Table 3. The peak force then manifested into SWR value after it is divided with vehicle curb weight as mentioned in Equation 1 previously. The SWR value is an important parameter to categorize the roof strength rating of the vehicle.

Table 3: Comparison of Peak Force and SWR between Test Data, LS-DYNA and RADIOSS

Results	Test Data	RADIOSS	LS-DYNA
Peak Force [kN]	94	125 (+33%)	115 (+22%)
SWR	4.10	5.43 (+32.33%)	5.00 (+21.95%)

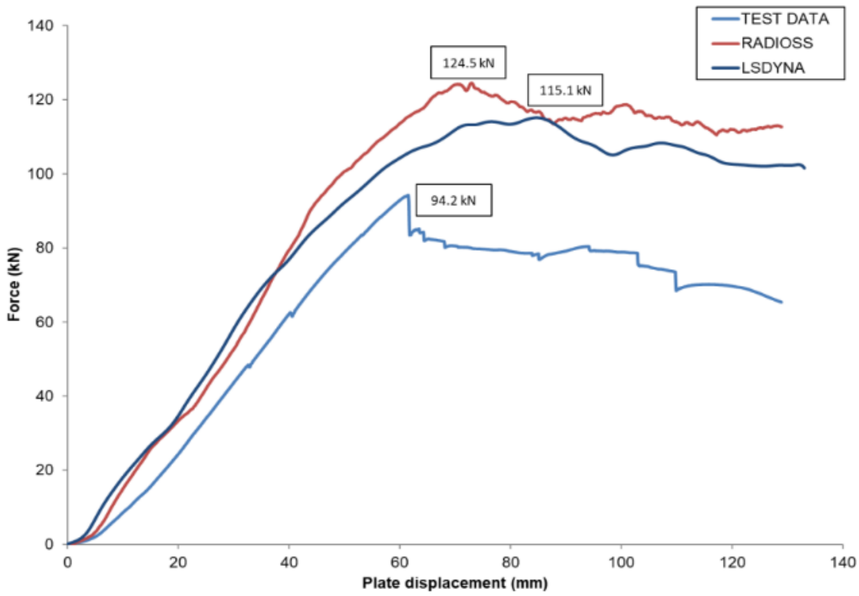

Figure 4: Graph of force value of Actual Test, Simulation by LS-DYNA and RADIOSS solver measured within 127 mm plate displacement

It can be deduced that the simulation is quite satisfactory to predict the vehicle roof strength. Based on the graph in Figure 5, displacement at highest SWR is compared between actual test, simulation using RADIOSS & LS-DYNA solver. Maximum SWR of 4.1 on actual test is achieved at the displacement of 61.40 mm, while using RADIOSS solver 72.89 mm, and LS-DYNA solver 85.20 mm respectively. Therefore, there is a difference of 18.71% & 38.76% respectively. This demonstrates that both simulation models produce stiffer responses compared to the actual test. Among the solver, RADIOSS produce higher peak force and at an earlier displacement value than LS-DYNA. This result may be explained by the fact that RADIOSS & LS-DYNA apply dissimilar yet commonly used element formulation which for RADIOSS solver, QEPH element is used while Belytschko Tsay (BT) element is used in LS-DYNA solver (Yadav & Pradhan, 2014). This finding is in accordance with Gonzalez et al. (2006) that QEPH elements produce a stiffer response. Further study will be conducted to improve the simulation models and is discussed in the conclusion section.

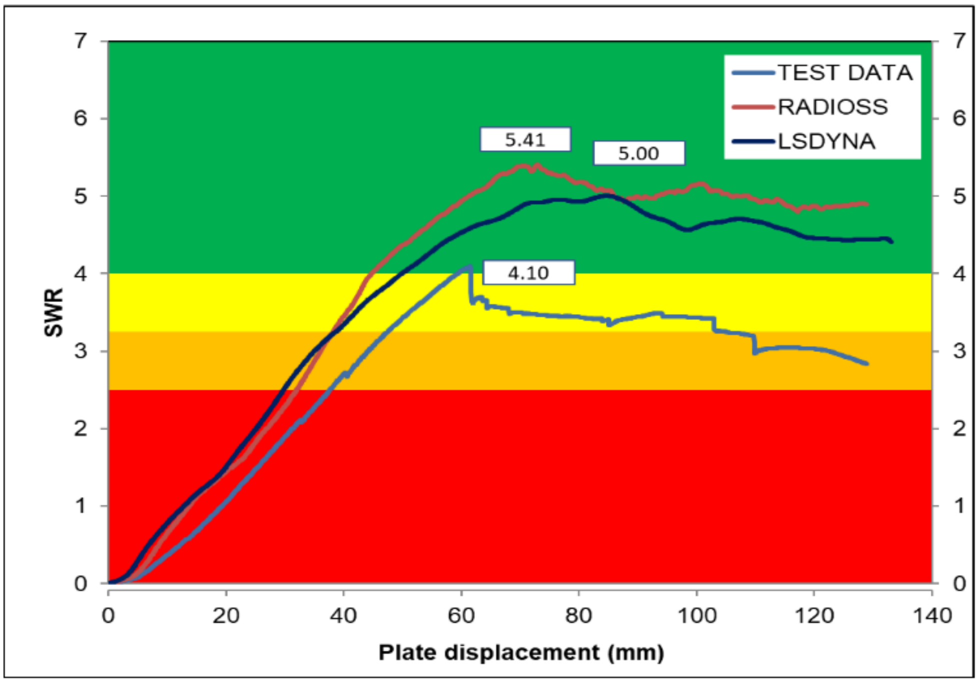

Figure 5: Graph of SWR value of Actual Test, Simulation by LS-DYNA and RADIOSS Solver measured within 127 mm plate displacement

Even though the SSF Rating of Chevrolet Silverado is relatively poor (1.19), the model is classified as good in IIHS Roof Strength Rating as stated in Table 1 because from the actual quasi-static roof strength test result by IIHS dated January 14, 2016, experimental SWR value obtained is 4.1. The value is classed as good since the peak force value is 4.1 times the vehicle's curb weight. Peak force was recorded to represent the maximum force required to deform the roof and affect occupant survival space. During the rollover, the roof must be able to retain the occupant survival space as much as possible as it will reduce occupant injury risk and be capable of preventing occupants who did not wear seat belts from being expelled through any broken openings because of the deformed roof.

According to research by Viano & Parenteau (2018), the roof SWR (strength-to-weight ratio) is inversely related to casualty and injury risks. There was a 24% decrease in the casualty and injury risk for each unit increase in SWR. Injury risk in non-ejected occupants was lower by 16% and ejection was lower by 41% (Viano & Parenteau, 2018). Furthermore, logistic regression results were done by Brumbelow & Teoh (2009) in their work revealed that a unit increase in SWR was linked to a 24% decrease in incapacitating and injury risk in single-vehicle rollovers case for midsize Sport Utility Vehicle (SUV).

4.0 CONCLUSION

In brief, the FE model for roof strength analysis has been completed using RADIOSS. Both solvers demonstrate quite satisfying SWR correlation to the actual quasi-static roof resistance test. Their SWR result is also comparable which translated into only an 8.60% difference. Nevertheless, both simulations require further optimization process especially for simulation using RADIOSS solver which differs 32.33% from the actual test result. Furthermore, the result could be further improved by implementing a glass failure model, material damage model, and also spot weld failure model. Chirwa et al. (2005) improving their study by refining roof mesh to remove roof stiff behavior in some areas to match the roof deformed pattern in the actual test.

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