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Fast fabrication of amphibious bus with low rollover risk: Toward well-structured bus-boat using truck chassis

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Abstract. This study investigates the structural integrity of the amphibious tour bus under the rollover condition. The multi-purpose bus called Dual Mode Tour Bus (DMTB) which explores on land and water has been designed on top of a truck platform. Prior to the fabrication of new upper body and sailing equipment of DMTB, computational analysis investigates the rollover protection of the proposed structure including superstructure, wheels, and axles. The Computer-Aided Design (CAD) of the whole vehicle model is meshed and preprocessed under high performance using the Altair HyperMesh to attain the best mesh model suited for finite element analysis (FEA) on the proposed system. Meanwhile, the numerical model is analyzed by employing LS-DYNA to evaluate the superstructure strength. The numerical model includes detail information about the microstructure and considers wheels and axles as rigid bodies but excludes window glasses, seats, and interior parts. Based on the simulation analysis and proper modifications especially on the rear portion of the bus, the local stiffness significantly increased. The vehicle is rotated to the contact point on the ground based on the mathematical method presented in this study to save computational cost. The results show that the proposed method of rollover analysis is highly significant not only in bus rollover tests but in crashworthiness studies for other application. The critical impartments in our suggested dual-purpose bus accepted and passed "Economic Commission for Europe (ECE) R66".

Keywords: rollover analysis; ECE R66; superstructure; crashworthiness; LS-DYNA; finite element modeling

1. Introduction

Vehicle safety is a serious concern for scientists, car companies, and governments, and therefore special attention and huge attempts were investigated to enhance vehicle safety (Pai 2017). Predominantly, rollover is one of the main types of accidents where researchers have focused due to the gravity of injuries and the social impact it generates (Meti *et al.* 2018). Among the different vehicles' rollover, the bus is one of the main concerns in current studies due to a higher risk of injuries by increasing the number of passengers (Jongpradist *et al.* 2018, Seyedi *et al.* 2019). Especially in M2 and M3 vehicle categories, the rollover risk is critical. Therefore, regulations monitoring the performance of superstructures are controlled through "Economic Commission for Europe (ECE) R66" standards. According to the report of the IG/R.66 meeting about global rollover-accident statistics, there have been more than 570 bus rollover accidents between 1973 to 2006 (GRSG-93-4 2007).

Although bus rollover accidents are less frequent than other types of crashes, rollovers are very severe when they occur (Matolcsy 2007). A strong superstructure is in this case critical to ensure the safety of the passengers (Kumar and Sharma 2017). The worst scenario in this type of accidents is a complete rollover, where the bus turns upside down and crushes the roof. Hence, the rollover test is essential before starting fabrication (Elitok *et al.* 2006). The test begins with the coach standing on a platform; the platform is then rotated slowly until the bus reaches its highest unstable condition (Liang and Le 2010). Then the bus falls on the ground onto its roof side (UNECE 2010).

Performing physical rollover tests are costly. However, they are computationally efficient and cheaper. As a result, rollover simulations using Finite Element Analysis (FEA) have been playing a significant role in the approval process of vehicles. Thanks to numerical methods like FEA (Arabnejad *et al.* 2011, Daie *et al.* 2011, Chirwa *et al.* 2015, Shah *et al.* 2016, Makarian and Santhanam 2018, Makarian *et al.* 2018) or non-local methods (Behzadinasab *et al.* 2018, Behzadinasab *et al.* 2018, Bobaru *et al.* 2018, Jafarzadeh *et al.* 2019), the investigation of the physical test is achievable before real analysis of each component. The finite element model of the vehicle should be verified as it is the compulsory requirement of the regulation (UNECE 2010). LS-DYNA, as a strong finite element modeling software, represents a unique platform for the analysis of large deformation and dynamic analyses ((LSTC) 2018, Abedini *et al.* 2018, Abedini and Mutalib 2019).

