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DOI: 10.1088/1757-899X/1137/1/012012

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Design for crash safety of electric heavy quadricycle structure

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Abstract

An electric small four-wheeler, categorized by the European Union as L7e so-called heavy quadricycle or microcar, is one of the solutions to eco-friendly and sustainable mobility for personal transport. Nonetheless, quadricycles typically do not offer the equivalent passive safety as larger passenger car models, in case of accidents, owing to the lack of energy absorption in the vehicle's structure. This paper presents a proposed heavy quadricycle structure using plain weave carbon fibre-reinforced polymer in the passenger cell and aluminium alloy 6061-T6 in the crumple zone. The behaviors of electric heavy quadricycles under impact are simulated in accordance with the test guidelines of European New Car Assessment Programme using a non-linear finite element analysis via LS-DYNA to examine structural crashworthiness and characteristics. A full-frontal crash with a rigid wall at 30 km/h to 50 km/h shows that the front crush box, longerons and subframes in the crumple zone can efficiently absorb energy from a frontal crash up to 54.8%. The maximum damage in the structure occurs at the joints of the A-pillars and side beams to the front panel. Whilst the occupant safety space is safe under side collision by a 1350-kg moving deformable barrier at 50 km/h speed. However, the quadricycle tends to experience overturns from a side crash due to the vehicle's lightweight and high center of gravity. Finally, suggestions for crashworthiness improvements to the composite passenger cell are provided based on the attained damage mechanism under a crash.

Keywords: Heavy quadricycle, Composite material, Crash safety, Energy absorption

1. Introduction

International Energy Agency (IEA) [1] forecasted greenhouse gas (GHG) emissions from various sectors would increase continuously from 2013 to 2050. Without any measures to reduce GHG emissions, the earth's average temperature will rise 6 degrees Celsius by the end of the century. The electric vehicle industry is one of the technology sectors aiming towards the reduction of CO_x emissions and pollution problems in big cities. Electric vehicles produce fewer direct and life-cycle emissions, that contribute to climate change, than conventional vehicles. Battery electric vehicles produce no GHG emissions at the tailpipe but cannot cause emissions from the carbon intensity of the electricity used to recharge and the vehicle's consumption.

The development of small and lightweight electric vehicles will improve energy consumption efficiency and reduce battery size. An electric small four-wheeler categorized by European Union as



L7e so-called heavy quadricycle is one of the solutions to eco-friendly and sustainable mobility for personal transport. The statistics of quadricycle registrations in the United Kingdom [2] between 2010 and 2018 show that quadricycles have become significantly popular, especially in London. In Europe the motorized quadricycles market is set grow at a CAGR of 5% between 2019 and 2029 [3]. This is mainly due to the car's flexibility in traveling and parking in the city and urban zones, low-cost maintenance and its advantages in reducing city pollution. With the rising trend of heavy quadricycles, the possibility of accidents from collisions is also increased. In the year 2014 and 2016, European New Car Assessment Programme (Euro NCAP) tested crash safety of several quadricycles in L7e class [4]. The Euro NCAP aims to assess the crashworthiness of quadricycles for passenger safety like several regulations of other vehicles such as bus rollover protection [5, 6]. The evaluation showed that the heavy quadricycles are more hazardous, and prone to occupant injury during a crash than other larger passenger car models. They typically do not offer equivalent passive safety owing to the lack of energy absorption of the vehicle structure and its crash incompatibility [7].

Fiber reinforced polymers are frequently used in structures where high strength-to-weight ratio and stiffness or rigidity are required. Liu et al. [8] analyzed the strength of car frames designed by using glass fiber and carbon fiber reinforced polymer (CFRP) under pole side crash according to the Euro NCAP criteria. It was found that the CFRP structure underwent less deformation and damage under crash. Stein et al. [9] designed a model of heavy quadricycle called Epsilon with CFRP space-frame made of woven carbon fibers square cross-section with low-density polyethylene foam core. The car structure was shown to pass all 6 crash tests following Euro NCAP testing. Moreover, the structural improvement of an L7e car based on Kriescher et al. [10] is unique in adding ring structure around the base of the passenger cell to help absorb and distribute energy when collisions occur.

This paper proposes a design of lightweight heavy quadricycle body made of plain weave CFRP in the passenger compartment and aluminium alloy 6061-T6 in the crumple zone. The structural behaviors of electric heavy quadricycles under front and side impact are then analyzed in accordance with the test guidelines of Euro NCAP via LS-DYNA finite element simulation to examine crashworthiness and crash characteristics.

