

**ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES**

MSc THESIS

Murat YILMAZ

**DIFFERENT TYPE OF MATERIALS AND FOAM APPLICATION
ON VEHICLE ROLLOVER ANALYSIS OF BUSES**

DEPARTMENT OF MECHANICAL ENGINEERING

ADANA, 2011

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ABSTRACT

MSc THESIS

DIFFERENT TYPE OF MATERIALS AND FOAM APPLICATION ON VEHICLE ROLLOVER ANALYSIS OF BUSES

Murat YILMAZ

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INSTITUTE OF NATURAL AND APPLIED SCIENCES
DEPARTMENT OF MECHANICAL ENGINEERING**

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A roll-over event is one of the most crucial hazards for the safety of passengers and the crew riding in a vehicle. In the past years it was observed after the accidents that the deforming body structure seriously threatens the lives of the passengers and the rollover strength has become an important issue for vehicle manufacturers. Today the European regulation “ECE R66” is in force to prevent catastrophic consequences of such roll-over accidents thereby ensuring the safety of vehicle passengers. In this study effects of using different type of materials and foam application on vehicle rollover analysis were investigated. As a result of this study it is seen that using materials which has better mechanical properties and application of foam to the steel sections increases the vehicle safety during rollover crashes.

Key Words: Roll-over, ECE-R66, Residual Space, LS-DYNA, Vehicle Safety.

ÖZ

YÜKSEK LİSANS TEZİ

**OTOBÜS DEVRİLME ANALİZİLERİNDE DEĞİŞİK ÖZELLİKTEKİ
MALZEME VE KÖPÜK UYGULAMASI**

Murat YILMAZ

**ÇUKUROVA ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ
MAKİNE MÜHENDİSLİĞİ ANABİLİM DALI**

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Devrilme kazası, araç içerisindeki yolcular ve mürettebatın güvenliğini tehdit eden en ciddi tehlikelerden bir tanesidir. Geçmiş yıllarda yapılan gözlemler, kaza sonrasında deforme olan araç gövdesinin yolcuların hayatını ciddi biçimde tehdit ettiğini göstermiş, böylece devrilme mukavemeti araç üreticileri için üzerinde dikkatle durulması gereken bir husus haline gelmiştir. Günümüzde bir Avrupa yönetmeliği olan “ECE-R66” sayesinde bu tür devrilme kazalarının yol açabileceği felakete varan sonuçlar engellenebilmekte ve araç yolcularının güvenliği temin edilmektedir. Bu çalışmada değişik özelliklerde malzeme kullanımı ve köpük uygulamasının devrilme analizi üzerindeki etkileri incelenmiştir. Yapılan çalışma sonucunda daha iyi mekanik özelliklere sahip malzeme kullanımının ve çelik kesitlerine köpük uygulanmasının aracı devrilme esnasında daha güvenli bir hale getirdiği görülmüştür.

Anahtar Kelimeler: Devrilme, ECE-R66, Yaşam Alanı, LS-DYNA, Araç Güvenliği

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LIST OF ABBREVIATIONS AND NOMENCLATURE

NHTSA	: National Highway Traffic Safety Administration's
UNECE	: United Nations Economic Commission For Europe
ECE R66	: Economic Commission for Europe Regulation No. 66
SRSM	: SuccessiveResponse Surface Method
UCC	: Unified Chassis Control
FMVSS	: Federal Motor Vehicle Safety Standards
FEM	: Finite Element Method
COG	: Center of Gravity
EKF	: Extended Kalman Filter
LQR	: Linear-Quadratic Regulator
MVC	: Motor Vehicle Crash
CAD	: Computer Aided Design
DMU	: Digital Mock-Up
CAE	: Computer Aided Engineering

1. INTRODUCTION

The risk of fatal injuries is more in rollover than any other type of accident. Bus and coach manufacturers are focusing more on passenger safety in case of catastrophic rollover accidents. Thus rollover strength has become important issue for all bus manufacturers (Deshmukh, 2006).

There are many tragic bus accidents. Although bus rollovers are not as common as other kinds of accidents, they are very serious. According to the worldwide rollover accident statistics from 1973 to present, there have been more than 570 bus rollover accidents (UNECE, 2007). For this reason, the Economic Commission for Europe enforced Regulation No. 66 for the Bus Strength of Superstructure in 1987 (ECE R66) in order to provide protection to bus and coach occupants during rollover accidents through the provision of a survival space (JASIC, 2006). Nowadays, ECE R66 is almost a gold standard for all motor coaches. It allows bus manufacturers to assess crashworthiness in rollover events in real tests or by computer simulation (JASIC, 2006). Thus, the design requirement must strictly satisfy ECE R66 while the vehicle's structural design has to carry the required load with minimum component weight without fail. The process of producing the best bus superstructure has been called structural optimisation. With the advances both in computer technology and structural analysis via the finite element method, this paper, based on ECE R66 procedure, presents an optimal study of bus rollover strength using successive response surface method (SRSM) performed by LS-OPT with respect to the ability of energy absorption.

