IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X, Volume 16, Issue 3 Ser. I (May. - June. 2019), PP 30-40
www.iosrjournals.org

The Effectiveness of Longitudinal Friction Force on Bus Structure Integrity During Rollover Accidents

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Abstract: *Finite Element Method (FEM), is a numerical method was used for checking on single deck bus body structure belonging to one of bus manufacturer in EGYPT according to standard regulations UN-ECE R66. The simulation implemented on a section of the proposed bus in A Static Structural module in ANSYS. Also, experimental rollover test has been used in this paper, some problems have been encountered in the weldment of side rails with the roof members during test. So, the authors fully depended on the simulation results. The purpose of this paper is to implement the simulation in order to evaluate the bus section during rollover, take to account the influence of the longitudinal friction force during rollover. investigate the influence of this additive force on the bus structure during rollover and compares the influence on the residual space and energy absorbed. The effectiveness of longitudinal friction force on the bus section and safety space during rollover are very limited, also the lateral force is the most influential on the structure deformation during rollover.*
Keywords: *-Bus Structure Integrity, Rollover Test ECE R66, Residual Space, Structure Topology Optimization*

Date of Submission: 06-05-2019 Date of acceptance: 20-05-2019

I. Introduction

The buses are designed to carry the occupants for so many to various points, thousands from the buses transport millions of passengers everyday around town or long distances, buses may use for a wide range of purposes, but the occupant safety hadn't taken adequate attention in buses compared to the passenger car. The safety in passenger cars include front and side airbags and seatbelt for every occupant, but the safety in the conventional buses depended on the structure response during the rollover crashes [1]. Passengers in the buses on highways are affected by dynamic loads during different operations conditions such as acceleration, braking and lateral maneuvering which could lead to many risks. These buses contain many occupants, so occupant's safety is one of the most critical apprehensions in the mind of the bus structure designer to maintain the occupant life and reduce the injuries, the current work focusing on rollover crashes apprehensions applied on one sector of the proposed bus structure. This point deserves a great effort to reduce the injuries and save the lives of passengers. At many of the rollovers crash lead to ejection the occupants from the bus due to high acceleration so seat belts should be used for the occupant safety during the accidents [2].The bus rollover accidents are one percent of all crashes, but these crashes account for about one-third of passenger occupant deaths. At 2016, 23,973 occupants died in crashes. Of those, 7,488 died in rollover crashes. Egypt loses in road traffic crashes about 12 000 lives every year. It has a road traffic accidents rate of 42 deaths per 100 000 population [3]. For example, at July 2018, on the coastal road in Matruh province,which lead to killed 10 people and injured 25[4]. Which gives importance to discussing the safety in buses as a result of numbers of occupants.

Generally, in passenger's buses design processes can rely firstly on geometry to build a suggest pre-design of the needed bus and evaluate the bus structural design under dynamics behavior and re-design the bus body structure based on the concluded results from the analysis by using engineering simulation software that needs to supercomputing facilities [5]. Bus rollover crashes defined as the necessary approval to superstructure strength to prevent the occupants from deformation injuries in the remaining space and to evaluate the proposed bus structure behavior during its subjected to rollover. Yu., Nian H., [6] Discussed the bus superstructure main components its will be governed in energy absorbing capacity. D.A. Micu, et. al, [7]. Have presented a computer simulation of rollover test on a body section. They used pendulum test on the section as a rollover test. The current work concerning on the bus safety during rollover and to save the occupant life from the intrusion. and need to enhance and issued proposed performance requirements especially in the new buses to meet and implement the recommended tests.

Figure (1): Rollover Crash on the coastal road, Matruh province, 2018.

II. Problem Statement

Buses overturning incidents are defined as rotational motion about the longitudinal axis. Bus rollover often happens in high speed during cornering or due to collision into small side wall or if the driver applies maximum steer angle in turns also if the road roughness decreased based on soft soil. Anyway. The rollover often occurs during movement. The upper corner of the bus body structure is exposed to rollover force in lateral direction in static case. While, the place indicated (red circle) in **Figure (1)** is exposed to two different directions of force in dynamic case. The first direction is the accidental trend resulting from the collision of the upper edge of the ground due to the overturning of the bus. The second direction is the longitudinal direction, resulting from friction with the upper edge of the ground, if the bus overturns during movement. The current work discusses and implement the rollover testing and simulation on the proposed design of the bus structure according to (UN-ECE Regulation 66) [8]. The simulation focuseson showing the effect of longitudinal force on the bus structure and the safety space. Generally, the problematic in rollover in the differentiation between structural rigidity and energy absorbed during the crash. The structural rigidity in other word defines as 'stiff structure' is pouring into a point of the structure durability and more lifetime during the operations. this is to increase the bus weight but that is probably dangerous of high acceleration during the impact on the other side more energy absorbed is opposite to the previous meaning, and that becomes more deformed bus structure [9].

