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Rollover Analysis of Passenger Bus as per AIS-031

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Abstract:—Road transport is the most commonly used way of transportation in India and in many countries. The passenger bus plays an important role in public transport. The capacity of carrying more passengers compared to other road transport medium is unfavourable in the event of major bus accident. The rollover crash accident of passenger bus, although occurs less frequently than any other type of accident, the fatality rate and severe injuries are highest in rollover crash. Hence the structure of the bus needs to be strong enough to ensure the minimum damage and at the same time it should absorb maximum impact energy. Safety regulations are in force defining minimum structural rigidity under rollover crash. The Automotive Industry Standard (AIS-031) is implemented in India since October 2008 which specifies the requirements and methods to calculate the strength of superstructure of buses during and after rollover. The AIS-031 specifies four different test methods viz. physical rollover test on a complete vehicle, rollover test on a body section, pendulum test on a body section, and verification of strength of superstructure by calculation (numerical simulation). In this work numerical simulation of rollover test using finite element method is followed. First the numerical model is build according to the guidelines provided in AIS-031 and validated by the experimental testing. A validated numerical model is used to evaluate the rollover performance of the superstructure of the bus.

Keywords:— Bus rollover, Occupant safety, AIS-031, Numerical simulation, RADIOSS

I. INTRODUCTION

A large number of road accidents take place every year causing many fatalities and severe injuries to the vehicle occupants. If adequate attention is given to injury prevention, by making the vehicles inherently safer, this problem can be reduced. Among the various modes of vehicle crashes, rollover crashes are often very severe and threatening to vehicle occupants. Though rollover crash occurs less frequently, the higher risk of serious injuries and fatalities makes the study of rollover analysis and providing solution becomes imperative.

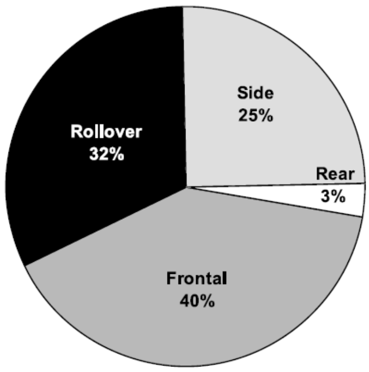


Fig.1 Distribution of fatal crashes by crash type [1]

The Fatality Analysis Reporting System (FARS) is a census of all vehicles crashes occurring in the USA. According to the statistics of FARS, shown in figure 1, 32% fatal crashes are rollover crashes. Due to this rollover analysis and its prevention has become the research topic in the recent years.

Rollover accidents are dependent on the vehicle's stability during turns. The stability is influenced by the height of centre of gravity and the track width. A high centre of gravity and narrow track can make a vehicle unstable while taking turns at high speeds resulting in rollover accident. A vehicle may rollover due to reasons such as excessive cornering speed, tripping, collision with another vehicle or object, sharp changes in direction at high speed etc [2].

Fig.2 Damaged bus structure after rollover accident

The damage to structure in the rollover accident is very severe and hence occupants are exposed to high risk of life. The bus structure may collapse due to severe impact load as shown in figure 2.

II. INTRODUCTION TO AIS-031

Automotive Industry Standard AIS-031 is in force in India which states the methods to calculate the strength of the superstructure of the passenger bus and thereby leading the safe manufacturing of buses. This standard applies to single-deck rigid or articulated vehicles designed and constructed for the carriage of more than 22 passengers, whether seated or standing, in addition to the driver and the crew.

The superstructure of the bus shall be so designed and constructed as to eliminate, to the greatest possible extent, the risk of injury to the occupants in the event of an accident. This standard specifies the requirement of strength of the bus superstructure for the protection of occupants of the bus.

A) General Specifications and Requirements

There are four different types of tests that can be performed to evaluate rollover performance. Each type of vehicle shall be verified according to one of the following methods-

1) A roll-over test on a complete vehicle
2) A roll-over test on a body section or sections representative of a complete vehicle
3) A pendulum test on a body section or sections
4) A verification of strength of superstructure by calculation

The superstructure of the vehicle shall be of sufficient strength to ensure that during and after it has been subjected to one of the methods of test or calculation prescribed above-

1) **No displaced part of the vehicle intrudes into the residual space, and**
2) **No part of the residual space projects outside the deformed structure.**

The rollover test on a complete vehicle is the most preferred way of testing because of better accuracy of results and good repeatability. There are minimum assumptions in this method. But it is the most expensive method as precise instrumentation is required during testing and manufacturer has to sacrifice the complete bus. Furthermore the method will not provide any solution if the structure does not meet the requirements of the regulation.

Nowadays CAE methodology is very well developed and is widely used for evaluation of impact scenarios in automotive industry. But to simulate the real-life event one has to understand and study the actual behaviour of the object under consideration. Following paragraph describes the actual rollover test procedure.

B) Physical Rollover Test

The bus is placed on a platform in order to be rolled over on weak side of the structure. It is ensured that the axis of rotation of the bus is parallel to the longitudinal axis of the bus. The typical rollover test setup is shown in figure 3.