Rollovers are complex crash incidents that are violent in nature and usually reflect the interaction of the driver, vehicle, and environmental factors. While all vehicles can roll over, taller, narrower vehicles that have a higher center of gravity tend to be less resistant to rollover compared to shorter, wider vehicles. Fatal rollover crashes are often speed related. According to NHTSA crash data, about 40% of fatal rollover crashes involve excessive speeding, and nearly three quarters of all fatal rollovers took place where the posted speed limit was 55 mi/h or higher. NHTSA data also show that nearly 85% of all rollover-related fatalities are the result of

single-vehicle crashes, which suggests that the behavior and skill of the driver play a significant role in rollover crashes.

There are two types of vehicle rollover. Tripped rollovers are due to side impact with hard curbs, soft soil, potholes, guard rails, and tire debanding, which cause the wheel rim to dig into the pavement. In contrast, untripped rollovers occur due to friction between the tire and road interface. The majority of rollover events are caused by the driver's attempt to recover the road pavement, while a small portion, less than 5%, are due to friction-induced rollover. Friction-induced rollover is typically caused by sufficiently large tire lateral forces during highly dynamic maneuvers on high coefficient-of-friction road surfaces. Examples of highly dynamic maneuvers are double lane changes, fishhook, or other aggressive obstacle-avoidance maneuvers. These maneuvers are characterized by the driver's steering wheel inputs, which exhibit a high rate of change, high magnitude, out-of-phase overcompensating adjustments, or a combination of these behaviors. Vehicle speed close to or above the vehicle's critical speed combined with a destabilizing large or rapid steering input can cause friction-induced rollover. While friction-induced rollovers occur less often, they can be mitigated by utilizing steering and braking actuators currently available on the market. Untripped rollovers cannot be prevented since the dynamic mechanism is outside the control authority of the commonly used chassis actuators. During these events, control algorithms are used to deploy side curtain and roof air bags to protect the occupants. In this article, we design a rollover-avoidance control to address friction-induced-rollover events by utilizing steering and braking actuators (Shih-Ken Chen et al., 2010).

The ECE R66 regulation was issued on 30 January 1987 and enforced by the Economic Commission of Europe, in response to the serious problem of rollover accidents. It applies to all single-decked vehicles constructed for carrying more than 22 passengers, whether seated or standing, in addition to the driver and the crew. 'Superstructure' refers to the parts of a vehicle structure that contribute to the strength of the vehicle in the event of rollover accidents.

- Residual Space: The purpose of the ECE R66 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 remains undamaged. 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 creation of a vertical transverse plane within the vehicle, which has the periphery described in Figure 1.1. The SR point is located on the seatback, 500 mm above the floor under the seat, 150 mm and 250 mm from the inside surface of the side wall (JASIC, 2006).

- Rollover Test: This regulation is continuously updated on the basis of actual requirements and it is used as an international bus rollover regulation. The current version was issued on 22 February 2006. The rollover test is a lateral tilting test, as shown in Figure 1.2. The complete vehicle stands on a tilting platform with blocked suspension and is tilted slowly to an unstable equilibrium position. If the vehicle type is not fitted with occupant restraints, it will be tested at an unladen curb mass. If the vehicle is fitted with occupant restraints, it will be tested at the 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 tips over into a ditch which has a horizontal, dry and smooth concrete ground surface with a nominal depth of 800 mm (Jassic, 2006). The rollover test is 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 proposals and in consideration of the following:
 - The lateral eccentricity of the centre 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)