In the pioneering study, a low-cost fabrication of an amphibious bus under rollover condition is evaluated using the FEA (see Fig. 1). The fabricated Dual Mode Tour Bus (DMTB) is a multi-purpose bus applicable in both lands and on water manufactured on top of a truck chassis. The prototype

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Fig. 1 (a) Prototype amphibious bus, (b) and (c) CAD and the finite element of the vehicle from the front and rear view

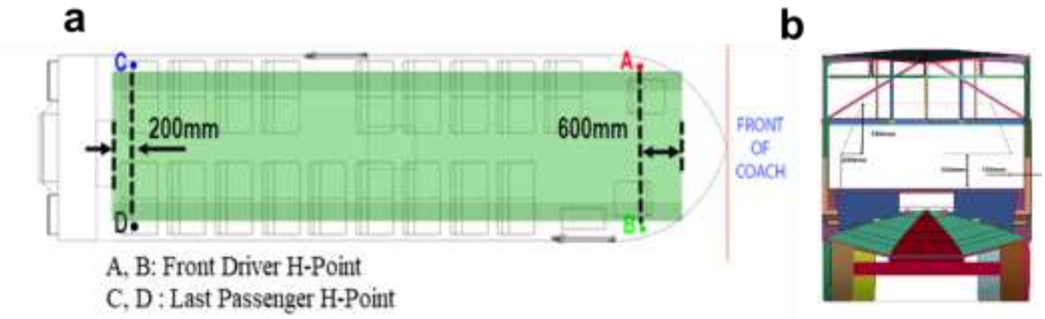

Fig. 2 The location of residual space in the bus: (a) front and rear distances and (b) side and vertical lengths of the residual space

vehicle is shown in Fig. 1(a). To the best of our knowledge, this is the first research article which discusses the method that rotates a vehicle having different front and rear tracks (Wong 2008, Rajamani 2011). First, the entire finite element (FE) model is cinematically rotated about the platform rotational axis to the unstable condition of the bus. Then, the vehicle FE model is rotated about an imaginary axis to the impact location to save the simulation time and cost. The impact simulation is then evaluated using LS-DYNA v971.

This paper is organized as follow: First, the rollover test procedure is introduced, and the position of the residual space is defined in the vehicle model. Bus components excluded from the intrusion investigation are discussed here. Moreover, the mathematical model which defines rotation rules for the rollover simulation is explained. Then, the FE model of the entire vehicle including superstructure and the residual space is presented. Experimental and simulation results which approved the integrity of the superstructure are then discussed. Lastly, the conclusions of the research and funding source are presented.

2. Evaluation of the DMTB superstructure

2.1 The residual space

According to the ECE regulation No. 66, the residual space refers to space for a single-decked vehicle made for carrying more than 22 travelers including drivers and crew (UNECE 2010). In fact, the strength of superstructure in a rollover accident should be sufficient to ensure that the residual space both during and after the rollover test on the complete vehicle is unaffected. Fig. 2 shows the vehicle's residual space positioned inside the vehicle. The rollover test as a lateral rotation test holds the vehicle standing on the tilting platform while the suspensions are fixed. Then the platform rotates very slowly until it reaches an unstable equilibrium position of the vehicle shown in Figs. 3(a) and 4(b) (Winkler 1999). The axis of tilting is shown in Fig. 3(b). The vehicle falls after this unstable condition with zero angular velocity and rotates about the axis of rotation passing through the wheel support contact points.

LS-DYNA as one of the most applicable software in the automotive industry to evaluate the performance of vehicle bodies was used to simulate the rollover accident. LS-DYNA is accurate, reliable, and can predict a vehicle's performance in a crash and other dynamic tests (Abedini *et al*. 2017, Martynenko *et al*. 2017).

2.2 Rollover test

Rollover analysis is performed on a fully laden vehicle placed on a test bench. The test bench holds the vehicle using a platform as illustrated in Fig. 3 while tilting (UNECE 2010). The tilting platform also includes two wheel supports which prevent the vehicle from slipping (see Fig. 3(b). According to the instructions of the test, the gravity center of the vehicle on the test platform should be similar to the complete and fully optimized vehicle.

