REPORT OF RESEARCH RESULTS
Mitsui Sumitomo Insurance Welfare Foundation Research Grant 2015

I. Title: Study on Frontal Impact Crashworthiness for Passenger Bus Manufactured in Thailand

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III. Summary:

Frontal impact is among the major causes of severe accidents occurred with passenger bus. Two standard procedures for frontal collision integrity are universally adopted; Economic Commission for Europe Regulation 29 (ECE-R29) in which a 1,500-kg rigid pendulum strikes the bus frontal structure with 55-kJ impact energy, and Federal Motor Vehicle Safety Standard 208 (FMVSS-208) in which the bus structure crashes to a rigid barrier at the velocity of 30 km/h. This study aims to use nonlinear explicit finite element method to analyze the safety of the driver of passenger bus manufactured in Thailand according to ECE-R29 and FMVSS-208 standards. The deformations of the baseline bus structure and driver injury severities are compared and improvement in bus frontal design is recommended. A finite element model of bus structure is developed by using Hypermesh and analyzed for structural deformations and the driver velocities during crash. A hybrid III 50th percentile dummy driver is employed in Hypercrash to predict severity of head and neck injury after impact. Comparisons between the two standards include the absorbed energy in each structure section and deformation of A-pillars show that FMVSS208 is more rigorous than ECE-R29. The critical points in design of bus frontal structure are crash absorption members connected with the bumper in front of the bus frame. Design improvement is then studied by adding triangular notching and window openings as buckling initiator to create folding under dynamic collision and increase energy absorption of the structure. The 4-row triangular initiator which yields symmetric mode under direct axial impact and local buckling mode under 15-degree oblique load is therefore recommended. When the new absorber is implemented to the baseline structure, the bus can now pass the ECE-R29 regulation. The new design is therefore suggested to Thai Bus manufacturing companies.

IV. Aim of Research:

1. Attain the techniques and significant parameters in finite element modelling to acquire a reliable frontal impact simulation according to internationalized regulations.
2. Use FEA to characterize the structural response of the bus structure designed and manufactured in Thailand under frontal collision as well as injury mechanism of the bus driver.
3. Implement thin-walled tubes as energy absorber to improve crashworthiness of the bus structure.

V. Method of Research:

The methodology is as follows:

1) Review the details of ECE-R29 and FMVSS208 regulations and past research on design and crashworthiness of bus structure under frontal collision and effects of different energy absorber profiles used in passenger cars.
2) Contact bus-manufacturing companies for the current design of bus bodies and bumpers for the bus manufactured in Thailand.
3) Prepare specimens tests for basic mechanical properties of materials used in the bus structure.

4) Validate a simplified finite element model of steel tubes under axial impact compared with experimental results.
5) Create the full model of bus structure under frontal impact according to UN-ECE R29 and FMVSS208 and accidental cases in Thailand.
6) Modify and improve the FE model for accuracy and efficiency of the model.
7) Analyse the FE results for deformation and crashworthiness of the bus structure as well as injury mechanism of the bus driver.
8) Investigate the efficiency of different profiles of thin-walled tubes as energy absorber under impact load including the folding form, energy absorbing ability, initial peak force and mean crushing force.
11) Implement the proper design of energy absorber to the FE model of the bus structure and examine the bus crashworthiness improvement.
12) Summarize the research findings, prepare the final report and a technical paper to present in an international conference.

VI. Results of Research:

ECE-R29 is a frontal crash test standard recommended by United Nations (UN). The vehicle is strike by a pendulum of impact energy 55 kJ. The pendulum plate has a surface of 2500 mm x 800 mm and made of steel with evenly distributed mass not less than 1500 kg. The pendulum is suspended by two rigid beams of 1000 mm apart and 3500 mm between axis point of suspension and geometric center of the impactor surface. Its striking surface shall be in contact with the front part of the vehicle at 50 mm below the R-point of the driver's seat. To meet the requirement, there should be no contact between the driver manikin and the non-resilient parts of the bus structure after the impact.

FMVSS-208 is a frontal crash test standard recommended by National Highway Traffic Safety Administration (NHTSA) in United States of America. The tests include full, oblique and offset frontal impact to a rigid barrier or deformable barriers. Head-on full frontal impact with a fixed barrier is similar to the real frontal crash accident and thus is widely used to analyze the strength of front member of vehicles. According to the standard, the velocity of 23 to 48 km/h is applied to the passenger bus traveling longitudinally forward into a rigid barrier.