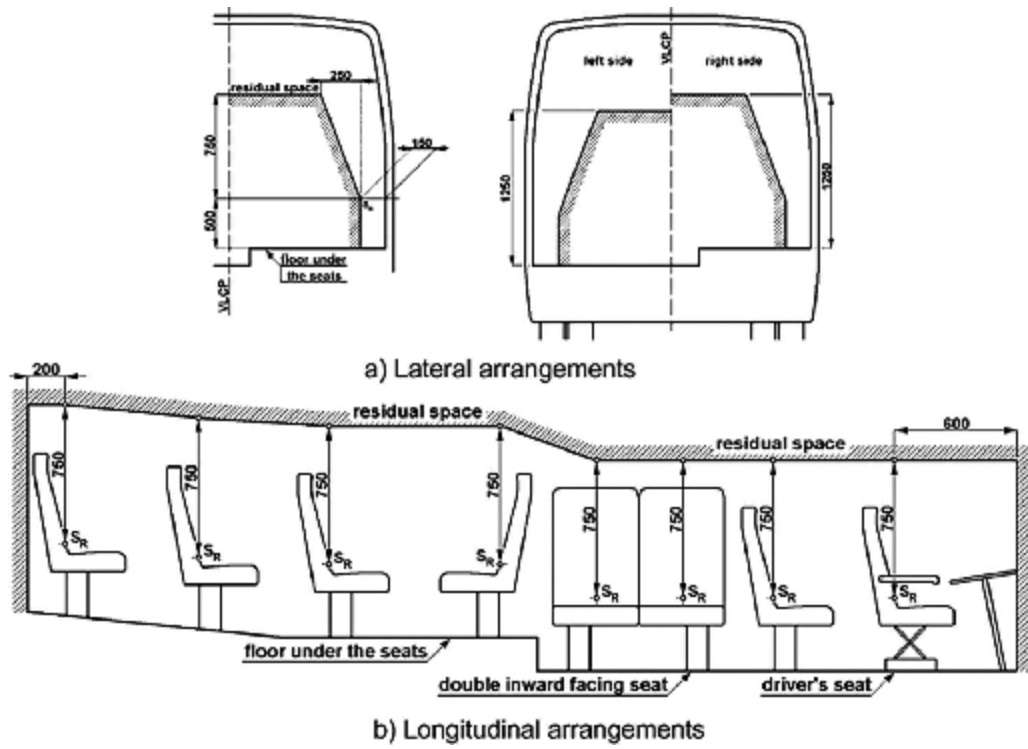


Figure 1.1. The residual space, measured in millimeters (mm) (UNECE,2006).

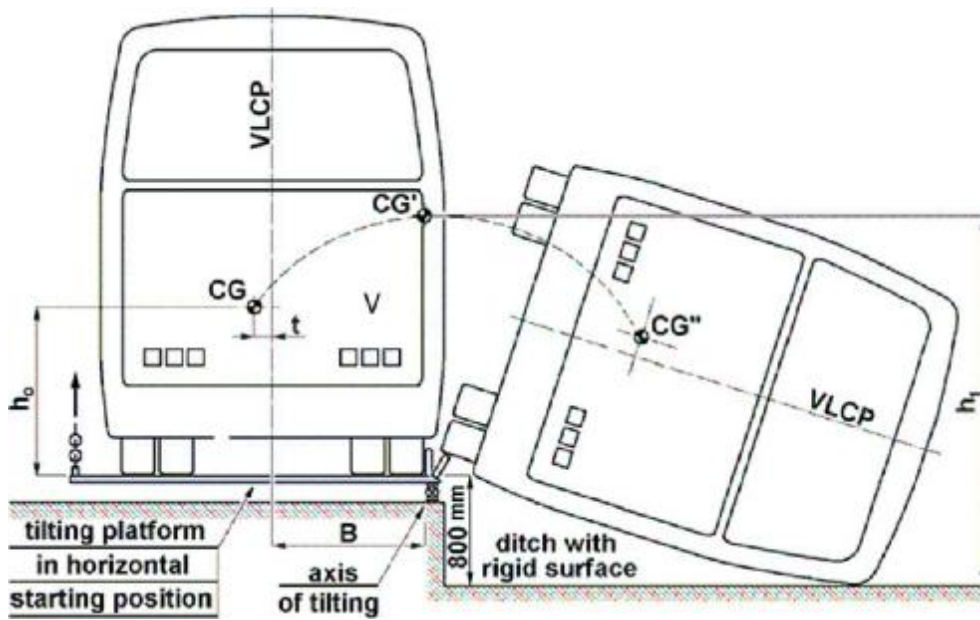


Figure 1.2. The rollover test process(UNECE,2006).

- Test methods; The latest version of ECE R66, version 2006, detailing the above requirements, describes a test to be chosen from these five different methods:
 1. Complete vehicle rollover test
 2. Body section rollover test
 3. Body section test with quasi-static load
 4. Component testing based on quasi-static calculation
 5. Complete vehicle rollover test based on computer simulation

Method (1) was accepted as the standard method. Others are equivalent methods. Amongst them, methods (3) and (4) are new methods in ECE R66, version 2006. Methods (1)–(3) are experimental methods based on the real test. Method (5) is officially accepted with full-scale computer simulation (Jassic, 2006).

2. PRELIMINARY WORK

Peters SC et. al. (2010), studied that stabilizing a vehicle near rollover. An analogy between the dynamics of a cart-pole system and vehicle rollover dynamics is used to derive a controller for tipping up and stabilizing a planar model of a passenger vehicle near rollover by controlling lateral tire friction forces. The controller is based on a previously published controller for stabilizing a cart-pole using partial feedback linearization and energy shaping. A necessary condition for tip-up is given based on the surface friction coefficient and the location of the vehicle center of gravity (c.g.). A multi-body vehicle model with suspension is presented in the form of the robotic manipulator equations. Simulation results are presented demonstrating the effect of friction and suspension properties on the tip-up problem.