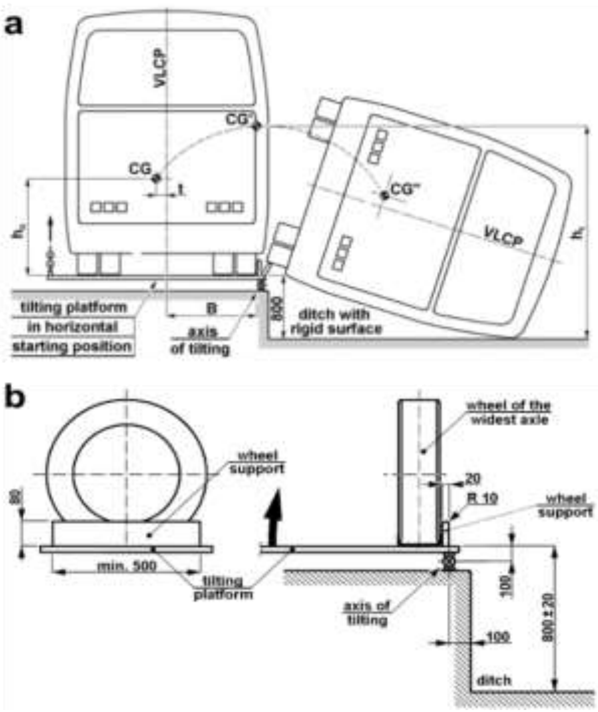

Fig. 3 Theoretical analysis of bus rollover test: (a) Conditions of the rollover test on a vehicle showing the path of the CG through the starting, unstable condition, and hitting the ground and (b) Wheel supports which stop the vehicle from moving (UNECE 2010)

Furthermore, the fully laden mass of the vehicle together with the mass distribution should be appropriate to the fully optimized version of the suggested vehicle. Additionally, contributed components in the total strength of the superstructure need to be installed in their appropriate location. Suspension travels are locked. For a complete demonstration of the rollover test as the worst accident scenario, battery acid, fuel, and all other high-risk components must exist in the vehicle during rollover analysis and should be considered in the total mass of the vehicle.

The platform that holds the tested vehicle has to be tilted with a fixed velocity limited to maximum 0.087 rad/s (58/s) until the vehicle loses its stability (UNECE 2010). According to the existing regulation of roller test, the total impact area that the whole structure is tilted must be smooth concrete surface and dry. In fact, this is very important as the total friction coefficient on steel, and dry concrete may highly relay on the humidity. According to PN-82/B-02003 "Actions on building structures – variable actions during exploitation and assembling" the static friction coefficient value for concrete and steel with a normal smooth surface is equal to 0.45-0.7, while this value for rough steel and concrete surface is 0.31 (Karlinski *et al*. 2014).

2.3 The mathematical model to obtain initial rotational velocity

The total energy (ET) absorbed by the superstructure is defined by Eq. (1).

$$E_T = 0.75mg\Delta h = 0.75mg(h_2 - h_1) \tag{1}$$

where m is the total vehicle mass, Δh is the change in the height of COG, h_1is the highest height of COG at the unstable condition, h_2is the height of COG before hitting the ground. The value of E_T is around ~80KNm. The exact values in this section are not given because of the confidentiality of the information with the manufacturer. The relation between the kinetic energy and the rotational velocity is of the form Eq. (2).

