Comparative analysis of bus rollover protection under existing standards

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Abstract

Both Europe and the United States (US) have enforced the legislations for bus rollover protection: Regulation number 66 of the Economic Commission for Europe (ECE R66) and standard number 220 of the American Federal Motor Vehicle Safety Standards (FMVSS 220) in order to prevent catastrophic rollover accidents. Therefore, this paper studied the legislation for bus rollover protection including both ECE R66 and FMVSS 220. Satisfying the rollover requirements by buses is obligatory by law. However, the scope of those two regulations does overlap for some group of vehicles. Thus, this study firstly presents a physical meaning comparative analysis of the ECE R66 with the FMVSS 220. The LS-DYNA 971/MPP was used for numerical analysis. The analysis models were constructed by the eta/FEMB that is a preprocessing module integrated in the LS-DYNA 971 package. The validation was turned from experimental data of body knots extracted from the real vehicle. This investigation performed the comparative analysis following ECE R66 and FMVSS 220 assessments, then moved to demonstrate the distortion configuration of the vehicle superstructure through the absorbed energy and its distribution in the vehicle and the vehicle frame sections, as well as the violation of the passenger compartment under the rollover testing conditions of both ECE R66 and FMVSS 220. Great differences were found between the rollover strength of bus superstructures depending on which regulations are followed. The results also demonstrate that the passenger compartment and residual space are more violated and more dangerous under the lateral rollover testing condition of the ECE R66 than the other. Above findings could be used for the automobile manufacturers in a new design of bus

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superstructure, incorporating the rollover safety legislation and lightweight designs.

Keywords: bus rollover, ECE R66, FMVSS 220, LS-DYNA.

1 Introduction

Today, transit buses are an integral part of each nation's transportation system. Although buses are one of the safest means of transportation, occupant injuries and fatalities in bus crashes do occur.

Thus, it was observed that rollover seriously threatens the lives of coach passengers. Rollovers are complex, chaotic, and unpredictable events involving the interaction of the driver, road, vehicle, and environmental factors. A rollover is a crash in which a vehicle revolves at least one-quarter turn (which would be on its side), regardless of whether the vehicle ends up laying on its side or roof, or even returning upright on all four wheels [1]. Thus, rollover strength has become an important issue for bus and coach manufacturers. For this problem, both Europe and the United State of America have enforced bus rollover safety regulation and standard to prevent catastrophic rollover accidents. Economic Commission for Europe had enforced Regulation No.66 (ECE R66) for the Bus Strength of Superstructure since 1987 in order to provide protection to the bus and coach occupants during rollover accidents through the maintenance of a survival space [2, 3]. Department of Transportation, the United States of America had enforced the FMVSS 220 standard for the school bus rollover protection since 1977 which included transit buses and vans, having the length less than 35 feet [4, 5].

In the social of globalize economic, Bus and Coach Manufacturers want to bring their products to Europe or the US or both of the markets. While the same problem of bus rollover safety for large bus, in Europe is controlled by ECE R66, and in the USA is controlled by FMVSS 220, although the scope of these regulations does overlap for some groups of vehicles. In recent years, automotive industries are concentrating more on vehicle rollover. There were many researchers to study the structure strength of buses and the injury analysis of passengers in accordance with tests of the ECE R66 [2, 3]. Although many studies have been done on bus structure strength, most of them are following in or based on ECE R66 to carrying out their researches. However, the comparative analysis between ECE R66 and FMVSS 220 is still limited.

Nowadays, with the advances in both computer technology and structural analysis via finite element method, the capacity of computer and FE software are confirmed in predictive analysis and computing assistances of bus structure. That is also new point in ECE R66 version 2006 in which the computer simulation with full scale model is officially used as an assessing method for the bus rollover protection requirements [3]. As a result, rollover strength of bus superstructure has been a topic of interest over the years, and a number of numerical studies of bus structure have been established. While a number of researches have been performed, a thorough development of rollover strength of bus superstructure under production costs and fuel economy has not yet received the same level of attention. In this study, both ECE R66 and FMVSS 220 were analyzed systematically and specified by the numerical study. In addition, distortion configurations of bus frame structure based on ECE R66 and FMVSS 220 tests were also be implemented. Finally, a guideline of bus rollover safety regulation then is recommended for the studies of bus body strengthening and optimal design of bus superstructure as follows.