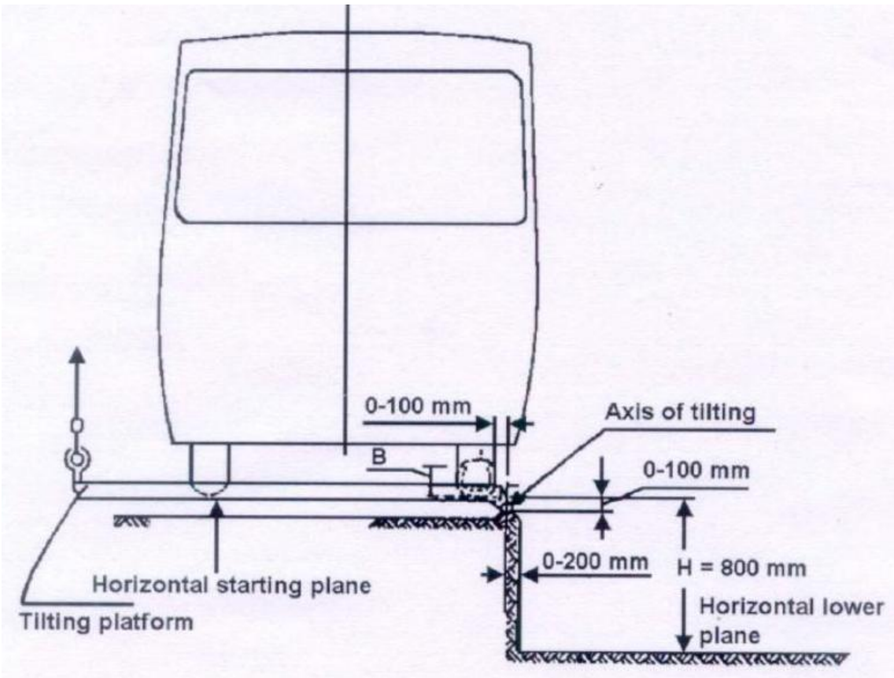
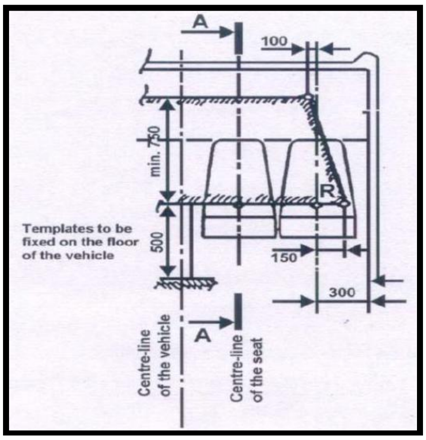


Fig.3 Physical rollover test setup [3]

Tilting platform is slowly lifted so as to tilt the bus without rocking and without any dynamic effects. The angular velocity is limited up to 5 degrees per second (0.087 rad/sec). As the tilting is increased the bus falls over in the ditch on its own due to gravitational acceleration. High-speed photography, deformable templates or other suitable means are used to determine the structural deformations.

C) Residual Space

The residual space is the volume within the passenger compartment which the bus structure must retain during and after rollover to protect the occupants. As mentioned earlier no displaced part of the structure shall intrude into the residual space. The major dimensions of the survival space are drawn from the following figures. All the dimensions in following figure are in mm.



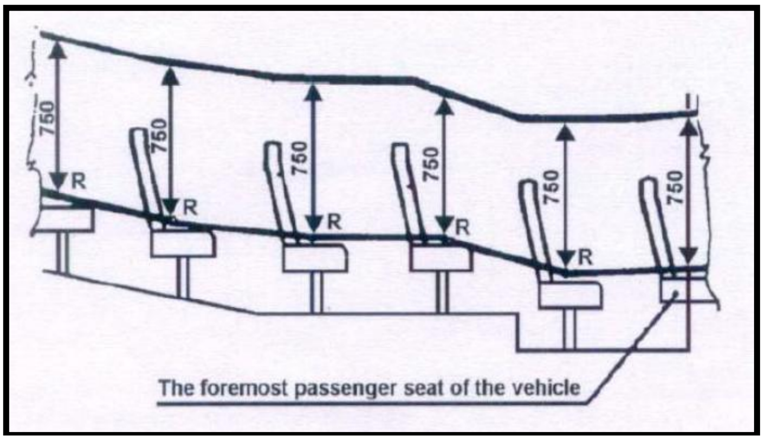


Fig.4 Lateral section of the bus [3] **Fig.5** Longitudinal section of the bus [3]

Figure 4 shows the sectional front view of the bus. The half trapezium portion in the figure indicates the passenger survival space. Figure 5 shows the sectional side view of the bus. The broad parallel lines in figure 5, which are 750mm apart, indicate the passenger survival space in longitudinal section which covers the entire bus length.

III. FINITE ELEMENT MODEL BUILDING

The main target of finite element model of the bus is to capture the deformation and interaction of bus subsystems during rollover impact. The accuracy of results depends upon the accuracy of CAD geometry and quality of meshing. As the rollover impact takes place on the sides of the bus, the main load bearing members are the superstructure members of the bus. The parts of the bus model lying below the position of centre of gravity contribute very little in absorbing kinetic energy [4]. The major part of kinetic energy is absorbed by the superstructure members in the form of deformations. Therefore dense mesh is used for the superstructure compared to the other parts. The complete bus structure along with chassis was modelled using shell elements. To ensure computational convergence and to keep computational time reasonably low, minimum element length used is 8 mm. The mesh quality criteria followed for shell meshing is given in Table I.