Yoon J et. al. (2010), studied that, design of an unified chassis controller for rollover prevention, maneuverability and lateral stability. This paper describes a unified chassis control (UCC) strategy to prevent vehicle rollover and improve both maneuverability and lateral stability. Since previous researches on rollover prevention are only focused on the reduction of lateral acceleration, the maneuverability and lateral stability cannot be guaranteed. For this reason, it is necessary to design a UCC controller to prevent rollover and improve lateral stability by integrating electronic stability control, active front steering and continuous damping control. This integration is performed through switching among several control modes and a simulation is performed to validate the proposed method. Simulation results indicate that a significant improvement in rollover prevention, maneuverability and lateral stability can be expected from the proposed UCC system.

Zhu TJ et. al. (2010), informed that parameter identification of heavy commercial vehicle rollover prediction model. Investigation presents the parameter identification technology of heavy commercial vehicle rollover prediction. In this study, a nonlinear truck model has been established for the rollover threat prediction. In order to achieve valid and representative truck model as close to the target real truck as possible, a set of key parameters are identified from experiment data collected from real truck ground test. At the last, the vehicle prediction model

simulation results compared with the experimental results, it is shown that the prediction model can be accurately predicted the rollover dangerous state.

Moshchuk and Chen (2010) informed that, vehicle rollover detection index. Vehicle rollover resistance can be enhanced using differential braking control, rear-wheel steering, front steering control, suspension damping control, or the combination of any of them. In each control action, the controller receives the vehicle dynamics information from various sensors, such as a yaw-velocity sensor, a lateral accelerometer, a roll-velocity sensor (if available), and suspension displacement sensors (if available), and determines a control action to be taken. A balance between controlling vehicle roll motion and vehicle yaw motion needs to be reached to achieve the optimal vehicle response. Therefore, detection of the current and impending vehicle situations, especially pertaining to the vehicle roll, is vital for the quality of control. Various methodologies have been developed in the past to detect vehicle situations that may lead to rollover. Generally, rollover detection is based on roll velocity sensor and roll angle estimation. In most of these methods, thresholds for roll velocity and roll angle are established to detect imminent rollover. Even though roll velocity and roll angle are the two most important elements in vehicle roll motion, they may not be sufficient to timely detect impending rollover. This paper proposes a vehicle rollover detection index that can be used in a control algorithm to enhance vehicle rollover resistance. It uses roll angle and velocity (measured or estimated), yaw velocity, vehicle speed, and lateral acceleration. Further enhancement to the proposed algorithm is then briefly discussed that includes the effect of vehicle lateral load transfer on the detection.

Wang et al. (2010), stated that Real-time Roll State Estimation and Rollover Prediction for Light SUVs. This study presents a roll state estimator and a rollover prediction model based on a real-time roll estimator. The real-time roll estimator is designed to estimate the current roll angle and roll rate of the vehicle body from a 3DOF vehicle model. The veDVNA dynamic simulation software was used to verify the performance of roll motion prediction. The prediction model calculates the time it takes for the inside tire lift-off to determine the danger of rollover based on current roll angle and roll rate. Obstacle avoidance and ramp entering maneuvers are

designed to verify the prediction model. Simulation results with driver model in the loop show that the prediction model could represent the severity of the rollover threat accurately across all the driving scenarios.

Liang et al. (2010), studied that Analysis of bus rollover protection under legislated standards using LS-DYNA software simulation techniques. A bus rollover is one of the worst vehicle accidents that can occur. Because of the large numbers of passengers, the casualties in a bus rollover are often high and severe. The compliance with rollover safety standards for buses and coaches is mandated by law. This paper presents a comparative analysis of the physical meanings of 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). This comparison was carried out using a LS-DYNA finite-element analysis. After performing a comparative analysis following ECE R66 and FMVSS 220 assessments, the investigation further demonstrated the distortion configuration of the vehicle superstructure through the absorbed energy and its distribution over the vehicle and in sections of vehicle superstructure 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 ECE R66 and FMVSS 220 in distortion configuration, reflecting differences in capability and rollover testing conditions. These findings provide a means of evaluating bus superstructure strength and provide guidelines useful in the assessment of regulations applied to the evaluation of bus rollover strength.

Rabhi et al. (2009), informed that Robust Observer for Prevention of Vehicle Rollover. In this study an approach for detecting impending rollover is proposed. The method includes an algorithm based on Takagi-Sugeno (TS) fuzzy observer to prevent rollover of the vehicle when road adhesion conditions change. To design such observer, we take into account that roll rate can be measured easily by sensor, but roll angle is not measured. The proposed method allows estimating the roll angle and the roll rate from measurable signals such as lateral acceleration yaw rate and the vehicle parameters. Performance and robustness of the estimator are evaluated through numerical simulations, using various scenarios.