$$K = \frac{1}{2} I_{xx}\omega^2 \tag{2}$$

where K is the kinetic energy and I_{xx} is the moment of inertia about the axis of rotation. The vehicle rotates about the center of the two reference points connecting the front and rear wheel support. The distance between this point and the COG is named *r*. Therefore, I_{xx} can be calculated as Eq. (3)

$$I_{xx} = I_{cg} + mr^2 \tag{3}$$

By matching the kinetic energy Eq. (2) with the absorbed energy (Eq. (1)) the initial rotational velocity is found as $\omega{\sim}1.85\, rad/s$ when hitting the ground and is applied to all nodes in the finite element model. The axis of rotation is along the line connecting two supports of the wheels. The direction of the rollover was chosen based on the lateral eccentricity of the CG of the model shown in Fig. 4(b). The Y-position of the C.G. defines the vehicle rotation. As shown in Fig. 4(a), the C.G is located *t*=12 mm to the right of the vehicle. Therefore, a higher energy will be absorbed if the vehicle rotates counterclockwise. Consequently, rotating to the left is more severe than rotating to the right. According to the section 3.2.2.1 on the "ECE R66r02", the reference energy E_R defining the energy at the unstable condition can be formulated as follows

$$E_R = mgh_1 = mg(0.8 + \sqrt{h_0^2 + (B \pm t)^2}) \qquad (4)$$

Where m is the curb mass, h_0 is the height of CG, t is the horizontal distance from the vehicle central plane to CG, B is the horizontal distance between the vehicle central plane to the axis of rotation in the rollover test (see Fig. 4).

3. Rollover simulation on the complete DMTB

Enhancements of the calculating computer's capability raise their popularity of destructive strength analysis using simulations. In accordance with "Annex 9" in ECE R66, the computer simulation is considered as an approval for the adequate strength of the superstructure. The detailed technical specification of the rollover test on a complete vehicle as the basic approval test is given in annex 5 in ECE R66 (UNECE 2010). The developed LS-DYNA model originally lies in highly nonlinear, transient dynamic finite element analysis which uses explicit time integration (Abedini *et al*. 2017, Mehrmashhadi *et al.* 2019). The simulation was solved for 500 ms.

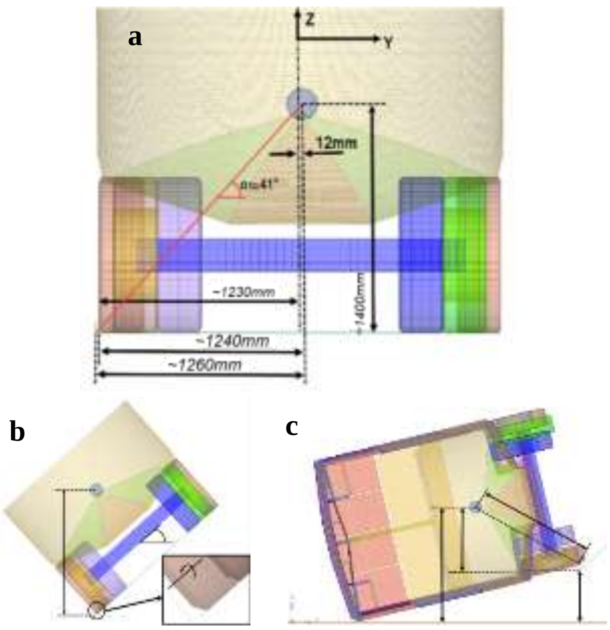

Fig. 4 (a) Dimension of the bus on the stable condition, (b) the bus location after the first rotation (unstable condition), and (c) the second rotation and the final position of the bus before hitting the ground