Table I: Quality Criteria Table

Sr. No.	Quality Checking Parameter	Allowable Value
1	Minimum length of element	>8mm
2	Aspect Ratio	> 5
3	Warping Angle	< 10 degrees
4	Skew Angle	< 45 degrees
5	Jacobian	> 0.6
6	Minimum included angle- Tria	> 20 degrees
7	Maximum included angle- Tria	< 120 degrees
8	Minimum included angle- Quad	> 45 degrees
9	Maximum included angle- Quad	< 135 degrees
10	Percentage of Tria	< 5%

Altair Hypermesh software is used for meshing purpose. The CAD model of the bus was imported into Hypermesh. The mid-surfaces were extracted from the CAD model. The features like fillet, small holes having dimensions less than 8 mm were deleted because of less structural significance.

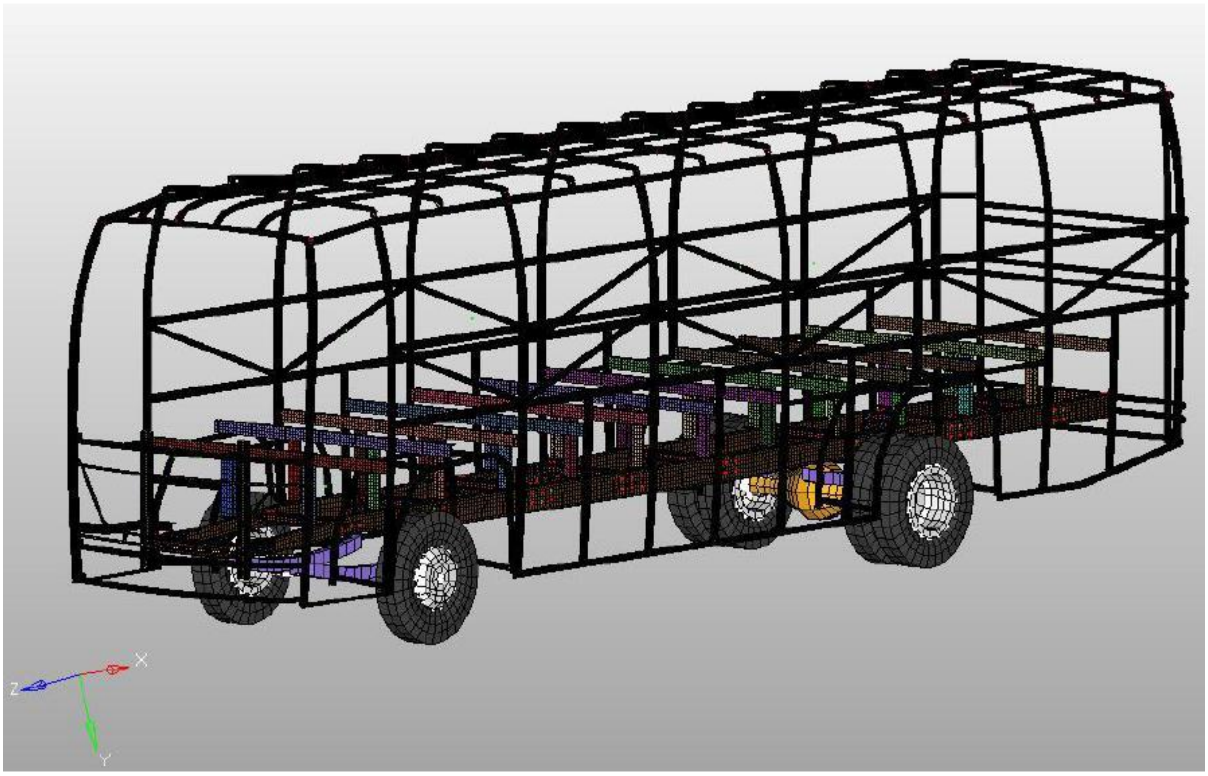


Fig.6 Finite Element (mesh) Model

Finite element model, shown in figure 6, can be distinguished between the bus superstructure and the chassis. The superstructure is the main load bearing member and has the dense meshing compared to the chassis and its components. Chassis consists of axles, tires, suspension system etc. mounted on it. It is required to capture the mass of various components on chassis accurately to maintain the centre of gravity of total bus close to the actual value. The chassis being the heaviest part, it controls the dynamics of total bus during rollover [5].

The exact distribution of mass is also important. Mass of various subsystems like engine, radiator, transmission, fuel tank and seats are applied as concentrated mass at respective locations. Axles are represented by '*shell*' elements and their mass is adjusted to account for the mass of entire axle assembly, differential and wheels. The exterior panels and leads were neglected for their small capacity of impact energy absorption. The finite element solver used for the simulation is RADIOSS, a non-linear solver developed by Altair Engineering. The FE model of bus has been made up of combination of shell, beam and rigid elements. All the structural members are modelled using shell elements. Bolt joints are simulated using 1-D beam elements, and 1-D rigid elements are used for weld simulation. The ground was represented by RIGIDWALL option.

A) Modelling of Residual Space

Residual space is defined as per the guidelines provided in AIS-031. It was introduced 500 mm above the floor under the passengers' feet, and 300 mm away from the inside surface of the side of the bus, throughout the entire bus. The model of the survival space consists of '*beam'* element frames rigidly mounted in the hard region under the floor. The connection of the residual space to the chassis channel is provided by *'rigidlink'* element of RADIOSS. The finite element model of the full bus comprised 5,83,048 first order explicit shell elements, 552 beam elements, 8,595 1-D rigid elements and 13 mass elements. Shell element length was assigned as 8 mm in both critical regions and up to 40 mm was used for those under the floor (lower structure-chassis).