Bouton et al. (2009), studied that An active anti-rollover device based on Predictive Functional Control: Application to an All-Terrain Vehicle. : The active devices dedicated to on-road vehicle stability cannot be applied satisfactorily in an off-road context, since the variability and the non-linear features of grip conditions can no longer be neglected. Specific solutions have then to be investigated. In this paper, the prevention of light All-Terrain Vehicle (ATV) rollover is addressed. First, a back stepping observer is designed in order to estimate on-line a rollover indicator accounting for sliding phenomena, from a low-cost perception system. Next, the maximum vehicle velocity, compatible with a safe motion over some horizon of prediction, is computed via Predictive Functional Control (PFC), and can then be applied, if needed, to the vehicle actuator to prevent from rollover. The capabilities of the proposed device are demonstrated and discussed thanks to an advanced simulation testbed that has proved to supply results very close to experimental ones.

Imine et al. (2009), stated that Rollover risk prediction of an instrumented heavy vehicle using high order sliding mode observer. In this study, an original method about heavy vehicles rollover risk prediction is presented and validated experimentally. It is based on the calculation of the LTR (Load Transfer Ratio) which depends on the estimated vertical forces using high order sliding mode observers. The validation tests were carried out on an instrumented truck rolling on the road at various speeds and lane-change manoeuvres. Many scenarios have been experienced: driving on straight line, curve line and zigzag to emphasize the rollover phenomenon and its prediction to set off an alarm to the driver.

Zhu et al. (2009), studied that This study sets up a vehicle dynamic model which is used to determine rollover risk of heavy truck under various driving conditions. Using this real-time dynamic model, it proposes a new measure of performance for vehicle rollover prevention, the Load Transfer Ratio (LTR), and design the differential braking controller based on LMI robust control to prevent rollover occur. The paper also obtains the controller which can adopt the robustness to variations in vehicle speed. The simulation results show that the LMI controller is very effective in vehicle rollover prevention control.

Ko et al. (2009), informed that this study describes the results of the numerical evaluation on crashworthiness and rollover characteristics of a low floor bus vehicle made of sandwich composites. The sandwich composite used for the vehicle structures was composed of aluminum honeycomb core and WR580/NF4000 glass-fabric/epoxy laminate face sheets. Material tests were conducted to determine the input parameters of the composite laminate face sheet model and the effective equivalent damage model for the orthotropic honeycomb core material. Crashworthiness and rollover analysis of the low-floor bus was conducted using the explicit finite element method (FEM) analysis code LS-DYNA3D with the lapse of time. The crash condition of the low-floor bus was a frontal accident with a speed of 60 km/h. Rollover analysis was done according to the safety rules of the European standards (ECE-R66). The angular and translation velocity and its angle with the ground just before impact for rollover were calculated using the dynamic analysis program. The results showed that the survival spaces for the driver and passengers were secured against frontal crashworthiness and rollover of the low-floor bus. In addition, the modified Chang-Chang failure criterion is recommended to predict the failure modes of the composite structures for crashworthiness and rollover analysis.

Haan et al. (2009), studied that isolated rollover mechanism does not warrant trauma center evaluation. Significant resources are expended on the assessment of trauma patients who arrive at the trauma center based solely on mechanism of injury. We hypothesized that rollover motor vehicle crashes (ROMVC) are not an independent predictor for trauma center care. All patients seen between January 1, 2001, and December 31, 2005, involved in a ROMVC, were reviewed. Patients with any confounding factors were removed, leaving those transported to the trauma center based on mechanism only. Five hundred sixty-nine patients were transported to our center for the mechanism of ROMVC. Of the 569 patients, 369 (65%) were evaluated and discharged with minimal Injury Severity Score and regional Abbreviated Injury Scale scores. Of the remaining 200 (35%) patients admitted, 130 required surgery, predominantly for closed extremity and facial fractures. Six patients required immediate surgery for life-threatening injuries: 3 splenectomies, 1 subdural evacuation, and 2 vascular repairs (1.1%). Of the remaining 123 (4.2%)

patients requiring surgery, 24 required urgent surgery (2 craniotomies, 9 laparotomies, and 13 spinal fixations). None of the patients with spinal injury had neurologic deficit. Eight patients were admitted to the intensive care unit for neurologic monitoring (1.4%). Only 6.7 per cent benefited from initial Trauma Triage Criteria. Therefore, ROMVC is not an independent predictor of the need for trauma center evaluation or admission. The majority of these patients could be safely evaluated and treated at nontrauma centers or transferred later.