2 Legislation for bus rollover protection

2.1 ECE R66 regulation

ECE R66 regulation was issued from on Jan 30th, 1987, and enforced by Economic Commission for Europe because of serious status of rollover accidents. It applies to single-decked vehicles constructed for carrying more than 22 passengers, whether seated or standing, in addition to the driver and crew. "Superstructure" refers to the parts of a vehicle structure that contribute to the strength of the vehicle in the event of a rollover accident. The purpose of this regulation is to ensure that the vehicle superstructure has sufficient strength so that the residual space during and after the rollover test on the complete vehicle is unharmed. This means that no part of the vehicle that is outside the residual space at the start of the rollover, like luggage, is intruding into the residual space and no part of the residual space projects outside the deformed structure. The envelope of the vehicle's residual space is defined by creating a vertical transverse plane within the vehicle which has the periphery described in Fig. 1. The SR points are located on the seat-back of each forward or rearward facing seat, 500 mm above the floor under the seat, 150 mm from the inside surface of the sidewall of the vehicle [3].

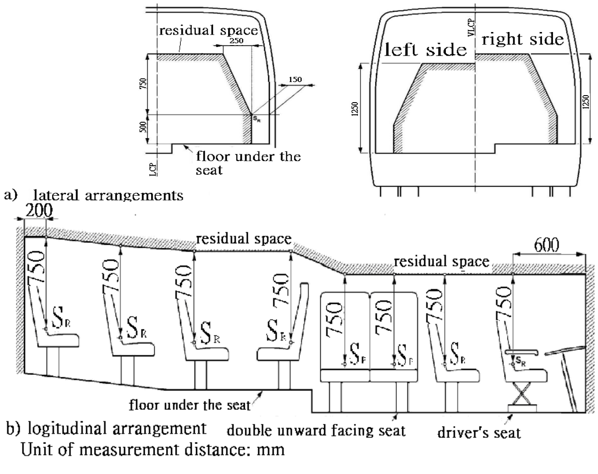


Figure 1: The residual space of a bus [3].

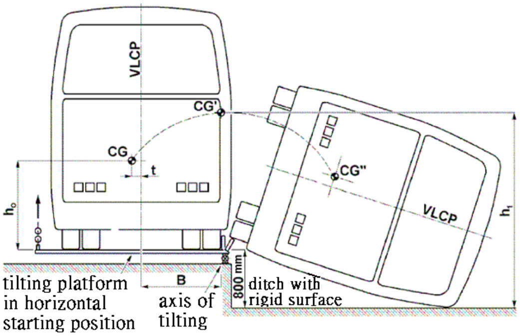


Figure 2: Specification of the rollover test [3].

This regulation is continuously updated based on actual requirements. And it is using as an international bus rollover regulation. The current version was issued on Feb 22nd, 2006. The rollover test is a lateral tilting test (see Fig. 2). The complete vehicle is standing on the tilting platform, with blocked suspension and is tilted slowly on its unstable equilibrium position. If the vehicle type is not fitted with occupant restraints it will be tested at unladen curb mass. If the vehicle is fitted with occupant restraints, it will be tested at total effective vehicle mass.

The rollover test starts in this unstable vehicle position with zero angular velocity, and the axis of rotation passes through the wheel-ground contact points. The vehicle rollover into a ditch, having a horizontal, dry, and smooth concrete ground surface with a nominal depth of 800 mm [3].

The rollover test shall be carried out on the side of the vehicle that is more dangerous with respect to the residual space. This decision was made by the technical service on the basis of the manufacturer's proposal, considering at least the following:

– The lateral eccentricity of the center of gravity and its effect on the reference energy in the unstable starting position of the vehicle.

– The asymmetry of the residual space.

– The different asymmetrical construction features of the two sides of the vehicle, and

the support given by the partition or inner boxes (e.g. wardrobe, toilet, and kitchenette).