2. Materials and Methods

2.1 Body design

The specifications for L7e require that the vehicle's unladen weight, excluding battery mass, must not be more than 450 kg for transport of passengers. The maximum power does not exceed 15 kW with a maximum speed not less than 90 km/h.

The baseline quadricycle is 1.38 m wide, 2.27 m long and 1.26 m high. The structure is separated into 2 main parts, i.e., the front crumple zone made of aluminum alloy 6061-T6 with thickness of 2 mm and the passenger cell part made of T700SC plain weave fabric with thickness of 5 mm. Figure 1 shows the quadricycle components and the finite element model. The front crumple zone comprises of longeron and subframe parts while the passenger cell includes A-pillars, B-pillars, roof frame, front panel, rear panel, floor, and side beam. All joints are assumed to be perfectly joined. To avert galvanic corrosion between carbon composite and aluminium alloy, application of anodizing as a pretreatment process to generate oxide coatings is necessary.

The whole structure is meshed by using a 4-node Belytshko-Tsay element with six degree-of-freedom (3 translations and 3 rotations) at each node. The element size is set to 10 mm. The model consists of 103,795 elements and 103,034 nodes. The mass of other components not included in this FE model such as, battery, motor and control system, as well as passengers and passenger seats, is applied to the model by adding uniformly distributed mass elements of 300 kg to the car body. The total weight of the baseline quadricycle is 386 kg.

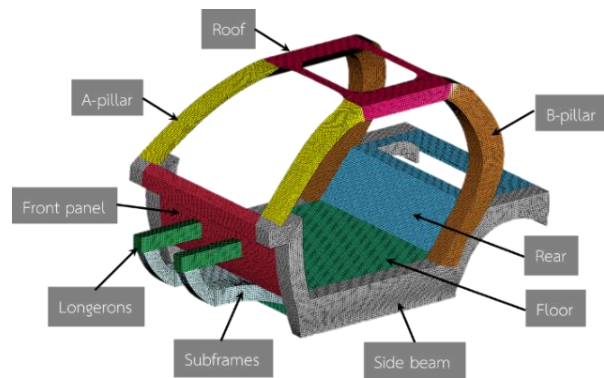


Figure 1. Baseline quadricycle components and meshing

2.2 Material model

Table 1 and 2 provide the material properties of Al 6061-T6 and CFRP T700SC, respectively. The material model for aluminium alloy is implemented by MAT24 Piecewise Linear Plasticity model. The CFRP is defined by MAT54 Enhanced Composite Damage model able to simulate damage progression in dynamic simulation. The material orientation is specified along the horizontal direction in the plane of the member. Material properties and model formulations are validated with simple experimental results from Osborne et al. [11].

Table 1. Material properties of Al 6061-T6 [12]

Property	Magnitude
Modulus of Elasticity (GPa)	68.9
Poisson's Ratio	0.33
Shear Modulus (GPa)	26
Ultimate Tensile Strength (MPa)	310
Tensile Yield Strength (MPa)	276
Shear Strength (MPa)	207

Table 2. Material properties of CFRP T700SC 12k/2510 plain weave fabric [11]

Property	Magnitude
Axial Young's modulus (GPa)	55.9
Transverse Young's modulus (GPa)	54.4
Shear Modulus (GPa)	4.2
Axial tensile strength (MPa)	910.1
Axial compressive strength (MPa)	910.1
Transverse tensile strength (MPa)	772.2
Transverse compressive strength (MPa)	703.3
Shear Strength (MPa)	131
Axial tensile failure strain (mm/mm)	0.0164
Axial compressive failure strain (mm/mm)	-0.0127
Transverse failure strain (mm/mm)	0.014
Shear failure strain (mm/mm)	0.03

3. Structural crashworthiness analysis

Crashworthiness of the quadricycle structure under full frontal and side collision is analyzed in this section.

3.1 Full frontal crash analysis

Full frontal crash analysis is performed with varying initial velocities of 30 km/h, 40 km/h and 50 km/h to a rigid wall as shown in Figure 2. To facilitate the analyses, the wheels are not modelled. Instead, the rear part of the car is constrained from translation in y-direction. Automatic surface-to-surface contact is assigned between the car front to the rigid wall and automatic single surface is specified to the entire quadricycle model such that when the structure deforms, penetration of its own parts does not occur. The residual space or the safety zone of the occupant is measured from the front of the vehicle to the driver's position, i.e., 640 mm from the front of the structure and 215 mm from the front panel.