Brumbelow et al. (2009), studied that Roof Strength and Injury Risk in Rollover Crashes of Passenger Cars. Study by the Insurance Institute for Highway Safety found that midsize SUVs with stronger roofs, as measured in quasi-static tests, had lower risk of ejection and lower risk of injury for nonejected drivers. The objective of the present study was to determine whether a similar association exists for other vehicle groups. Methods: Twelve small passenger cars were evaluated according to Federal Motor Vehicle Safety Standard 216 test conditions. Crash databases in 14 states provided more than 20,000 single-vehicle rollover crashes involving these vehicles. Logistic regression analyses were used to evaluate the effect of roof strength on the rate of driver injury while assessing and controlling for the effects of driver age, vehicle stability, state, and other factors where necessary. Results: Small cars with stronger roofs had lower overall rates of serious injury, lower rates of ejection, and lower rates of injury for nonejected drivers. Although the effect on ejection was somewhat smaller for cars than for SUVs, the overall pattern of injury results was consistent. For roof strength-to-weight ratio measured within 5 in. (SWR5), a one-unit increase (e.g., from 2.0 to 3.0) was associated with a 22 percent reduction in risk of incapacitating or fatal driver injury in single-vehicle rollovers. This compares with a 24 percent reduction estimated for a similar change in roof strength among midsize SUVs. Conclusions: The association between vehicle roof strength and occupant injury risk in rollover crashes appears robust across different vehicle groups and across roof SWR5 values, varying from just more than 1.5 to just less than 4.0. If roofs were to increase in strength by one SWR5, a 20-25 percent reduction in risk of serious injury in rollovers would be expected. Still, even if all vehicle roofs were as strong as the strongest roof measured, many rollover

injuries still would occur, indicating the need for additional research and countermeasures.

Zhu et al. (2009), studied that Rollover Prevention for Heavy Trucks Using Robust Control. This study discusses a robust control algorithm to improve the roll stability of heavy trucks. The controller minimizes the lateral load transfer (LTR) to reduce the rollover probability using differential braking. The paper also designs the robust controller which can adopt the robustness to variations in vehicle speed. The simulation results show that the robust controller is very effective in vehicle rollover prevention control of heavy trucks.

Champion et al. (2009), informed that the importance of vehicle rollover as a field triage criterion. Vehicle rollovers represent a small but significant percentage of crashes; of the almost 12 million vehicle crashes reported by NHTSA in 2004, only 2.4% were rollovers, but these accounted for one-third of all crash-related occupant deaths and about 25,000 serious injuries every year. Rollovers are associated with the second highest number of vehicle occupant deaths by crash mode, three times the risk of injury when compared with other impact directions ($p < 0.0001$), specific types of injury such as head and spinal cord injuries, and a risk of death > 15 times the risk in non rollover crashes. The data and literature unequivocally show a strong and disproportionate association between vehicle rollover and injury severity and death. Because it is difficult to devise simple, accurate decision rules for point of wounding and vehicle crash scene triage, simple, powerful relationships should be used when possible. Thus, the exclusion of rollover as a triage criterion seems to be ill advised.

McKnight and Bahouth (2009) studied that Analysis of Large Truck Rollover Crashes. Close to a tenth of all large truck crashes result from rolling over during some maneuver. The aim of this study was to identify causes of these serious events as well as preventive measures that could be taken to reduce their number. Methods: Detailed descriptions of 231 rollovers provided by field investigators were analyzed to identify causes. The descriptions addressed crash location, the nature of the crash, effect upon the vehicles involved, injuries and treatment, and contributing conditions. Causes were inferred from the nature of the crash. Results: Almost half of the

rollover crashes resulted from failing to adjust speed to curves, loads, brake condition, road surfaces, and intersections. A second major contributor involved lack of attention, including general inattention, misdirected attention, falling asleep, and distraction. The third major factor involved control errors, including oversteering, understeering, overcorrecting for errors, and minor control errors. The remainder was not driving errors and included those of other drivers, those occurring before the truck took to the road, and the condition of the vehicle before it was driven. Conclusions: Although they account for but a tenth of all large truck crashes, rollovers result from causes that are relatively unique to the vehicle and where it is driven. Programs could improve safety through the use of video to expose truck drivers to the situations causing rollovers, along with simulation allowing drivers to experience the consequences of errors without the harmful results of actual rollovers.

Huang J.H. (2009) studied that vehicle state estimation for rollover avoidance. To enhance vehicle/road safety, rollover warning and control systems have received considerable research interest in recent years, especially for vehicles with high center of gravity (CG). Accurate and reliable estimates of the relevant vehicle states facilitate the design of such systems. This paper investigates the state estimation for rollover avoidance, in which the relevant states include vehicle roll velocity and roll angle, as well as sideslip velocity and yaw velocity. The main challenge of the design comes from the fact that, under near rollover situations, vehicle dynamics is complex and nonlinear. Not only vehicle suspension and tires are in their nonlinear region, but also vehicle yaw, sideslip and roll motions are highly coupled. In addition, the estimation needs to deal with sensor biases and sensor nonlinearity under this extreme condition. To address those issues, this paper proposes a vehicle state estimation design that consists of three parts: a sensor pre-filter, an Extended Kalman filter (EKF), and a sideslip velocity estimator. The sensor pre-processor removes sensor biases by utilizing the Recursive Least Square technique with a varying forgetting factor. The EKF is designed based on a linear yaw/sideslip/roll model, and its feedback gains are further scheduled based on vehicle lateral acceleration in order to reduce the effects of increased model inaccuracy as vehicle roll motion becomes more severe. The sideslip velocity

estimator adjusts the sideslip velocity estimated by the EKF to extend the estimation to the nonlinear region. Both simulation and vehicle fishhook testing have been used to verify the effectiveness of the design.