The number of elements per profile width was at least 3 for the upper part of the structure and the number of elements per profile width was 4 for sidewall pillars (main pillars) which are significant for rollover impact deformation [6].

B) Material Data

Non-linear material properties are assigned to the superstructure. The tension test was performed on sample components to obtain the engineering stress-strain curve. The true stress and true strain were used as the input to the material card in software. The material card used in RADIOSS is *"M36_PLAS_TAB"* Elastic Plastic Piecewise Linear Material. This law models the isotropic elastic plastic material using user defined functions for the plastic stress-strain curve. This is an elastic model made of plastic which applies the Young's Modulus if the stress is lower than the yield stress, and measured stress-strain-curves if the stress is greater than the yield stress [7].

C) Material Coupon Testing

RADIOSS, a nonlinear finite element solver, is used for the rollover crash simulation. To represent the vehicle dynamic behaviour more realistically, exact material properties were first determined from laboratory tests. Two material types which represent most of the bus body were selected for laboratory structure-property quantification. Structural material used for the passenger compartment includes box tubing sections of 60mm x 40mm x 3mm thick and 40mm x 40mm x 2mm thick. The standard test specimens were cut from the hollow sections by using milling machine.

Fig.7 Test specimen cut from the hollow tube

Figure 7 shows the hollow section tube used in the construction of bus structure as well as the sample specimen. The encircled piece is the specimen prepared as per standard ASTM tensile test. The engineering stress- strain curves and mechanical properties like ultimate tensile strength, breaking strength, elongation at UTS and breaking elongation etc. were obtained from the tension test.

IV. EXPERIMENTAL VALIDATION

Before the start of the analysis of complete bus model material model validation is required. It was decided to compare the force versus displacement graph of experimental and finite element specimen to validate the material model. A sample specimen was prepared for the three point bend test and loaded on Universal Testing Machine as shown in figure 8. The specimen was loaded with the support span of 550mm. The mid-span deflection was recorded as a function of load applied at the mid-point of span. The maximum displacement of 9.2 mm was recorded.

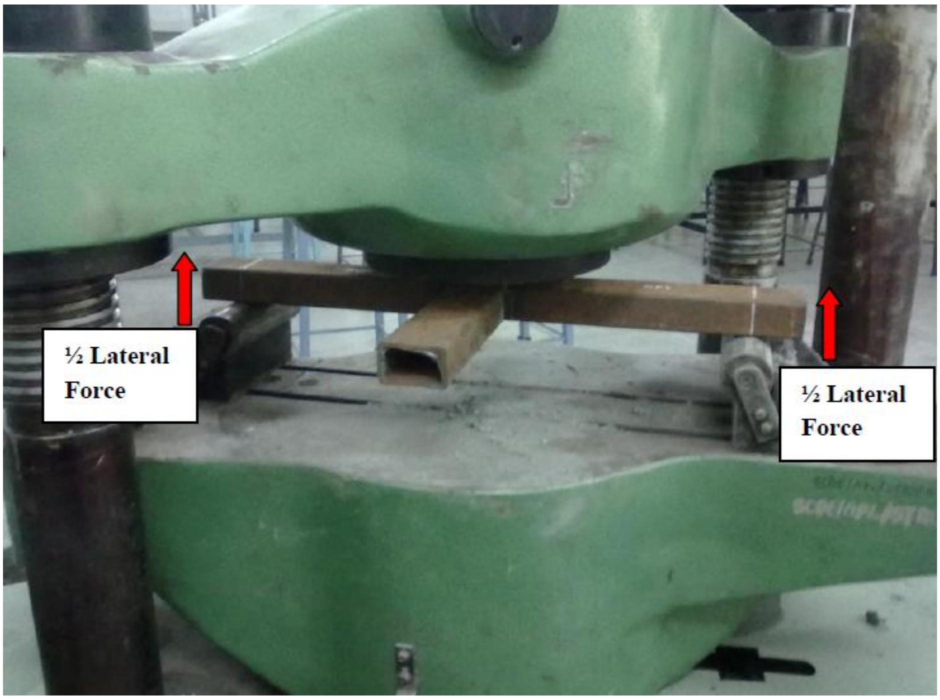


Fig.8 Bend test experimental setup

To simulate the three point bend test the finite element model was prepared as shown in figure 9 with the exact dimensions as that of the test specimen. The material properties obtained from the tension tests were applied to the finite element model. The true stress- strain curves obtained in coupon test were used as input to the elastic-plastic material card in RADIOSS. The displacement contour after the simulation is shown in the figure 9. The position of the specimen before and after the deformation is also presented.