Table 1 Vehicle Parameters

Gross Vehicle Weight	11945 kg
Track (FR/RR)	2015/1837 mm
Vehicle Length	5585 mm

The vehicle was placed on the rig and is rotated cinematically about the longitudinal axis of the rig to its highest unstable condition. Then, the model cinematically rotated one more time about the axis connecting the front, and rear wheel supports to the impact location. After that, using the balance of energy and the mathematical model, the rotational velocity was calculated and applied to the entire model.
The fully integrated shell element formulation (Elform #16) is used for the deformable shell elements, whereas the default element formulation (Elform #2) is utilized for rigid shell elements. Axles are connected to the chassis via beam elements (Elform #1). The cross-section is defined so that no bending will happen on beam. Moreover, the weight of axles is distributed over some points on the elastic part of the chassis. The total number of nodes and elements are about 720k and 732k, respectively. Components such as the engine, axles, and gearbox (see Table I) were defined with mass elements (*ELEMENT_MASS) without a rotational degree of freedom and were added to the rigid parts via *CONSTRAINED_EXTRA_NODES_NODE. The vehicle center of gravity is adjusted via an extra lumped mass included passenger weights to match with the experimental center of gravity. To distribute forces of mass elements to bodies, several *CONSTRAINED_INTERPOLATION cards were used. The vehicle weight and dimensions are listed in Table 1.

3.1 Material model

The entire amphibious superstructure was made of aluminum alloys except for the antiroll bar which was made of steel. DMTB Superstructure components were butt welded with aluminum alloy. Failure is important in the modeling of material behavior especially in the dynamic loading (Jafarzadeh *et al.* 2017, Rami *et al.* 2017, Abedini *et al.* 2019, Mehrmashhadi *et al*. 2019). To consider failure due to element deletion, we use failure strain which varies between 0.12 to 0.18 according to the material numbers. All deformable materials were modeled with *MAT_24 whereas wheels, axles, and the residual space was considered rigid. Rigid materials are selected for these parts because they do not deform during the simulation. Thus, we can save computational cost with choosing rigid materials.

3.2 Contact

Special contact features are included in the LS-DYNA which make contact between surfaces very efficient. The contact card *CONTACT_AUTOMATIC_SINGLE surface is mostly used in this study. This contact prevents a surface of one body penetrates with itself or the surface of another body. The contact card *CONTACT_SURFACE_TO_SURFACE is also defined between wheels and wheel supports. Wheel rims are constrained to the axles with *CONSTRAINED_RIGID_BODIES, and the residual space is constrained with the rear axle with the same approach.

4. Experimental tests of DMTB rollover analysis

Simulation results are shown in Figs. 5-7. Energy plots shown in Fig. 5(a) confirm that the kinetic energy started with the value close to 80 KNm (see Eq. (1)) and continued to decrease. The potential energy, on the other hand, increased accordingly. With the use of fully integration deformable shell element, the hourglass energy was certainly less than five percent of the total energy meaning the legislative requirement was met. The vehicle had low kinetic energy at a time equal to 500 ms which was low, and no permanent deformations were observed. Deformations of the vehicle in the consecutive screenshot of the crash at different times are shown in Fig. 7.

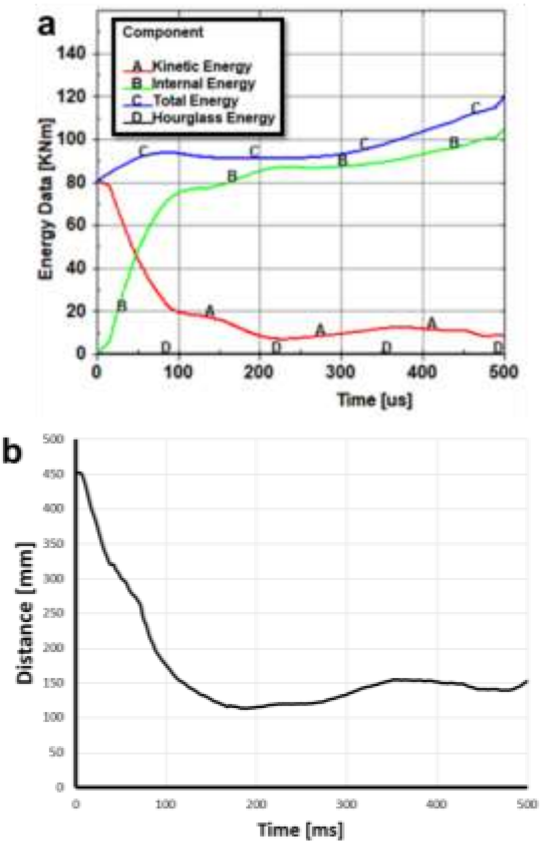

Fig. 5 (a) Energy plot showing zero hourglass energy and low kinetic energy at the end of the simulation and (b) Minimum distance from the superstructure to the residual space showing no intrusion to the residual space