1. Bus Structure Specifics

The proposed bus structure consisted of 122 square tubes from structure steel with different lengths, and the most use cross-sections are 30 X 30 X 1.80 also 40 X 40 X 1.80 and some other sections. The current structure does not use any diagonals Figure (2). The roof consists of three longitudinal members, and the position of these members are above the main chassis with using wood separators using U bolts or other fixation methods [10]. The window dimensions must be according to standard regulation to clear vision zone, the minimum height and width of the window aperture shall be 550 x 550 mm. However, in the current proposed design, the window width is 1600 mm, the window height 800m. The chassis-level based on the side panel in between the crib rail and the skirt rail and in the vertical rails. the bus body structure arranged from A-pillar to I-pillar and divided into nine pillars.

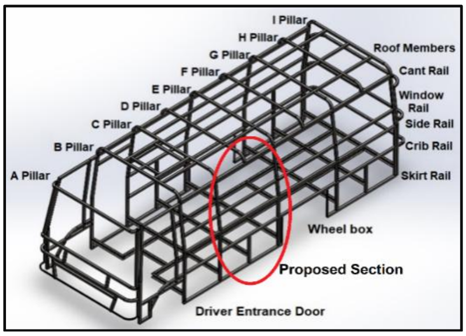


Figure (2): Bus Body Details and Proposed Section.

The selected sector in between C pillar and E pillar (red ellipse) in **Figure (2)** for implement both the simulation and experimental rollover test. Where the axial gravity center and most passenger seats are in the bus internal sections. The front cabin contains the front axle, doors and windscreen frontside as a support during rollover and the rear sector contains a rear side and axle. While the target section in the proposed bus usually consists of two sectors. For that reasons, the middle area was more appropriate for testing and simulation.

2. Bus Rollover Dynamics

Lateral stability of the bus during maneuvering divided into two stages, side skid and overturning. Mainly the two stages depending on the operation parameters such as speed during curved path and the radius, also depend on the bus stability factors such as vehicle mass, vehicle width, the center of gravity position [11]. Road inclination in the right direction is very useful to minimize the influence of overturning, especially in maneuvering. Modeling assumption of bus rollover in the first is consists of a solid mass with solid tires, stable suspension, and the obtained required velocity by sliding the vehicle laterally down a tilted table to a stop which initiates the rollover action. The pivot point is point A, at which the lateral sliding motion ceases and rollover. Ensures the transformed of lateral motion into angular motion, which raises the center of gravity. The bus can then impact onto its corner on the pavement. For a bus rolling over on level pavement, this would constitute a rollover second turns [12].Bus stability while turnover is dependent on the position of Center of stability (CoS). If the height of the bus CoS is higher behind the ground level, (instability case) the chance of rollover will be more than one having lower CoS to ground level. Also, the radius of rotation will increase if the CoS is higher, which producing more kinetic energy on the bus structure before impact and resulting from more damage to the superstructure during the bus rollover crashes. During design steps, proper caution should be taken to achieve minimum Center of stability of the Bus and variate the design parameters to ensure the real objective as (Bus Stability).

Σ Moment about outer wheels' equal zero [static –rigid bus]

- Roll moment equation: $F_{Lateral} \ . h_{C.G} = W \ \frac{B}{2}$ (1)
- Lateral acceleration $[m.a_y]h_{C.G} = W \ \frac{B}{2}$(2)
- Static stability factor $\frac{a_y}{g} = \frac{B}{2h_{C.G}}$ (3)

Two external forces act on the bus during maneuvering. First, tirecornering forcefrom thecontact patch in the opposite direction to the centrifugal force and push the vehicle towards the center of the curve under lateral adhesion coefficient in **Figure (3).** Second, the centrifugal force in lateral direction acts through the center of gravity of the bus mass away from the center of the turn. These forces make the bus roll motion towards the outside of the curve [13].