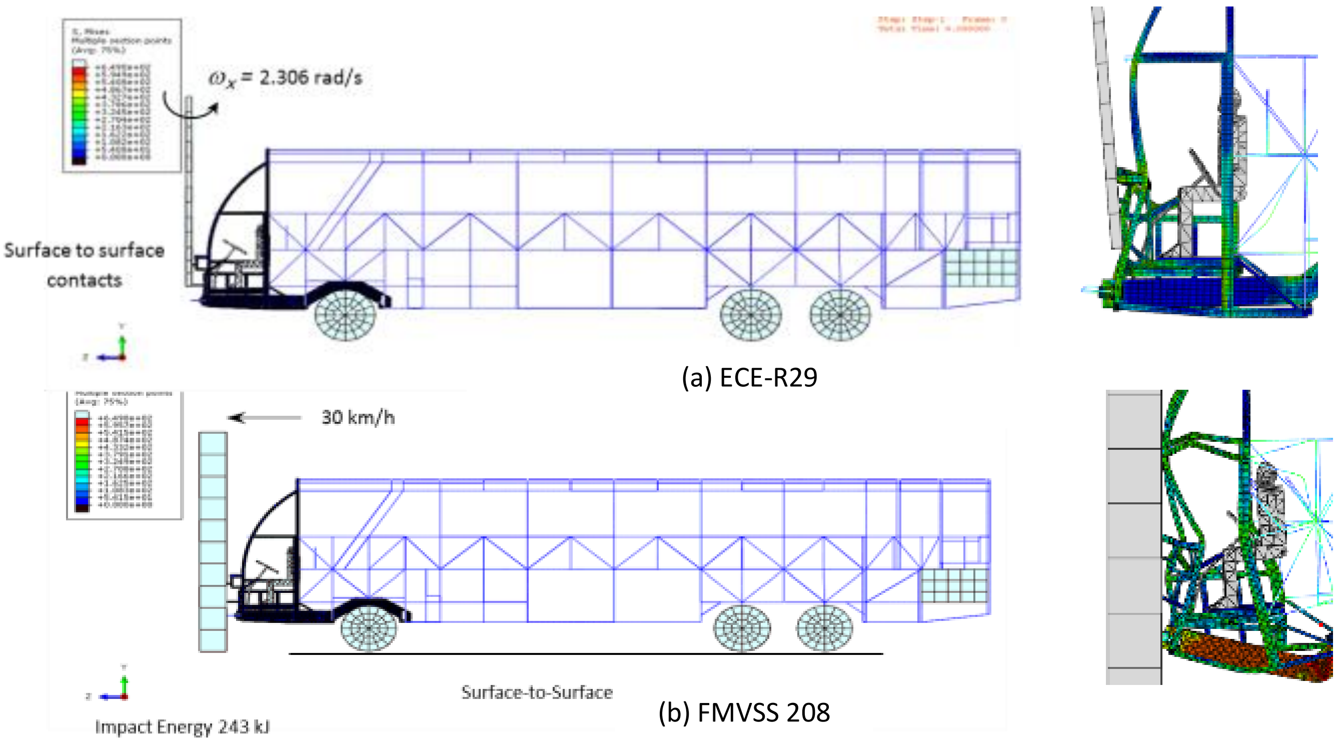
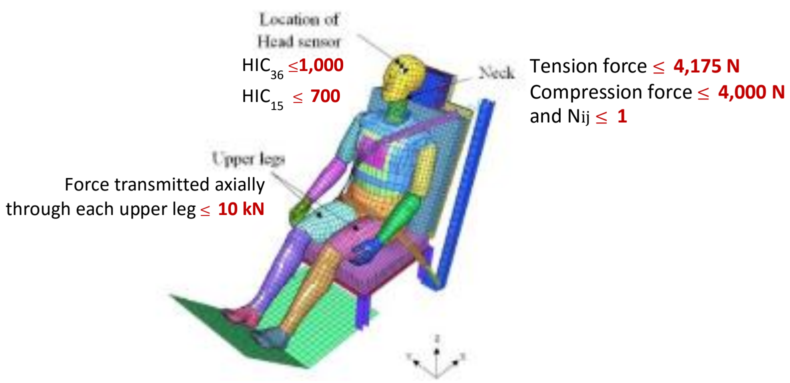


Fig. 1 FE model and condition for simulation for baseline bus structure manufactured in Thailand

The baseline passenger-bus model in this study obtained from a Thai bus builder company. it has the dimensions of 2.52 m wide, 14.5 m long, 3.25 m high that carries 42 passengers. The bus body frame are made from steel rectangular cross sections of 50x50x2.3 mm and 50x25x2.3 mm. The material density is 7,860 kg/m^3. The elastic modulus is 210 GPa and Poisson's ratio is 0.3. The chassis is made of structural steel with yield strength 570 MPa and ultimate strength 650 MPa while other parts are made of mild steel with yield strength and ultimate strength of 330 MPa and 375 MPa, respectively. The total weight of the bus frame is 3.51 tons. The front parts of the bus body are meshed with 55,652 4-noded shell elements while the other parts are modeled with 11,160 beam elements. The mesh size is chosen to be 5 to 25 mm where the deformations are large whereas the 60 mm element size is applied to other parts. A rigid driver dummy is fixed on the floor plate at driver position to capture the imposed velocity from the crash.