According to the ECE R66, vehicle components already in the residual space can be neglected from the evaluation of the intrusion. Therefore, two front column posts were excluded from intrusion evaluation. Other columns located in front of these posts are also excluded since they are not within the minimum distant to the residual space because of the front curve of the vehicle (Yang *et al.* 2016). As presented in Fig. 7, no intrusion to the residual space can be seen. Thus, the residual space is untouched, and this bus would meet the ECE R66 requirement. The minimum distance from a front post to the residual space is shown in Fig. 5(b). The closest distance from the vehicle component to the vehicle is 110 mm at 170 μs. We run the simulation on a single CPU with Intel Xeon E5-2670 2.60-GHz processor and it takes about 11 hours to perform a complete simulation.

According to the rollover simulation result performed based on "Annex 9" in ECE R66, the superstructure of the bus was subjected to plastic deformation. Specifically, the driver's cabin, roof, and columns were the most deformed components (Dagdeviren *et al.* 2016). According to the consecutive screenshots of the vehicle deformation shown in Fig. 7, the front section of the structure had the largest deformation, which is the most dangerous factor of passengers' safety during rollover accidents.

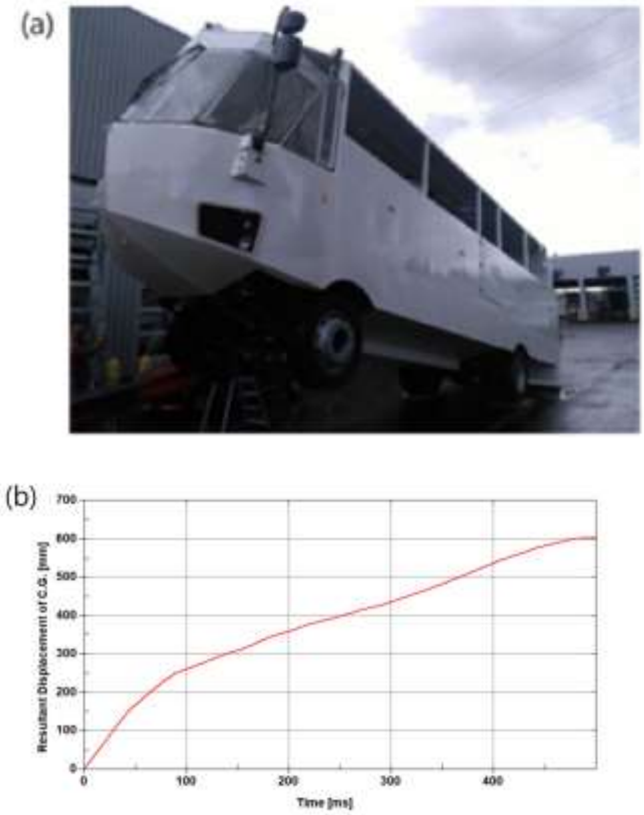

Fig. 6 Experimental tests of rollover analysis: (a) Fabricated DMTB C.G test and (b) Resultant displacement of C.G. of the DMTB