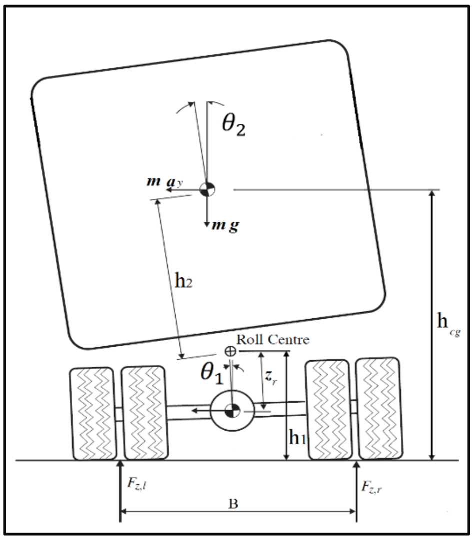


Figure (3): Tire and Suspension Flexibility during rounds a corner.

Σ Moment about outer wheels' equal zero [quasi-static rigid bus]

- $(F_{Lateral} \ . h_{C.G}) - \left(W \ \frac{B}{2}\right) = (w_{Inner} \ . B)$ (4)

Lateral acceleration limit (Overturning Limit)

- $\frac{a_y}{g} = \left[\frac{V^2}{gR}\right] = \left(\frac{B}{2h_{C.G}}\right) - \left(\frac{w_{Inner}}{w} . B\right)$ (5)

bus lateral acceleration capability of hard tires and rigid suspension depended on the static stability factor even the bus width and the heights of the center of gravity these factors based on the bus skeleton design and dimensions, driveline arrangement, and luges distribution. Dynamically, lateral acceleration of the bus during turns variant according to the bus speed and the radius of the bus path [14]. The phenomenon of bus rollover can be achieved during rounds a corner in small radius or driving in high speed in maneuvering that producing maximum lateral acceleration, the load transferred from inner wheel to outer wheel in case of the ground reaction on the inner tires down to (zero) when the cornering forces and centrifugal forces are enough to overcome the bus weight, the bus body will start in turn over [15].

The moment at the inner wheel in curved path.

- $F_{Lateral}\ h_{C.G} = W(\frac{B}{2} - x)$ (6)

Where $h_{C.G} = h_1 + h_2$, $x = L_1 + L_2$, $L_1 = h_1 . \tan\theta_1$, $L_2 = h_2 . \tan\theta_2$

- $\left[(\frac{W}{g})\frac{V^2}{R}\right](h_1 + h_2) = (mg)\ (\frac{B}{2} - (h_1 . \tan\theta_1 + h_2 . \tan\theta_2)$ (7)

Overturning limit (OTL)

- $\frac{a_y}{g} = \left(\frac{B-(h_1 . \tan\ \theta_1 + h_2 . \tan\ \theta_2)}{2\ (h_1+h_2)}\right)$(8)

III. Standard Rollover Test According to UN-ECE R 66

Economic Commission of Europe (ECE) R 66. Establishes the recommendation for the testing of the bus superstructure strength to reduce the deformation in bus roof in order to minimize the risks and injuries, this Regulation applies to single-deck small bus to categories M2 or M3 having more than 16 passengers. Under this test type, select the bus body section which includes at least two windows and provide the equivalent section weight from overall bus weight and adding occupant ballast weights were each fitted with 68 kg to the passenger seat or in the same position to maintain the same center of gravity. The test applies by using the tilting platform above the concrete ground surface with a depth of 800 mm, **Figure (4)**. The test procedures are by raising one side of the platform at a constant rate not more than 5 degrees/second until the bus rolls off the platform and impact the ground surface below. The distance between the structural support and the center of rotation no higher than a 100 mm, also the maximum height of tilting platform is 100 mm. Monitoring distortion that will occur in the residual space and mark the vertical members to measure the inclination angle and record the moment of separation of the body section and the time preceding the impact with the ground [8].