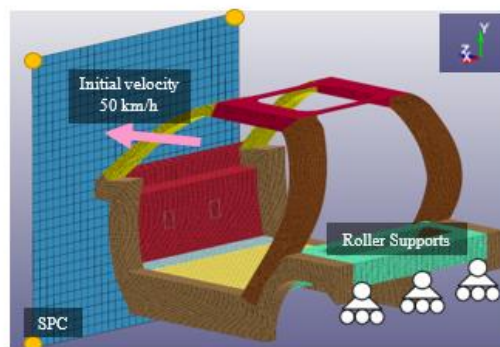


Figure 2. Model set up for full frontal crash test

Figure 3a shows damage of the structure at the end of front crash simulations with different impact speeds. When the crash speeds are 30 km/h and 40 km/h, the crumple zone can efficiently absorb all impact energy and the passenger compartment is intact. When the crash speed is at 50 km/h, the crumple zone is extremely damaged and not able to absorb all impact energy. In this case, damage of the passenger cell occurs at areas where the front panels connected to A-pillar and side beams (Figure 3b). Table 3 listed the energy absorption of the crumple zone and specific energy absorption for each part (shown as numbers inside the brackets) at varying impact speeds. The crumple zone can absorb most of the impact energy when the crash is at a lower speed of less than 40 km/h. Although the longerons seem to absorb slightly higher energy than the subframe, when the parts are compared in terms of specific energy absorption, it is obvious that the EA of the longerons is more efficient.

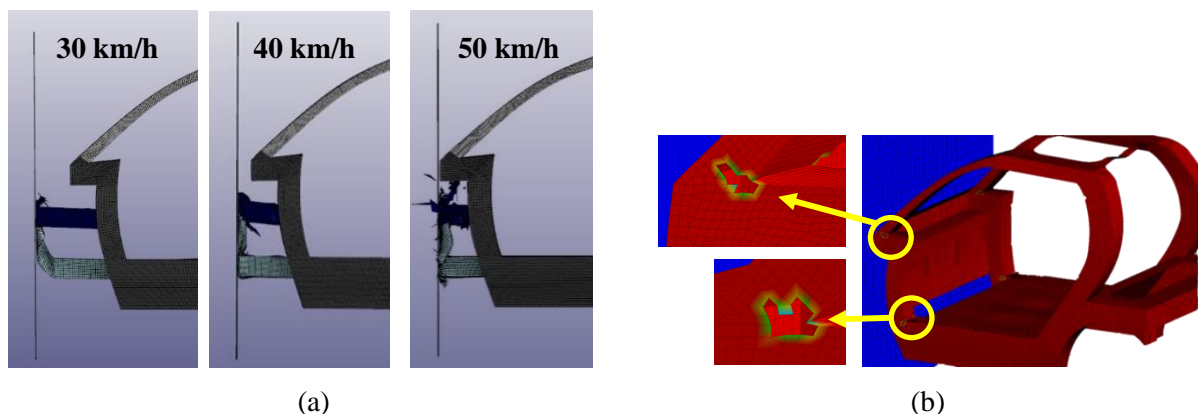
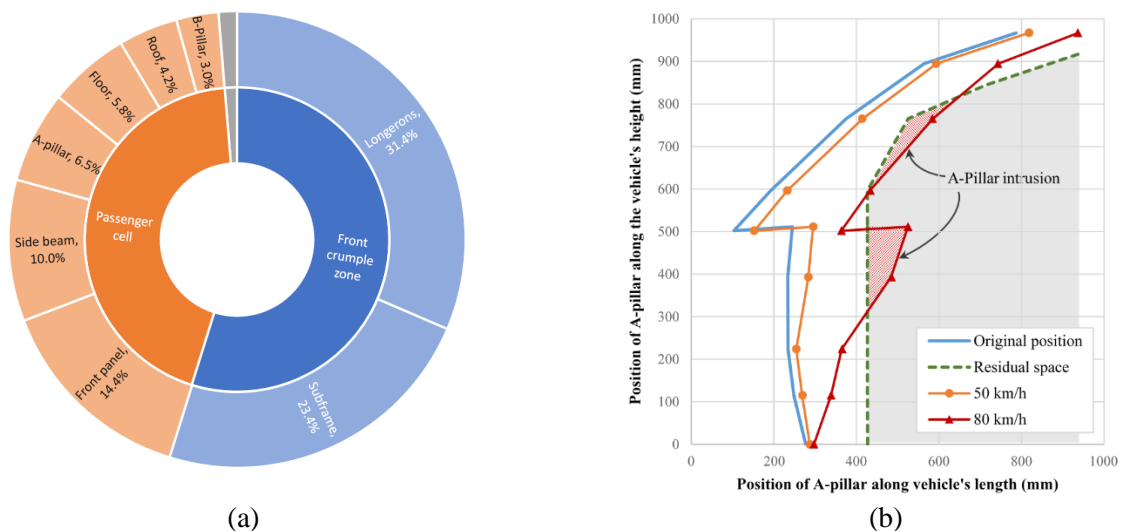