Yedavalli and Huang (2009) studied that controller design for multi-body ground vehicle rollover prevention using modified lqr framework. This study addresses the issue of control design for rollover prevention of a multi-body ground vehicle with army applications. The novelty of the approach lies in expressing the traditional rollover index as a quadratic performance index in Linear-quadratic regulator (LQR) design thereby integrating the roll over index directly and explicitly in the optimization procedure. The control gain obtained based on rollover performance index is more effective for rollover prevention than the gain obtained based on standard LQR design in which there is much ambiguity and labor involved in assigning the weights. The control gain obtained based on the proposed rollover performance index outperforms the standard LQR design, essentially because it introduces a cross coupling term between the state and control variables in the modified performance index. Thus, the proposed rollover prevention technique effectively incorporates the physical nature of the vehicle dynamics in the problem formulation resulting in significantly improved performance.

Ball et al. (2009) studied that upper extremity amputations after motor vehicle rollovers. The upper extremity is vulnerable to injury during a rollover motor vehicle crash (MVC). There is some concern that positioning one's arm on a vehicle door/window eliminates the benefit of maintaining containment within a protective structure. Mangled extremities with associated vascular injuries have an amputation rate exceeding 40%. The primary goal was to describe the care process and outcome of patients requiring an emergent upper extremity amputation after a rollover MVC. All patients requiring an upper extremity amputation after a rollover MVC (2000-2008) were included. Patient demographics, injuries, and outcomes were analyzed. Seventeen patients required an upper extremity amputation after a rollover MVC (mean injury severity score = 23; hemodynamic instability at presentation 29%). Injuries occurred on the side ipsilateral to the occupant vehicle position in 88% of cases. Most (76%) amputations occurred between May 1 and August 1 of their

respective years, with 11 (65%) in the past 24 months. All amputations except one (replantation attempt) were completed within 24 hours. Concurrent operative procedures were performed in six (35%) patients, including three diagnostic peritoneal lavages, two laparotomies (splenectomies), one craniotomy, and one thoracotomy (atrial rupture). Mortality (12%) was a direct result of traumatic brain injuries. Temporary intravascular shunts were used before amputation in four (24%) patients. The majority (65%) of amputations were above the elbow joint. Blunt mangled upper extremities requiring completion amputations are most often caused by MVC rollovers. The risk of this injury is strongly associated with summer days and seems to be increasing in frequency.

Friedman and Hutchinson (2009) studied that review of existing repeatable vehicle rollover dynamic physical testing methods. Two repeatable dynamic rollover performance testing systems have been demonstrated and reported upon. Here a review of each system is presented in which the general characteristics of each system are discussed. To assess how the results obtained from the two systems would compare, finite element models of rollover tests characterizing the two design approaches were utilized. The results from a published rollover test using one of the systems was utilized as a reference test. For each system, the vehicle rollover impacts were simulated under the same initial impact conditions. The results of the simulations were then compared. It was found that the simulations for both hardware systems produced results that were consistent with each other using state-of-the-art finite element analysis tools.

Grzebieta et al. (2009) studied that occupant injuries and roof strength in rollover crashes. This paper shows how a mathematical relationship can be derived linking serious neck injuries to excessive roof deformation and that this relationship depends on the vehicle's Centre of Gravity (COG) lateral velocity at the moment of touchdown of the vehicle's roof structure. The relationships have been greatly simplified for an idealized condition to facilitate derivation of the equations. In the case of a very strong roof, occupant neck loading resulting from torso augmentation reaches a threshold value that depends on the coefficient of friction between the road

surface and the vehicle's steel body or tires and the height the vehicle's COG drops during a quarter turn impact sequence.

Lilley and Mani (1998) studied that roof-crush strength improvement using rigid polyurethane foam. By using foam, it is possible to reduce pillar sections, and to reduce thicknesses or eliminate reinforcements inside the pillars, and thereby offset the mass increase due to the foam filling. Further tests showed that utilizing the foam filling in a B-pillar to reduce section size can save ~20 mm that could be utilized to add energy absorbing structures in order to meet the new interior head impact requirements specified by the federal motor vehicle safety standards (FMVSS) 201 Head Impact Protection upgrade.