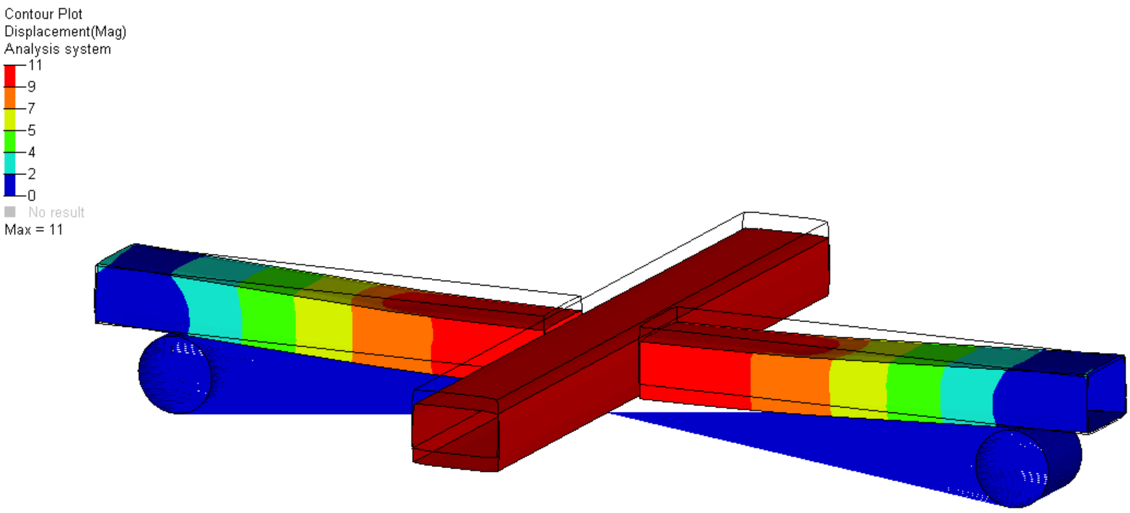


Fig.9 Displacement plot during bend test simulation

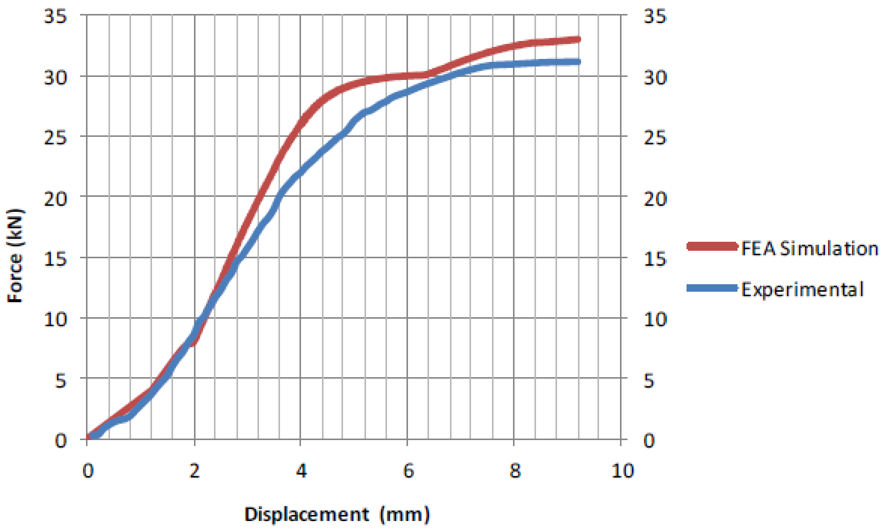


Fig.10 Force versus displacement during bend test

Figure 10 shows the comparison of the force versus displacement plot of the experimental and FEA bend test. The FEA curve shows the same behaviour as the experimental curve. The experimental test shows the 9.2 mm displacement at mid-span when the force is 31.20kN while the FEA result shows the same displacement at a force of 33.05kN. The displacement is in close agreement with the experimental values and hence it is concluded that the material model is validated.

V. SIMULATION OF BUS ROLLOVER

The bus model is first rotated along the longitudinal axis about rotation axis of tilt table until the center of gravity point reaches the highest position along vertical axis as shown in figure 11. The angle of rotation and the height of center of gravity point are recorded. The model is further rotated till it touches the ground. At this position also the angle of rotation and the height of centre of gravity point are recorded. The rollover simulation begins at the moment of impact.

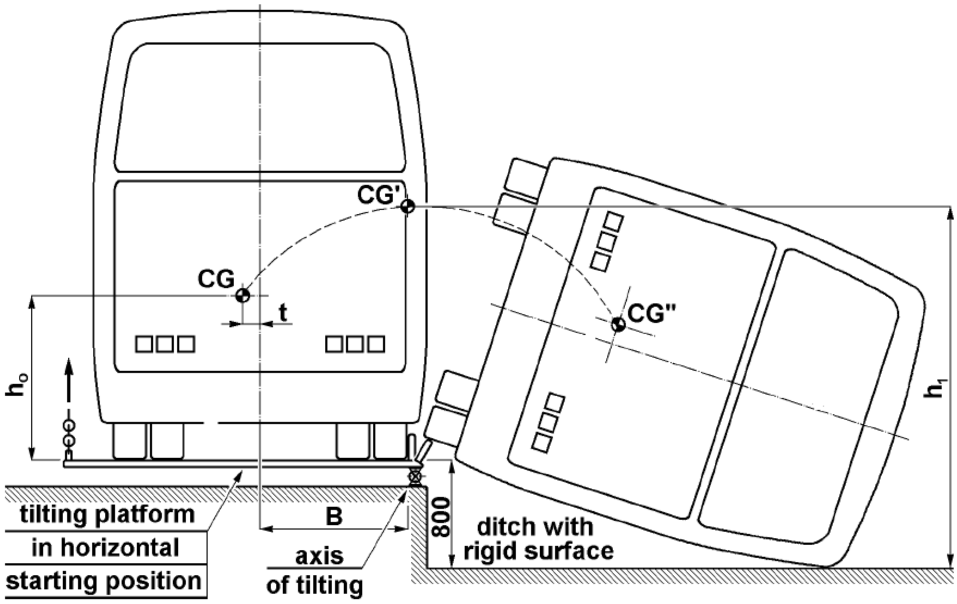


Fig.11 The path of the centre of gravity through the starting, unstable equilibrium position [8]