Figure 3. Structural damage from full frontal crash (a) damage of crumple zone at different speeds (b) damage of passenger cell at 50 km/h speed

Table 3. Energy absorption of the crumple zone

Impact velocity	Impact energy (kJ)	Energy absorption, EA (kJ)			Percent of EA
		[Specific energy absorption, kJ/kg]			
		Longerons	Subframe	Crumple zone	
30 km/h	12.1	5.0 [0.46]	3.8 [0.12]	8.8	72.5 %
40 km/h	22.0	8.0 [0.74]	7.5 [0.24]	15.5	70.0 %
50 km/h	33.8	10.6 [0.98]	7.9 [0.25]	18.3	54.8 %

An example of energy absorption distribution after frontal crash at 50 km/h is displayed in Figure 4a. Most of the impact energy dissipates to four main parts, i.e., subframe, longerons, front panel and side beam. This shows that the impact force effectively transmits from front of the car to the base of the passenger cell. The passenger compartment is re-analysed based on the remaining impact energy when the crumple zone is fully damaged or when the crash speed greater than 50 km/h. It is found that when the crash speed reaches 80 km/h, the plastic hinges at A-pillars are fully formed and damages at B-pillars initiate. This causes the front structure to intrude into the residual space and the occupant safety is compromised. Figure 4b illustrates clearances from the rigid components of the front structure when the crash speed is 50 km/h and 80 km/h. It can be noticed that the A-pillars intrude into the safety zone by 98 mm at the occupant's chest and 52-mm intrusion is found at the location of passenger's head. Further investigation by including occupant dummies into the FE model can predict the passenger's injury severity from both the crash deceleration and direct impact of these rigid parts to the occupant.

**Figure 4.** (a) Energy absorption distribution under frontal crash (b) A-pillar deformation after crash

3.2 Side impact analysis

Euro NCAP side impact analysis is conducted by collision of a 1350-kg mobile deformable barrier (MDB) to the side of the heavy quadricycle at 50 km/h. The MDB is used to represent another passenger car crash into the vehicle of interest. The location of impact corresponds to the location of the center of gravity (CG) along the length of the quadricycle. In this case, the car's wheels need to be included into the FE model. The front wheels are constrained to the longerons while the rear wheels constrain to the rear part of the car. Automatic surface-to-surface contacts are assigned between the MDB and the quadricycle side and between the vehicle wheels to the floor as shown in Figure 5. Static and dynamic friction coefficients between the wheels and the floors are 0.85 and 0.80, respectively.