The side with less support shall be chosen as the direction of the rollover test. The latest version of ECE R66, version 2006, with above requirements, describes a test to be chosen among five different methods:

(1). Complete Vehicle Rollover Test.
(2). Body Section Rollover Test.
(3). Body section test with Quasi-static load.
(4). Component testing base on Quasi-static calculation.
(5). Complete vehicle rollover test base on computer simulation.

Method (1) was accepted as the standard method. Others are equivalent methods. In which, method (3) and (4) are new methods in ECE R66, version

2006. (1), (2) and (3) are experimental methods base on real test. The Body Section Pendulum Impact Test of previous version had been deleted from Regulation No. 66 due to experimental tests and numerical studies found that it was not equivalent [4, 5]. The method (5) is officially accepted with full scale computer simulation [3]. In this study, method (5) was used to perform a numerical analysis because of the LS-DYNA ability and a powerful computation of the computer.

2.2 FMVSS 220 standard

The FMVSS 220 was effected from on Jan 4th, 1977, enforced by Department of Transportation, the United States of America. The FMVSS 220 is the school bus rollover protection regulation, specifies performance requirements for school bus rollover protection. This standard increases the structural resistance of school buses in rollover-type accidents. It only applies to school buses and covers all styles of school bus and transits buses, vans having less than 35 feet length. The requirements of this regulation are displacements of the application plate shall not exceed 5-1/8 inch (130.175 mm) and capable of being opening of emergency exits during the full application of the force and after release the force, with a force equal to 1.5 times the unloaded vehicle weight (UVW) shall be applied to the roof of vehicle's body structure through a flat, rigid, rectangular force application plate at any rate not more than 12.7 mm (1/2 inch) per second, as in Fig. 3 [6]. The FMVSS 220 test is real test however, this research makes use of full advantage of computer simulation power tries to perform by numerical simulation meet package of FMVSS 220 requirements.

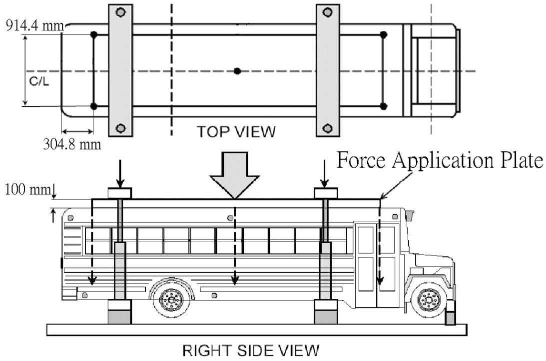


Figure 3: The FMVSS 220 standard test [6].

Comparing with the ECE R66, the FMVSS 220 only supports one testing method that is a quasi-static test of vertical compressing of vehicle roof without concern of CG position. Whilst the ECE R66 support five methods for testing, where the lateral rollover test concerns the impact of CG position on the evaluation results.

3 LS-DYNA introduction

LS-DYNA was developed by LSTC (Livermore Software Technology Cooperation). It is a multifunctional applicable explicit and implicit Finite-Element program to simulate and analyze highly nonlinear physical phenomena obtained in real world problems. Usually such phenomena manifest large deformations within short time durations, e.g. crashworthiness simulations. The significant features of LS-DYNA are the fully automatic definitions of contact areas, the large library of constitutive models, the large library of element types and the special implementations for the automobile industry [7, 8].

This study uses the FE software to carry out the bus rollover and the bus roof compressing simulation. The behavior of the bus rollover simulation belongs to the area of transient, dynamic, nonlinear, large deformed problems. And the bus roof compressing simulation belongs to the area of transient, quasi-static, nonlinear, large deformed problems. The Finite Element Analysis code, LS-DYNA, is a favorite tool for both of these two problems which often include contact and impact. The main solution is based on explicit time integration. The package LS-DYNA software contains a pre-processing finite element model builder (FEMB), an LS-DYNA solver and a post-processing LS-PREPOST. With LS-DYNA, the standard input such as geometry, mesh density, materials, element properties, boundary conditions, and contact modes can be used. The LS-DYNA solver will produce solutions. The output results such as stress and strain on elements, displacement, velocity and acceleration of nodes and energy distribution etc. can be shown clearly through the user interface (Hallquist [7]; LSTC [8]). The main solution is based on explicit time integration.