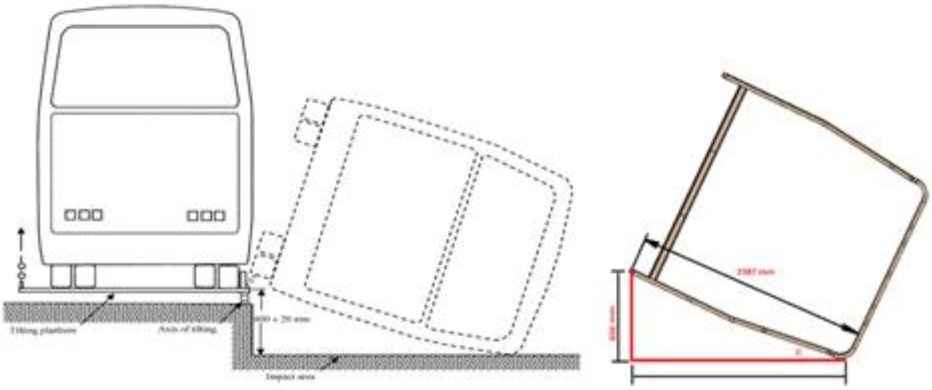


Figure (4): The tilting platform compared with the proposed model.

IV. Testing and Simulation Evaluation Parameters

1. **Residual Space:** The bus body section prepared to test the integrity according to UN-ECE regulation No. 66 using real model scale 1:1 and contains the remaining space as shown in **Figure (5)**in the bus compartment to the occupants after the rollover test.

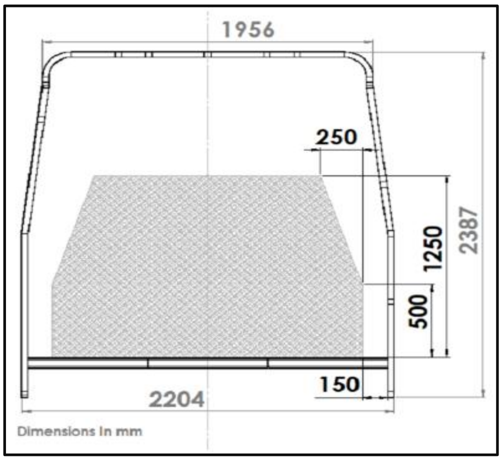


Figure (5): Residual Space Dimensions.

2. **Deformation Index (I_d):** Deformation factor according to bus deformed members Figure (6), due to rollover crash forces at the acting position of thebus upper corner.

- I_d. d = L. tan ($\Delta\alpha_1$) + [(h-L) tan ($\Delta\alpha_2$)](9)

Where, L–height from the floor to window rail connection
h– height of the residual space 1250 mm
d– distance from the side wall to the residual-space corner 400mm.

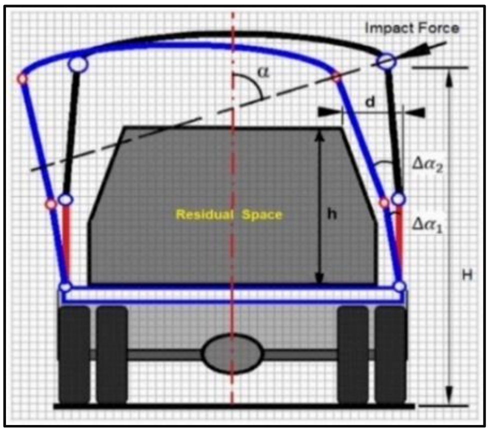


Figure (6): Members Inclination Angle.

3. **Energy Absorbed:** The injury in bus rollover is primarily due to large deformation of structure inside the occupant residual space. Hence, the bus structure should be strong enough to absorb the rollover energy at the same time, the intrusion of the superstructure should not affect the safety area of the occupant compartment. The total energy of rollover is determined by Equation.

$$E_t=0.75\ \ m\ \ g\ \ \delta h \quad (10)$$

Where, m- the curb mass of the bus in kilogram, g- the gravitational constantin m/sec2.
$\delta \boldsymbol{h}$- the center of gravity from highest position till impact position in m.

4. ANSYS Simulation and Geometry Meshing Characteristics

Simplify the bus geometry from the full model to section model and Importing the geometry creation file in STEP 214 extension into Ansys Software, the bus section consisted of 67 square tubes with different dimensions and thickness. The geometrical model developed using finite element analysis in ANSYS software **Figure (7),** based upon the mesh independent study to improve the mesh quality.