At the start of the simulation an initial angular velocity has been applied to all nodes, equal to the angular velocity that the bus would have if the rollover started with zero velocity, and with the centre of gravity of the bus located over an imaginary vertical line passing through the axis of rotation. The initial angular velocity of the bus at this instance is calculated by applying law of conservation of energy. To simulate the free-fall of the bus, gravity load is applied to all the nodes. There are no external constraints to the model.

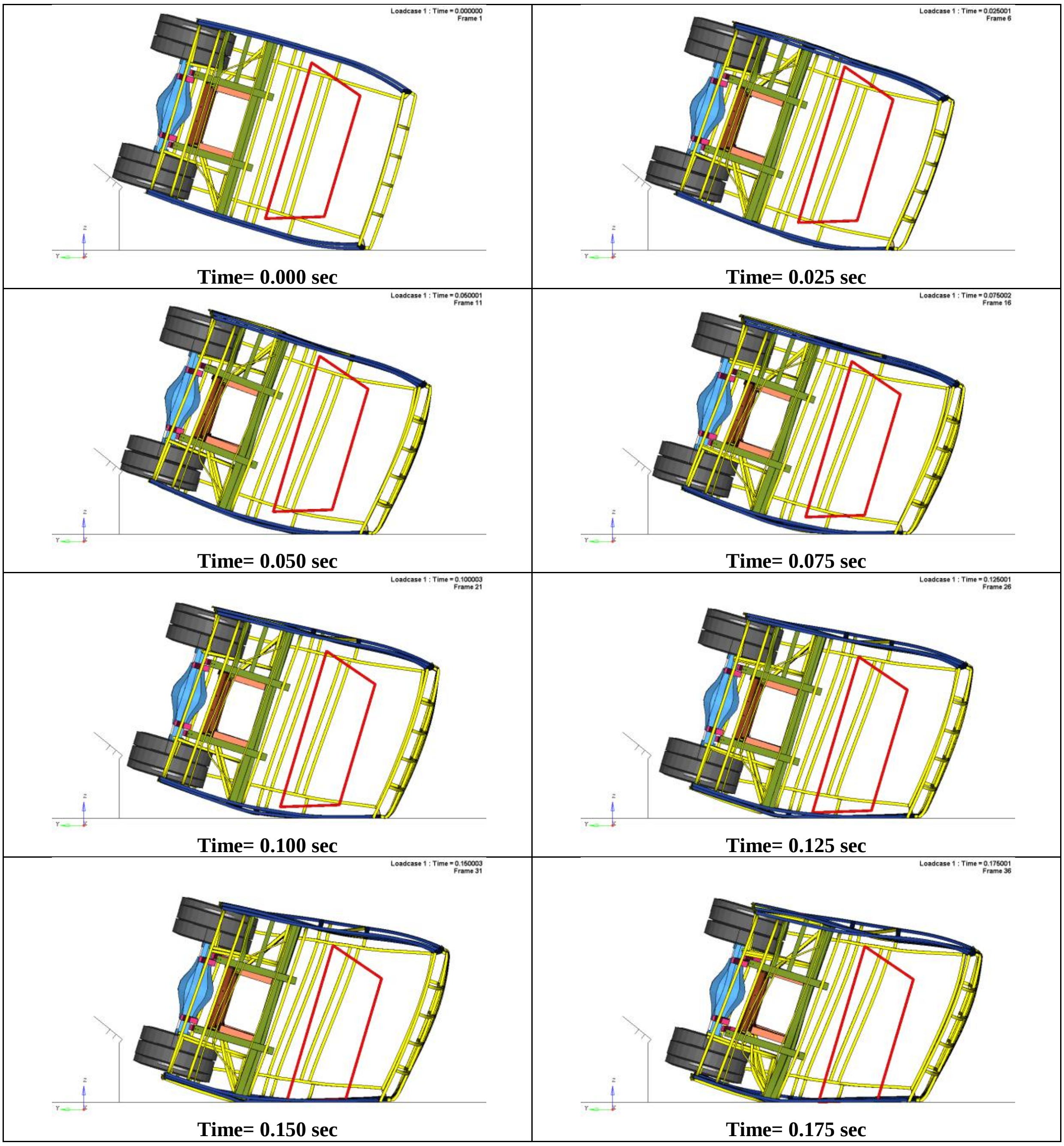


Fig.12 Deformation of bus model

In figure 12, a general overview of the simulation results for the selected time steps is illustrated. The bus first comes into contact with the ground when the roof corner hits the ground. It starts absorbing kinetic energy by elasto-plastic deformation. As the deformation progresses the main pillars start bending and thereby absorbing the major part of kinetic energy. The deformation stops when the waist-rail touches the ground. The bus starts sliding now as the heavier part of undercarriage falls from the tilt platform. The deformation stops when the kinetic energy in the model is completely absorbed in deformation and gets converted into internal energy. The residual space is represented by red trapezoidal section. It can be clearly seen at time step of 0.0175 seconds that the model cannot withstand the rollover impact load and the structure intrudes into the residual space. The enlarged view of the deformed position of bus and the residual space is illustrated in detail in figure 13.