4 Numerical analysis procedures for bus rollover protection

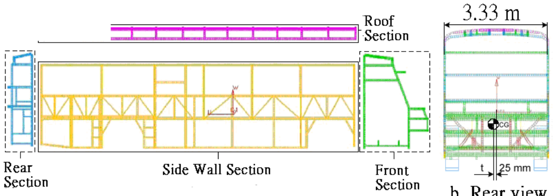
Computational models of vehicles are convenient for the comparison of respective performance between the ECE R66 and FMVSS 220 regulations. This study prepares and considers two models; one is an original model, and one is a strengthened model of vehicle.

4.1 Original model – model I

This FE vehicle model used for simulation is based on a full scale bus model developed at Da-Yeh University, Taiwan for rollover crashworthiness investigation and evaluation of reinforcement structures [9–11]. It includes 68132 elements. These consist of 67084 quadrilateral elements, 914 triangular elements, 35 hexagons and 99 mass elements. The description is based on the shell elements and their materials as in the Table 1. All deformable parts are modelled with the 4-noded Belytschko-Tsay shell elements with three integration points through the shell thickness. The shell element formulation is based on Belytschko-Lin-Tsay formulation with reduced integration available in LS-DYNA [7, 8]. This element is generally considered as computationally efficient

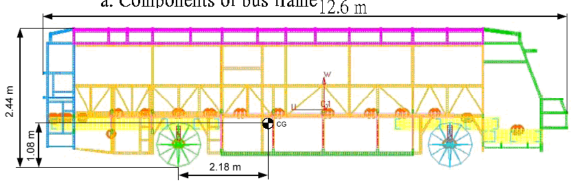
Table 1: Material for simulating bus superstructure, chassis, tyres, axis and tilting plate.

	Bus Superstructure	Chassis of Bus	Axis and tilting plate	Tires
Density (ton/mm3)	7.83E-09	2.783E-08	7.83E-09	2.85E-09
Young's Modulus (N/mm2)	210,000	205,000	200,000	11,000
Poisson's Ratio	0.28	0.3	0.3	0.3
Yield Stress (N/mm2)	282	270		
Plastic Fracture Pressure (N/mm2)	3.76E08	1.0E08		



a. Components of bus frame

b. Rear view



c. Side view

Figure 4: Full-scale FE bus model.

and accurate [12]. The shell element that has been, and still remains, the basis of all crashworthiness simulation is the 4-noded Belytschko-Tsay shell.

The CG (Center of Gravity) of the vehicle was measured using a test platform at the ARTC (Automotive Research & Testing Center, Taiwan, R.O.C). The measured values were in good agreement with the ones coming from the FEA model. To exactly match the measures and calculated CG, the CG of engine, gearbox and the axles were fine tuned in the FEA model. The unloaded vehicle weight is 7716.47 kg (7.71647 ton), and its capacity is 49 passengers. The vehicle size and its position of CG are shown in Fig. 4.

4.2 Strengthened model – model II

The strengthened model was developed from the original model following the design criteria of Roca et al. [13]. Each structural connection used the reinforcement obtained by Chiu [9], and bus frame thickness considered followed Liang and Le [14]. This model II has the same design style and vehicle size as model I. The unloaded vehicle weight of model II is 7916 [kg], and its height of CG is 1.10 [m].

4.3 Survivor space definition of a bus

For estimation of ECE R66 requirements, the survivor space was specified in the FEMB in line with the statement in the ECE R66. Throughout the whole vehicle, the SR points are located on the seat-back of each outer forward or rearward facing seat, 500 [mm] above the floor under the seat, and 150 [mm] from the inside surfaces of the side walls of the vehicle. The model of the survivor space consists of a rigid shell frame in each section along the vehicle interior (Fig. 1), rigidly mounted in the stiff region under the floor. There is no stiff connection between these rigid shell frames because these shell elements are modeled with "NUL_MATERIAL" for visualization only.