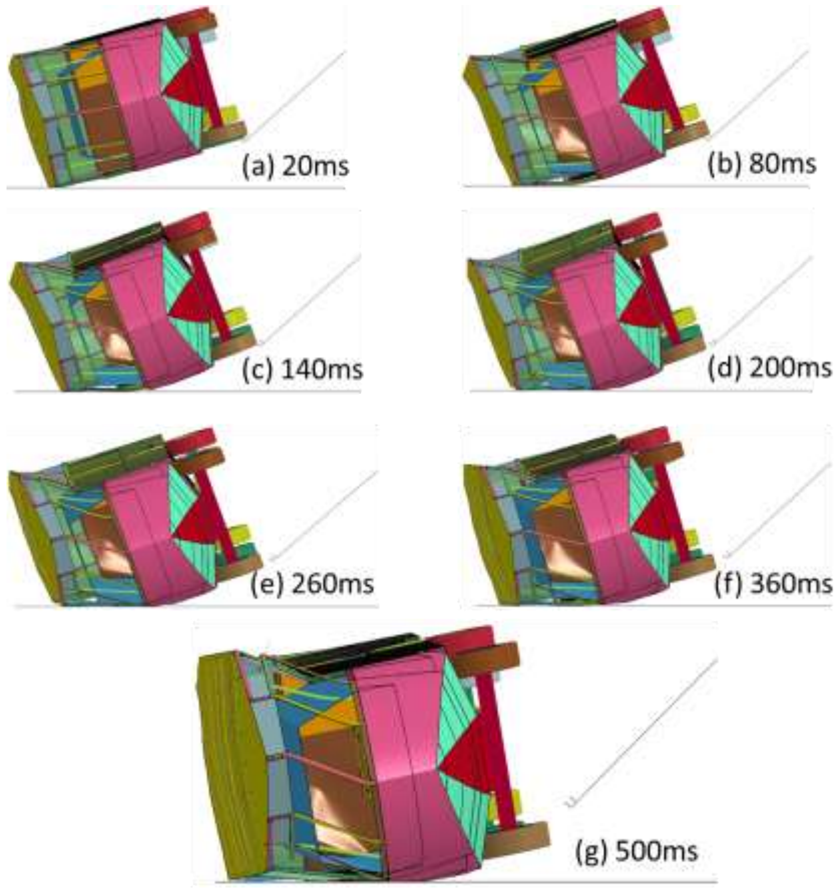

Fig. 7 (a)-(g) Consecutive screenshots of the DMTB deformation at 20 ms, 80 ms, 140 ms, 200 ms, 260 ms, 360 ms, and 360 ms under impact simulation

The anti-roll bar systems placed at the back of the DMTB plays a vital rule in limiting the vehicle displacement and keeping the residual space untouched. Anti-roll bar system is attached to the superstructure by bolts and stiffeners. Parts of the superstructure were additionally stiffened and reinforced with extra frames to reduce the total displacement of the columns keeping them far from the residual space.

The resultant displacement of the gravity center (C.G.) is shown in Fig. 6 which shows the displacement reached a plateau after 500 ms of the solution. According to the results, the center of gravity started to move appropriately in the roller analysis. However, the maximum movement of the G.C. is 600 mm which was accrued at 480 ms. Furthermore, the slope was slightly decreasing after 100 ms of roller test starts which indicates that the most if the G.C movement is happening while the bus is not its maximum unstable phase.

5. Conclusions

The structural integrity of the multi-purpose bus regarding ECE Regulation No. 66 was evaluated in this study. The center of gravity and total DMTB weight were the same as manufacturer data. The rotational velocity of the entire bus was calculated according to the presented mathematical model which rotated the bus about the axis connecting wheel supports. Initially, the bus failed to comply with the regulatory requirement. Hence, modifications carried out on the rear part of the bus helped to increase the local stiffness. Final results clearly showed that initial kinetic energy matches well with theoretical calculation, the residual space was untouched, and the level of hourglass energy was below five percent which is the requirement of ECE Regulation No. 66. Overall, based on the current center of gravity measurement and modification on the superstructure, the modified DMTB has attained a pass from the ECE R66. The suggested method coupled with demonstrated results showed that this method of rollover simulation was highly significant not only in bus rollover analysis but in crashworthiness studies for other applications. This bus was granted the vehicle type approval by French authorities in July 2018.

Acknowledgments

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