- Maximum face size: 0.01 m.
- Nodes: 863554
- Elements: 294914

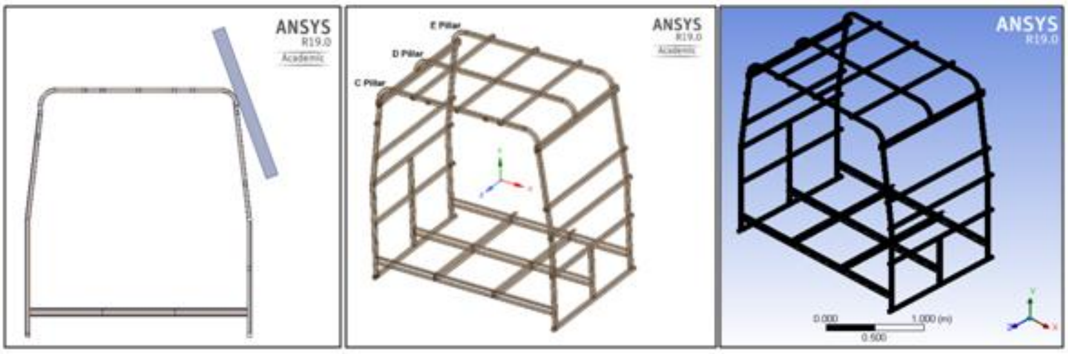
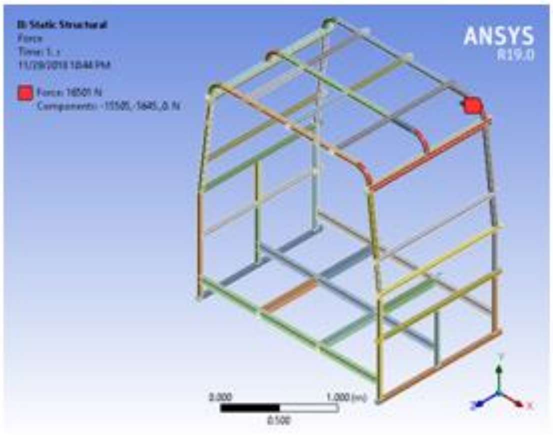


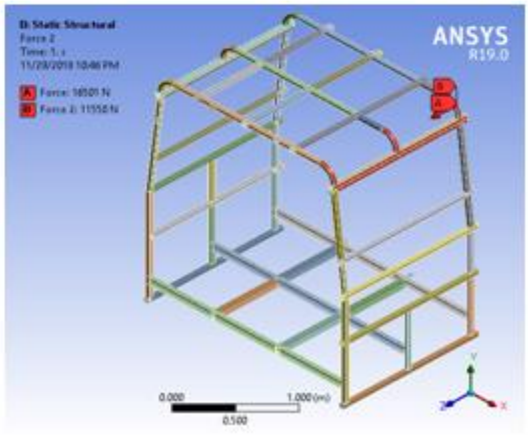
Figure (7): Bus Section Geometry and Finite Element meshing.

5. The Model Environment preparation

The longitudinal friction force Fxduring the rollover between the upper corner and the ground surface is worth to considering and studying to investigate that influence on the bodywork. $Fx = W_s * \emptyset$. In the left applying the nominal rollover force on the bus section, while in the right adding the proposed force according to roll over in dynamics case as shown in **Figure (8).**



Case a. Lateral force (FY) applied on upper corner.



Case b. Lateral and longitudinal forces (FX, FY).

Figure (8): Rollover Simulation in two cases (a,b)based upon applied force.

V. Experimental Resultsand Discussion

After preparing the section of the bus structure to implement the rollover test and analyze the behaviour and obtained by attaching the gross weight up to 1650 kg on occupants' seats and bus ground surface. The bus section is installed on the tilting platform, which is rotated around the roll axis of the tilting using Hydraulic lifting crane.

Figure (9): Loaded Bus Section on tiltableand weldment problems regions

Unfortunately, the test has been failed due to some defects in the welding of side rails and the roof members as shown in **Figure (9),** that need to repeat the test in the future after some modifications in the welding process, in future work we will explain this problem in detail after analyzing it and correcting the reasons after solving.

VI. Simulation Results and Discussion

1. Rollover Dynamics Results Using MATLAB

The results of SSF will used to study the dynamic characteristics of the bus body based on the proposed structure dimensions such as wheel base, wheel track and the height of center of stability and so on, to estimate Static Stability Factor (SSF) from the investigated equations using MATLAB software, to avoid the rollover crashes. Based upon the current bus data where is the gross weight is 7065 kg and the wheelbase 3365 mm and wheel track 2200 mm and consider the variation in center of stability height in range between 0.45 and 1.2 m and the output results at turns in curve 25 m and the speed range from 11 to 18 m/s as shown in **Figure(10)**.