Figure 13 shows the passenger survival space by red colour and all other components in green colour to differentiate survival space clearly. The structure of the bus deforms severely and the intrusion of 25 mm is observed on top side and the intrusion of the 40 mm is observed on the bottom side of the survival space.

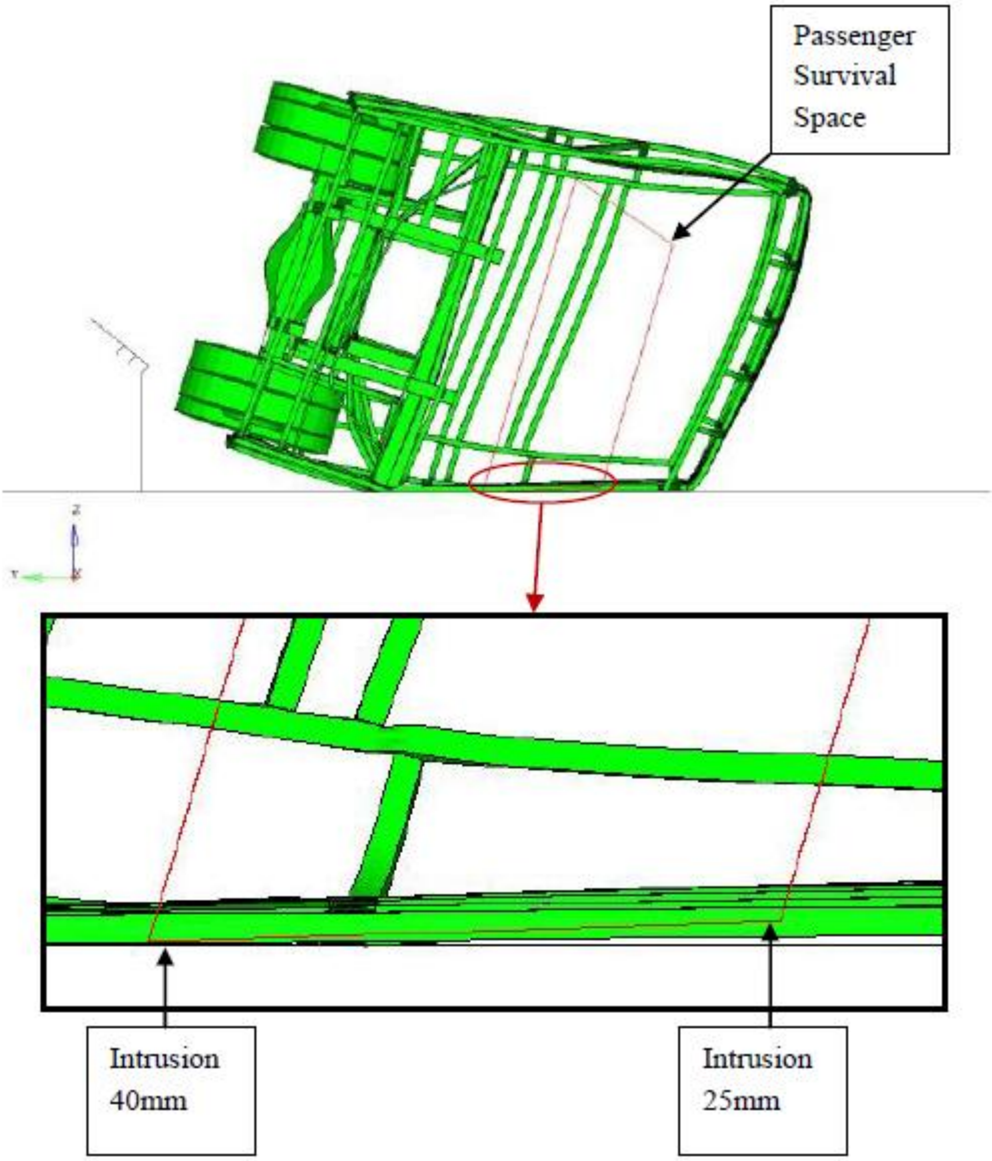


Fig.13 Intrusion of bus structure into survival space

As per AIS-031 the superstructure of the vehicle shall be of sufficient strength to ensure that during and after it has been subjected to rollover test-

1) **No displaced part of the vehicle intrudes into the residual space, and**
2) **No part of the residual space projects outside the deformed structure.**

It is concluded that the bus model under consideration does not meet the structural requirements of AIS-031 and will fail in the rollover test.

VI. RESULT AND DISCUSSION

After the rollover analysis is performed the energy curves are plotted as shown in figure 14. The energy balance is a method to evaluate the correctness of the numerical analysis. The kinetic energy drops continuously right from the start of the run (time 0 seconds to 0.05 seconds). At the time instance of 0.05 seconds the window rail touches the ground. The undercarriage of the bus now starts sliding down the tilting platform. As the mass of the undercarriage is very high, the magnitude of kinetic energy increases slightly from time of 0.05 seconds till 0.075 seconds. From the time instance of 0.075 seconds onwards the kinetic energy starts decreasing again. The bus starts sliding in the lateral direction. The curve slopes down sharply which shows that the energy is absorbed due to sliding friction (time 0.125 seconds to 0.175 seconds). The curve becomes nearly flat after time interval of 0.200 seconds. Ideally the kinetic energy must reach to zero, but for this the total simulation time has to be increased. From the figure 14 it is clear that the model still has the kinetic energy in it which is the residual energy in the model due to sliding.