The FE model is created and discretized by using Hypermesh as shown in Fig. 1. Fig. 1(a) shows simulation conditions and deformed shape of the cabin part after frontal crash based on ECE-R29. Fig. 1(b) illustrates results for FMVSS 208. When energy absorption of crumple structure, cabin structure, and the back parts are studied. It was found that crumple structure can absorb only 11.3% in first case and 1.6% in the second case. These numbers are much less than the expected performance of crumple structure than should be able to absorb about 50% of the crash energy. Thus, a large amount of energy is transferred to the cabin structure and the driver is at high risk for injury and death.

The driver's injuries are analyzed by using hybrid III dummy model based on neck forces and moments, head accelerations and upper leg forces as shown in Figure 2 and Table 1. It was found that the injuries are severe and do not pass the regulations' requirement.



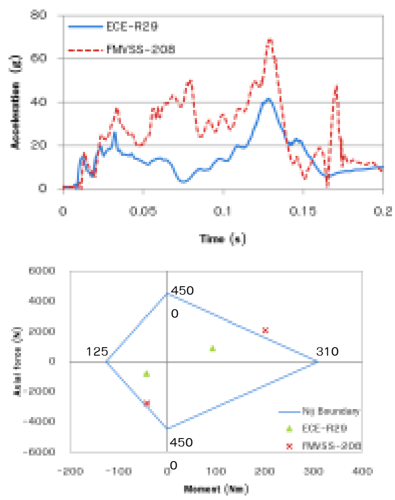


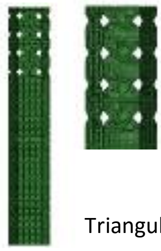
Figure 2 Injury criteria, head accelerations and neck inury

Injury	Standards		Limit
	ECE-R29	FMVSS-208	
HIC_{15}	124.6	362.4	700
HIC_{36}	163.2	490.9	1,000
Nij	0.5	**1.26**	1
Upper neck tension(N)	901	2072	4,175
Upper neck compression(N)	786	2758	4,000
Femur force(N)	1,130	2,550	10,000

Table 1: Injury criteria of driver dummy compared to the limited values

Table 2: Initiator types and locations

Initiator shapes	Numbers per section	Locations
		First buckling mode
Triangular	2, 4, 6 sides	Critical elements
Window	2, 4, 6 corners	Prescribed location
		Several rows (2-12 rows)



Triangular notching

Window opening type

To improve crumple zone performance, different section profiles of thin-walled tubes are studied under direct and oblique dynamic impact. It was found that desirable properties of energy absorbers are high energy absorption (EA) per mass ratio to absorb as much energy as possible to the tube, low peak force to decrease impact to the driver and passengers, and high ratio of average force to peak force. Hexagonal tubes establish satisfactorily EA under collision. However, to further improve the crushing performance, buckling initiators of triangular and window types with different designs and locations shown in Table 2 are added to the hexagonal tube.

Simulation results show that triangular notching type is preferable because symmetric failure mode is typically achieved under dynamic impact while window opening causes extensional mode. Peak forces in the former case are lower. Among all designs, 4 row triangular initiator is recommended due to its high performance in EA and local buckling mode in which high specific EA is obtained under 15-degree oblique load. When hexagonal absorber and absorber with initiator are assigned to the bus model, EA of the crumple zone is increased to 21.8% and 37.6%, respectively, as shown in Table 3. Therefore, the new design proves higher efficiency of the frontal frame in energy absorption.

Table 3: Energy absorption in absorber zone and cabin zone under front crash

Model	Absorber zone		Structure zone	
	EA(kJ)	Rate(%)	EA(kJ)	Rate(%)
Baseline	5.9	10.7	49.1	89.3
Hexagonal absorber	12.0	21.8	43.0	78.2
Hex with initiator	17.4	37.6	31.6	68.4

In conclusion, it was found that the baseline bus structure manufactured in Thailand does not pass ECE-R29 and FMVSS-208 requirements for frontal impact test because crumple structure cannot absorb energy during frontal crash and a large amount of energy transferred to the cabin structure resulting in high risk of driver injury. Bucking initiator of triangular notching type can be added to thin-walled crush absorber to improve crashworthiness of the front structure.

VII. Future Areas to Take Note of, and Going Forward:

Results from Kinematics of the driver under crash shows that neck injury is the most severe compared to other injuries as shown in Table 2. Improvement on head rest design and seat belt parameters should be further studied.

VIII. Means of Official Announcement of Research Results:

1. International conference: Muangto, B., and Jongpradist, P. "Study on Effectiveness of Frontal Crash Standards for Passenger Bus using Finite Element Analysis", The 7th TSME International Conference on Mechanical Engineering (ICoME), December 13-16, 2016. Chiang Mai, Thailand.
2. National Journal: Kinematics of Driver Injury for Passenger Bus under Frontal Crash (manuscript is under preparation to submit to Maejo International Journal of Science and Technology).