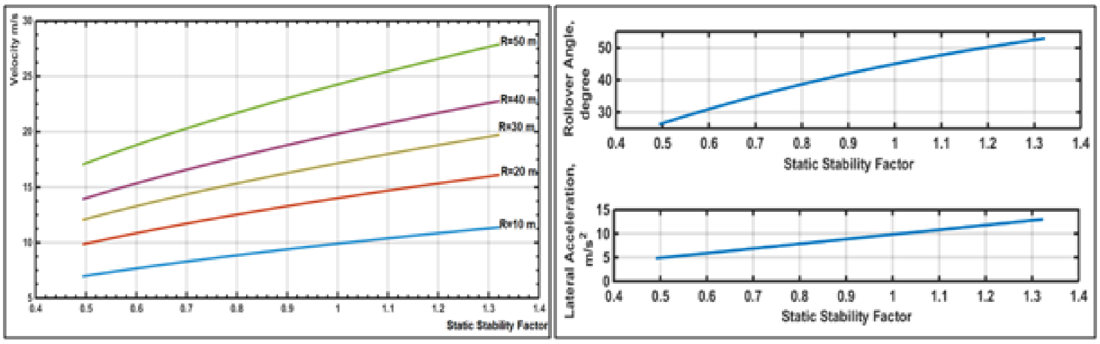


Figure (10): SSF versus road inclination angle and lateral acceleration, and bus speed during different radii.

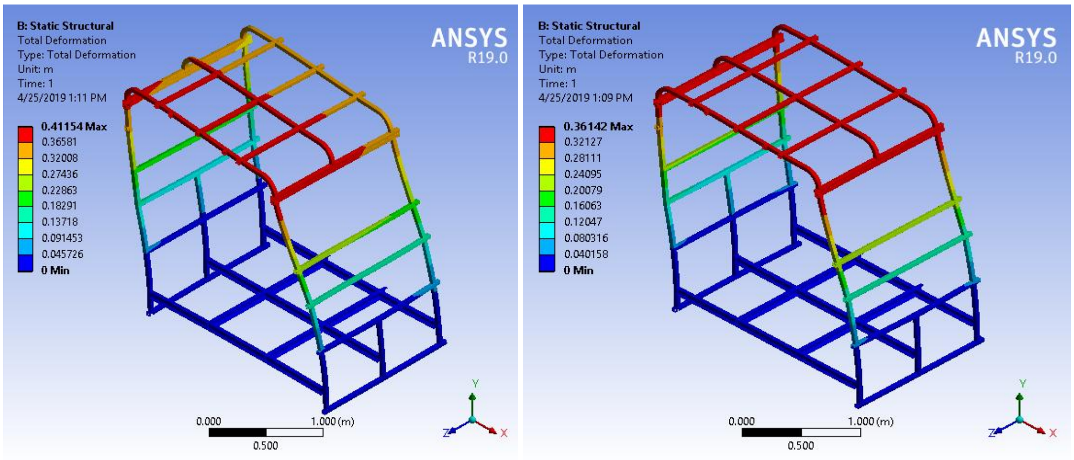
The study considers the variation of (SSF) in the range between 0.5 to 1.3 and with the actual bus dimensions can estimate the bus rollover angle statically. The statement the influence of stability factor on the nominal bus speed on a curved path with different radii from 10, 20, 30, 40 and 50m**Table (1),** the relation between SSF and COS height mainly based on the bus weight.

Table (1): Stability Factors in case of loaded and unloaded

Radius (m)	loaded, SSF= 0.988	Unloaded, SSF= 1.12
	Speed (m/s)	Speed (m/s)
10	9	10.5
20	13.6	14.9
30	16.9	18
40	19.3	21
50	23.8	25.5

2. Finite Element Results Using ANSYS

The solutions are performed with ANSYS 19. The module of Static Structure on two individual models with different initial conditions. The test results are projected to investigate the influence of rollover impact force on the bus compartment and residual space to evaluate the structural integrity according to standard regulation, So the actuation force recommended in lateral direction, if the bus moving during rollover, the bus upper corner implicate in resistance force in longitudinal direction due to friction between road surface and bus side panel.



Case a. Total Deformation due to Fyon upper corner. **Case b**. Total Deformation due to (Fx and Fy).