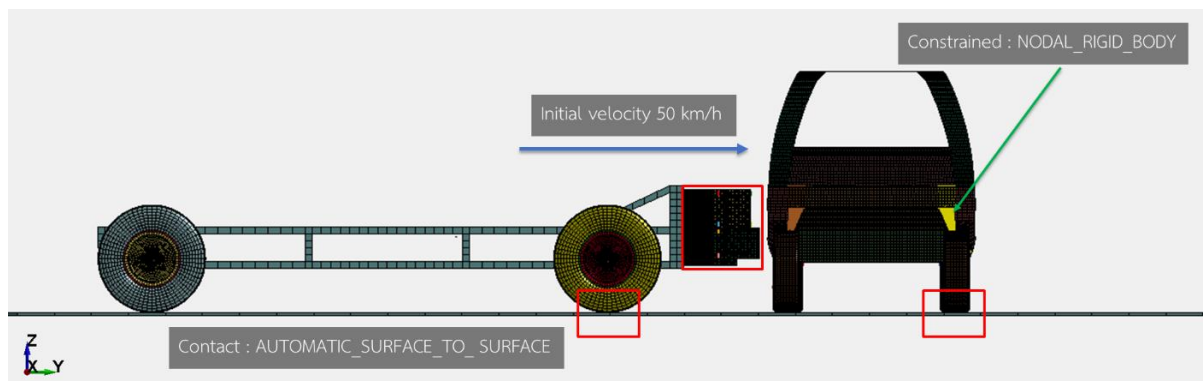


Figure 5. Side impact analysis by mobile deformable barrier

The CG of the baseline quadricycle is 599 mm from the floor when the ground clearance is at a typical value of 180 mm while the CG of the MDB is 500 mm. It is found that at this height, overturning of the quadricycle may occur when it is crashed by the MDB trolley due to its small weight and its incompatibility with other passenger cars.

The baseline model is then modified by lowering the ground clearance of the quadricycle to 150 and 130 mm. The quadricycle is analysed at crash speeds of 50 km/h and 80 km/h. It is found that the car with the ground clearance of 150 mm does not overturn when the MDB speed is 50 km/h but still overturns at high-speed crash of 80 km/h. Nevertheless, the car does not experience overturning during crash when the ground clearance is lowered to 130 mm. Damage from side crash simulation at 50 km/h of the modified model is shown in Figure 6. The car structure can well-resist energy from side crash of another passenger car. The honeycomb profile impactor is completely damaged and absorb most of the crash energy. The quadricycle is slightly damaged at the joints of near-side beam with pillars while the passenger cell is still unharmed. Thus, the occupant's residual space is safe.

The thickness of the car frame is decreased to 3 mm to study the energy absorption of structural parts under severe damage. Damages are noticed to first occur on the side beam at the same locations as in the previous cases and afterward B-pillar collapses and the occupant's safety space is intruded. It is observed that, in this case, the impact energy can mostly be absorbed by the side beam and pillars. Energy dissipation to other parts via the structural parts is not as efficient as in the case of frontal crash. Redesign of the base structure with crossbeams to dissipate the side impact energy is therefore recommended.

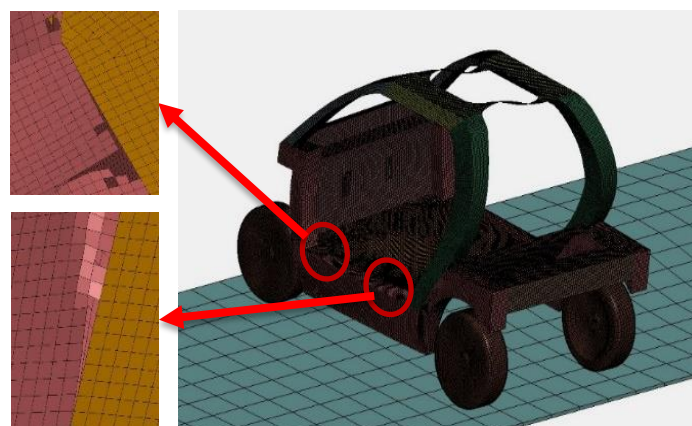


Figure 6. Damage from side crash test at 50 km/h

4. Conclusions

This study presents finite element analysis of a heavy electric quadricycle with a CFRP passenger cell and aluminium crumple zone under frontal and side crash. It is shown that the front crumple zone can efficiently absorb impact energy from frontal crash and the car structure can efficiently distribute energy and guarantee safety of the occupant under Euro-NCAP front crash test with a rigid wall. When the baseline structure is side-crashed by an MDB representing another car, quadricycle is prone to overturn due to the light vehicle's weight and high center of gravity. Lowering ground clearance can be an option to avoid overturning of the quadricycle. When overturning does not occur, the baseline structure is proved to be safe under side impact test up to 80 km/h. However, if the quadricycle is severely crashed, the side structure cannot efficiently dissipate the impact energy to other structural parts and thus supplementary energy dissipated members should be added to improve crashworthiness of the structure under side crash. Experiments and further investigation on the actual behavior of the CFRP components under crash scenario should also be examined in the future work.

Acknowledgments

The authors wishing to acknowledge financial supports from Mitsui Sumitomo Institute Foundation Grant 2020.

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