5 Numerical experiments for bus rollover protection

5.1 ECE R66 numerical simulation

The testing model is established by full scale bus model as in Fig. 4 and tilting platform model as in Fig. 5. According to ECE R66, the initial condition is that the angular velocity of the tilted platform shall not exceed 5 degrees / sec (0.087 radians / sec) [3]. To reduce the computing time, the testing model can be already rotated to reach its just before unstable position. The boundary condition is the vehicle model shall be tilted without rocking and without dynamic effects until it reaches unstable equilibrium and commences its rollover. The solving algorithm for that contact and this ECE R66 simulation is based on the explicit LS-DYNA solver. The problem time is 7 sec and a fixed time step of 0.9 microseconds is used. The simulation is carried out by the LS-DYNA version 971 with the 4-CPU Workstation. The CPU time for each of these two ECE R66 simulations of the original model and strengthened model is about 12 hours. The simulation process is shown in Fig. 6.

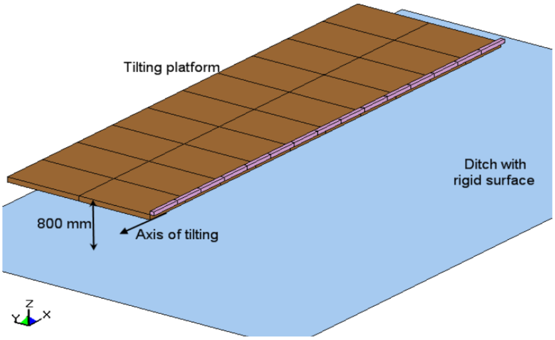
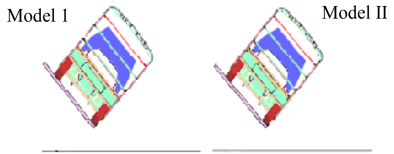
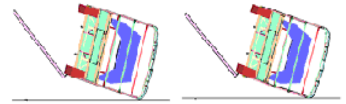


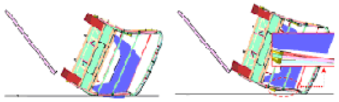
Figure 5: Tilting platform.



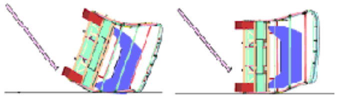
a. the unstable equilibrium position: t = 0 sec



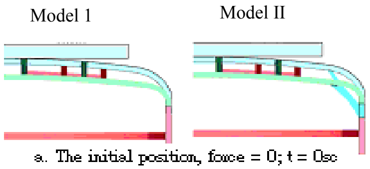
b. the first contact with ground: Modle I, t = 2.4sec; Modle II, t = 2.7sec



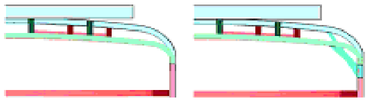
c. The maximum displacement position : modle I, t = 2.7sec modle II, t = 2.9sec



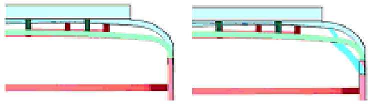
d. The stability position : t = 7sec



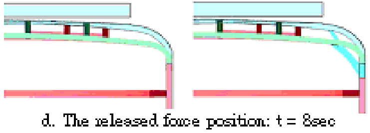
a. The initial position, force = 0; t = 0sc



b. The position of force = 2224.1[N] = 500[pound]
modle I, t = 1.2sec; modle II, t = 0.9sec



c. The full force position, force = 1.5times UVW:
modle I, t = 6.39~6.89sec; modle II, t = 5.49~6.99sec



d. The released force position: t = 8sec

Figure 6: Rollover process versus time for model I and II.