Figure (11): The total deformation of the body section in two conditions

At this stage the solutions in ANSYS workbench, static structure simulation was implemented, and results were compared for two different scenarios which are investigated to be more realistic cases according to rollover analysis in cases of static and dynamic are shown in **Figures (11).** where, the equivalent total deformation in the bus section during rollover is 361 mm resultant from the lateral force at the upper corner as a static case and the section consider safely passed. While the deformation due to longitudinal force added to previous lateral force is 411 mm. this force considers produced from dynamic movement during rollover event and is in the opposite direction of movement.

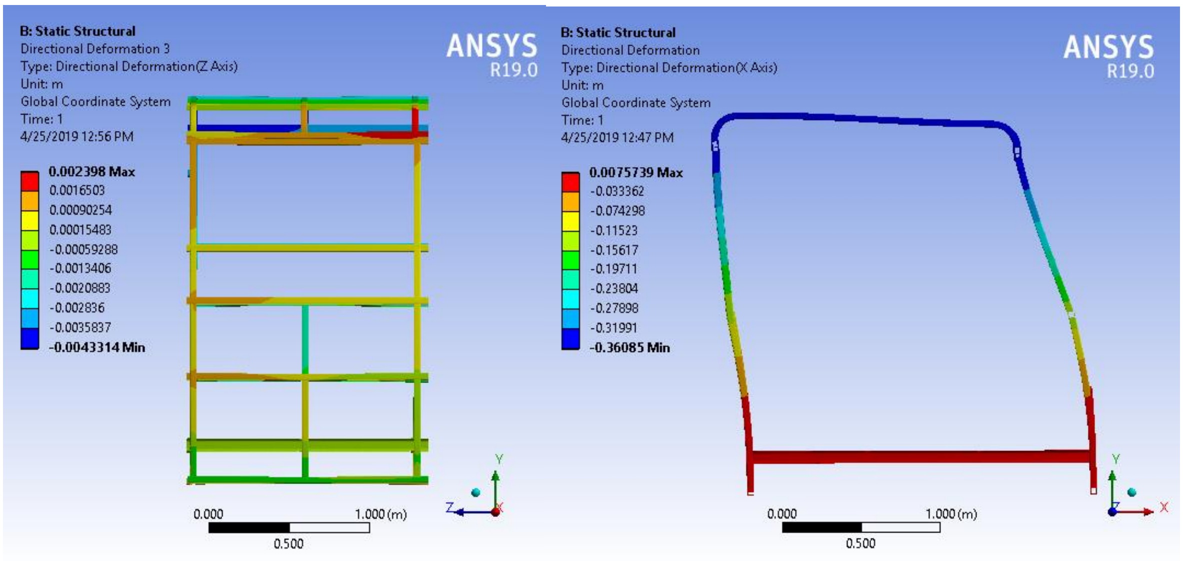


Figure (12): Case (a) Deformation in X and Z directions due to Lateral force (Fy).

Case (a), the deformation in (X- direction) due to the pure lateral force,**Figure (12)** is 360 mm. The roof deformation in the vertical direction (Y-direction)is 30 mm, and the deformation is 4 mm in (Z-direction). According to the structure simulation in Static structural module, the deformation in three directions islimited, and completely different with experimental results.