One of the indications for correct analysis is that the total energy remains constant. It can be observed that the kinetic energy drops and transforms into internal energy (strain energy + sliding energy) over the time. The hourglass energy is negligible.

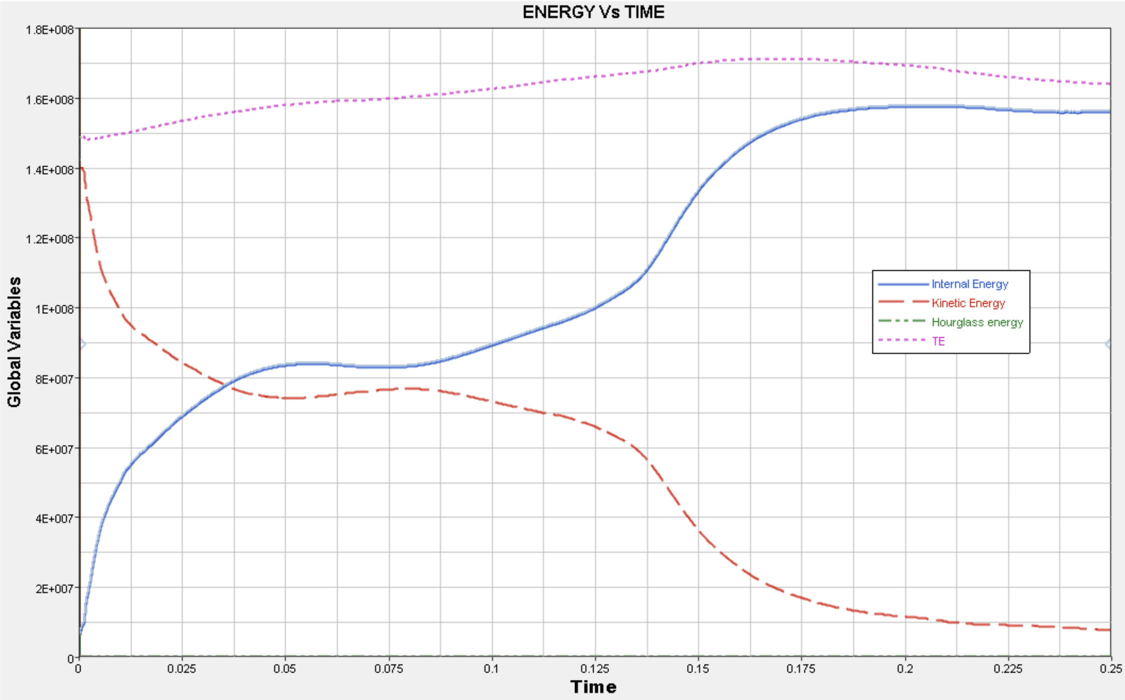


Fig.14 Energy balance during rollover analysis

A) Verification of Calculation

AIS-031 defines the tilting platform test in which the bus is tilted without rocking and without any dynamic effects until it rolls over. It is in unstable equilibrium position when the centre of gravity is at the highest position. Rollover simulations have been carried out by positioning the bus models at a moment just before impact. At the start of the simulation an initial angular velocity has been applied to the bus model, equal to the angular velocity that the vehicle would have gained, if the rollover started with zero velocity from unstable equilibrium position. As per AIS-031 initial zero velocity is considered at the start of the rollover test. Angular velocity can be calculated by applying law of conservation of energy.

Potential Energy at unstable equilibrium position = Kinetic energy at the impact

$$M\ g\ \Delta h = \frac{1}{2}\ I\ \omega^2 \qquad (1)$$

Where,
M = Kerb Mass of the bus, kg
g = Gravitational constant, mm/sec^2
Δh = Drop of centre of gravity from highest position till impact position,
I = Mass moment of inertia of bus, kg-mm^4
ω = Angular velocity, rad/sec

Kinetic Energy at the moment of impact can be observed from the energy balance curve to verify the correct angular velocity has been applied to the model. Referring to figure 14 Kinetic Energy at the moment of impact is 1.38x 10^8 N-mm.

Potential energy = 9200x 9810x 1505
= 1.36x 10^8 N-mm

As the value of energies by mathematical calculation and from analysis results are in close agreement, the mathematical model is verified.

VII. CONCLUSION

In this work a methodology to analyse the bus structure during rollover using finite element method is presented. The used computational model provided comparable results to experimental measurements and can be used for other type of bus to avoid expensive full-scale crash tests. Following points can be concluded from this work-

1) The numerical simulation of the bus model showed that it does not fulfil the requirements of minimum structural resistance described in AIS-031. There are intrusions of structure into residual space throughout the length of the bus.
2) The methodology used in this work can be applied for the verification of bus structures in a rollover cases in future.
3) This methodology can also be used to evaluate the effect of any structural modifications on the rollover performance before finalizing the design.
4) The finite element simulations can be used to avoid or reduce the physical testing of mechanical systems and components. Overall effect of this is cost saving and same is done with rollover analysis.

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