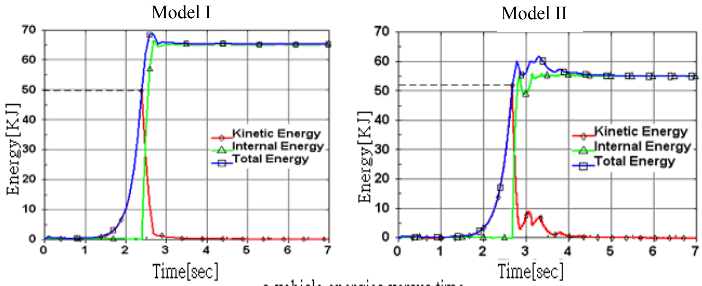
Figure 7: FMVSS 220 simulation process versus time for model I and II.

5.2 FMVSS 220 numerical simulation

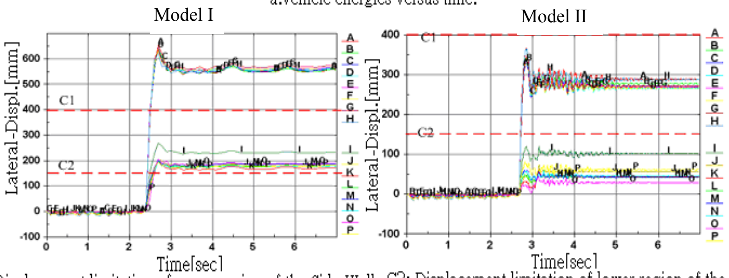
The testing model is established by the full scale bus model as in Fig. 4 and a force application plate model as in Fig. 3. The force application plate is determined with respect to longitudinal and lateral centerline. It is 304.8 mm (12 inches) shorter than the roof and 914.4 mm (36 inches) wide. This place weight 1528.289 kg. According to FMVSS 220, the initial condition is the direction of the force to application plate at continuous rate of not more than 12.7 mm (½ inch) per second until the force is equal to 1.5 times the UVW (unloaded vehicle weight). The boundary condition is evenly distributed vertical force, and the record on the distance versus time plots the deflection where the downward force is 500 lbs in order to eliminate slack from the system, and the solving algorithm for that contact and this FEVSS 220 simulation is based on the explicit LS-DYNA solver. The problem time is 8 sec and a fixed time step of 0.9 microseconds was used. These simulations are carried out by the LS-DYNA version 971 with the 4-CPU Workstation. The CPU time for each of these two FMVSS 220 simulations is about 13 hours. The simulation process is shown in Fig. 7.

6 Results

By FE analysis using the LS-DYNA 971solver, two rollover problems were simulated, one following ECE R66, one following FMVSS 220. Each simulation was performed with two vehicle models: model I is the original vehicle model, and model II is a strengthened model following Roca et al. [13], Chiu [9] and Liang and Le [14].



a.vehicle energies versus time.

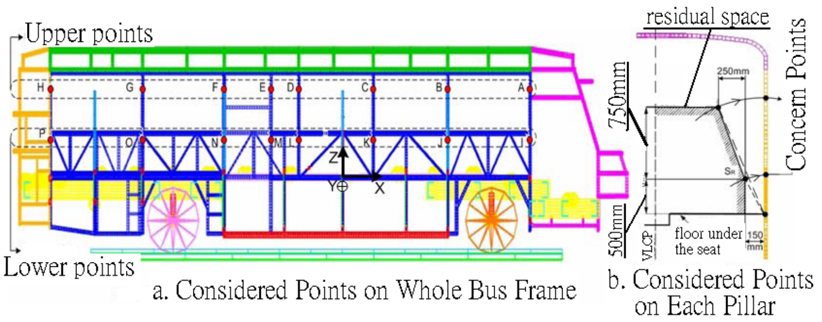


C1: Displacement limitation of upper region of the Side Wall C2: Displacement limitation of lower region of the Side Wall

b. Displacement of Side Wall versus time

Figure 8: Vehicle energies and displacements of the side wall versus time for models I and II.

Fig. 8 displays the vehicle energies and deformations of vehicle frame versus the survivor space of both models following ECE R66 during and after rollover. The energy balance, Fig. 8a, is one of the rules for verification of simulation by itself. Where, the energies may be observed. The kinetic energy drops and transform into internal energy. When the kinetic energy is gone to zero, the total energy is the internal energy (a summary of plastic and elastic strain energy), which is one of the indications for correct analysis results. The deformations at considered points are shown in Fig. 9 of outside parts versus the survivor space which is shown in Fig. 8b. These figures display clearly the status of the two vehicle models and that the vehicle model I does not satisfy the ECE R66 and model II satisfies the ECE R66.