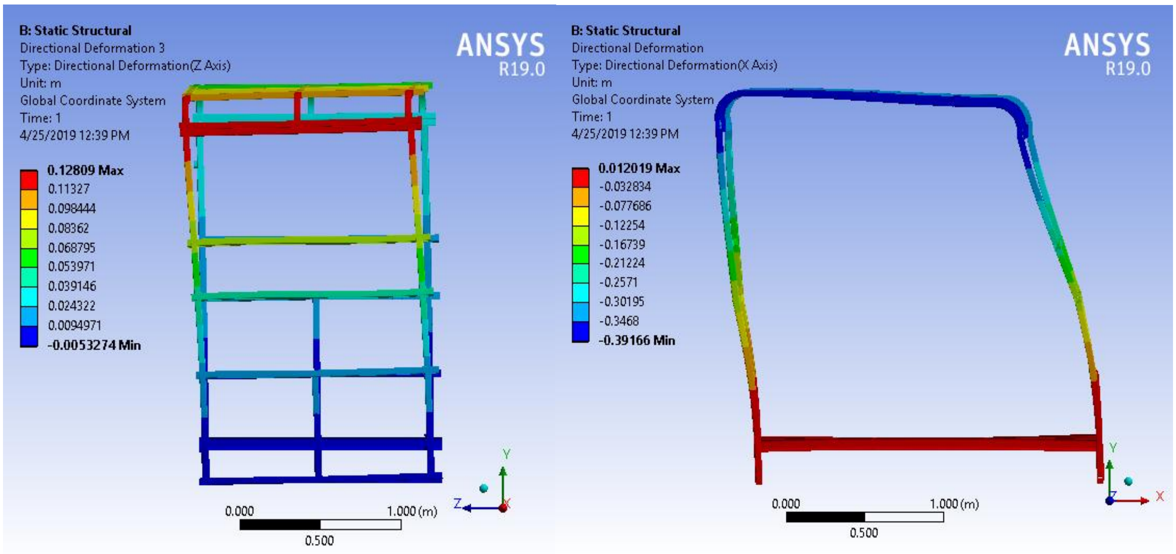


Figure (13): Case (b) Deformation in X, Z directions due to Lateral force (Fy) and longitudinal force (Fx).

Case (b), whiledue to the friction force in the opposite direction to the bus movement, the deformation is 391 mm in (X-direction) shown in **Figure (13).** The increase in the structure deformation indicated to more required energy absorption in the structure. The friction force in the longitudinal direction added to the rollover force increased the deformation in (Y-direction) to become 43 mm. The direction of the proposed friction force that applied on the structure in Z-direction and their effect is reflected in the large difference between distortion in this direction. While the deformation with the friction force is 128 mm in (Z-direction), Under the influence of this force appears and illustrates the exposure of the structure to torsion next to the bending which may cause breakage and increasing the dangerous. Simulation results shown in **Table (2).**

Table (2): Results of the Simulation in two different cases.

Parameters	Total Deformation	Deformation (X, Y, Z)	Residual Space	$\Delta\alpha_1, \Delta\alpha_2$	I_d	EA
Case (a) Simulation with Fy	361 mm	(360,30,4) mm	Safe	9, 20	0.700	8.18 kJ
Case (b) Simulation with Fy and Fx	411 mm	(391,43,128) mm	Safe	10, 23	0.799	8.34 kJ

3. Topology Optimization and Weight Reduction

Topology designs for structural shape and size. Topology optimization method consider as one of real tools for least weight and perform the objective design based upon the operation states. The load is applied laterally in the upper corner of the bus section. The structure is symmetric along the roll axis, but the longitudinal friction force gives different structure deformation and almost need for redistribute the structure shape, **Figure (14).**

Mass constraints: 40%
Number of design variables: 294914 cells
Design variables: Density of each design cell
Subjected to: Lateral and longitudinal forces in (X and Z) directions

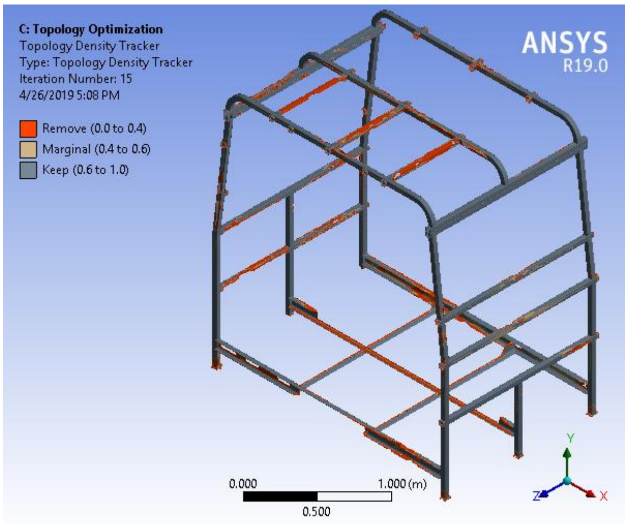


Figure (14): Organic shape of bus section.

VII. Conclusion

According to the simulation results, the bus body section succeeded in the recommended rollover test where the intrusion still outside the passenger's residual space. in case adding the longitudinal friction force at the bus upper corner during the rollover, this force effect on the outer surface of the body edge, the distortion appears more in the longitudinal direction, while the increases in total deformation up to 50 mm, also the deformation more than the previous by 31 mm in X- direction and the deformation in Z- direction increased 124 mm ,the difference between absorbed energy in the two cases during rollover test is very small as well as the deformation index. In this case, it is enough to use the static rollover test on the buses according to UN-ECE R66 to check the occupant residual space. The results of the experimental work completely different compared to the simulation results because the structure main pillars assembled as welded pieces. The optimization results indicate that the structure endure these forces in two directions and can even be minimize the weight or at least redistributed the structure geometrical shape.

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