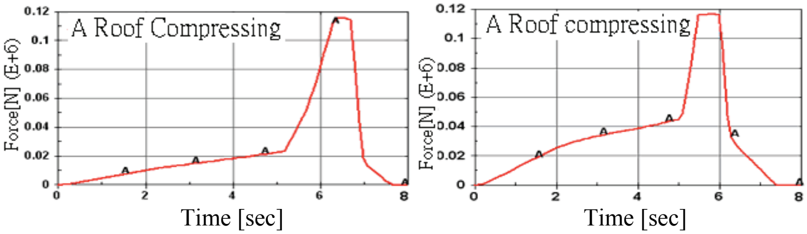


a. Considered Points on Whole Bus Frame

b. Considered Points on Each Pillar

Figure 9: Concerned points on the bus frame for ECE R66 test.

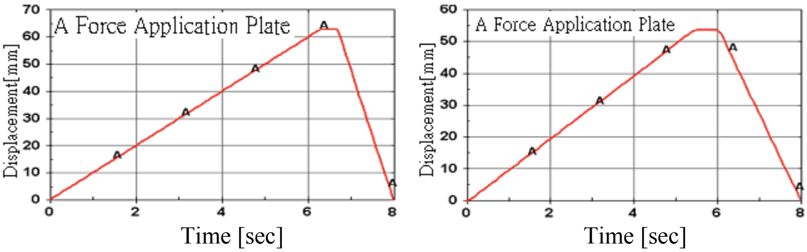
Fig. 10 displays the application forces applied to the vehicle roofs and the displacements of the force application plates of two vehicle models. Loading curve with three stages of the roof compressing, including quasi-static increasing force up to 1.5 times UVW, maintaining the maximum value of force, and releasing the force that are shown in Fig. 10a for model I and model II. These are the FMVSS 220 requirements for the application force. Displacements of the force application plate (Fig. 10b), express the status of those two vehicle models following the FMVSS 220. Maximum displacements of the force application plate of both vehicle models do not exceed 130.175 mm.



Model I, max = 1.5UVW = 113547.68 [N]

Model II, max = 1.5UVW = 116483.94 [N]

a. Loading force history.



Model I, maximum displacement = 63.3 [mm]

Model II, maximum displacement = 56.4 [mm]

b. Displacement history of the force application plate.

Figure 10: Model I and model II, loading force and displacement histories for the force application plate.

7 Conclusions

The objectives of this research are vehicle deformation configuration analysis in accordance with energy absorption and large bus rollover protection analysis following the legislation for standard. The following conclusions can be drawn:

(1) This study established two numerical simulation processes of the bus rollover event, one following ECE R66, and one following EMVSS 220. Thus, the strength of vehicle superstructure as well as the survivor space status and deformation modes of vehicles can be estimated.

(2) The absorbed energy of the vehicle superstructure and its distribution (Table 2) expressed the distortion configuration of body structure according to ECE R66 and FMVSS 220. A significant difference between the requirements of ECE R66 and FMVSS 220 for the body structure strength is discovered. With 57.16% total absorbed energy, the side wall section is the highest requirement following ECE R66. However, with 50.01% of the total absorbed energy, the roof section is the highest requirement following FMVSS 220.

(3) The structural behaviors of a coach were different when submitted to the two different assessment procedures prescribed by the ECE R66 and FMVSS 220. However, the investigation of distortion configuration of two testing models

(4) showed that the passenger compartment and residual space were more violated and more dangerous under the lateral rollover testing condition of ECE R66. The physical meanings of the bus rollover safety regulations (ECE R66 and FMVSS 220) are considered followed the regulations' requirements as well as the distortion configuration of vehicle superstructure under rollover conditions. In this study shock resistant capability of the ECE R66 and the FMVSS 220 was compared: one bus superstructure passing the FMVSS 220 assessment may not pass the ECE R66 assessment.

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