3. MATERIAL AND METHOD

3.1. Preperation of the Models by Using CATIA

CATIA, which stands for Computer Aided Three-dimensional Interactive Application, is the most powerful and widely used CAD (computer aided design) software of its kind in the world. CATIA was created by Dassault Systems of France and is marketed worldwide by IBM. In this thesis two non commercial vehicles were designed with CATIA.

3.1.1 Part Design

The CATIA Part Design application makes it possible to design precise 3D mechanical parts with an intuitive and flexible user interface, from sketching in an assembly context to iterative detailed design. CATIA Part Design application will enable you to accommodate design requirements for parts of various complexities.

This application, which combines the power of feature-based design with the flexibility of a Boolean approach, offers a highly productive and intuitive design environment with multiple design methodologies, such as post-design and local 3D parameterization. As a scalable product, CATIA Part Design can be used in cooperation with other current or future companion products in the next CATIA generation such as CATIA Assembly Design and CATIA Generative Drafting.

3.1.2 Assembly Design

CATIA Assembly Design workbench allows the design of assemblies with an intuitive and flexible user interface.

As a scalable workbench, CATIA Assembly Design can be cooperatively used with other current companion products such as CATIA Part Design and CATIA Generative Drafting. The widest application portfolio in the industry is also accessible through interoperability with CATIA Solutions to enable support of the full product development process from initial concept to product in operation. Digital

Mock-Up (DMU) Navigator inspection capabilities can also be used to review and check assemblies. Interactive, variable-speed techniques such as walk-through and fly as well as other viewing tools let you visually navigate through large assemblies.

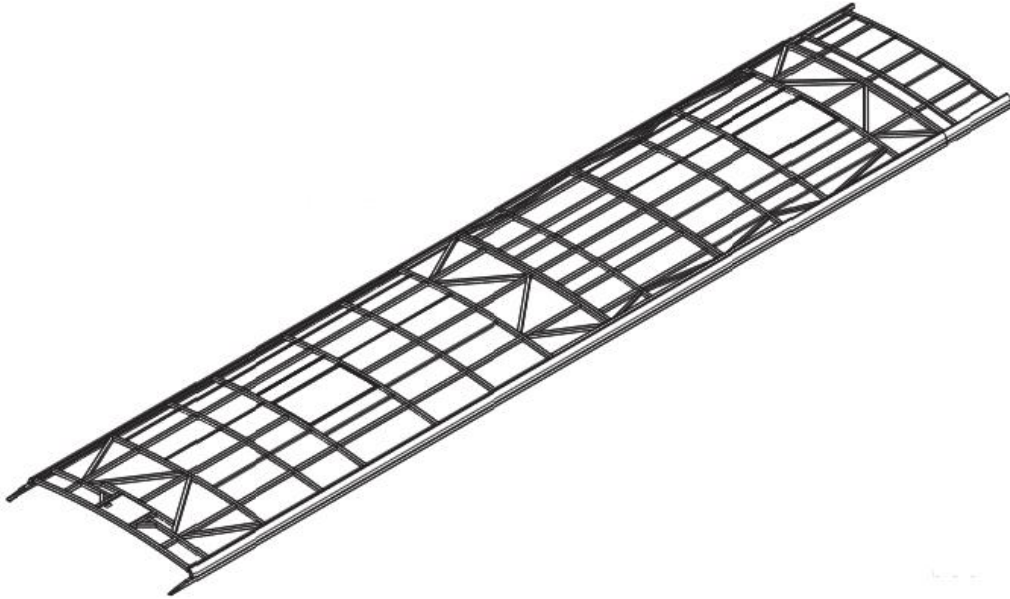


Figure 3.1. Roof design with CATIA(Model-1).

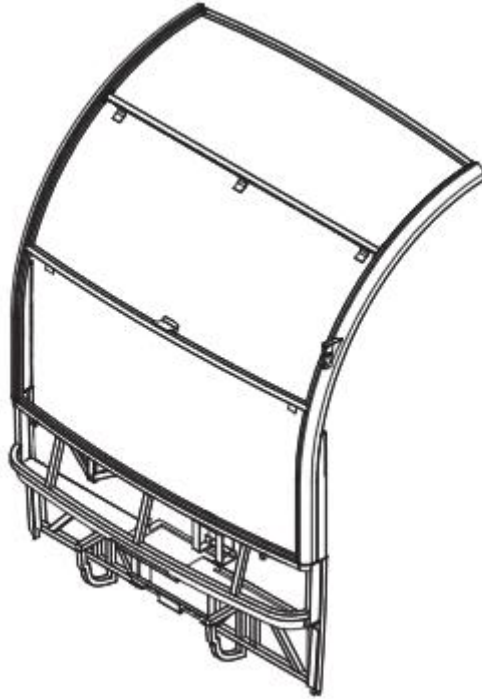


Figure 3.2. Front body design with CATIA(Model-1).



Figure 3.3. Rear body design with CATIA(Model-1).

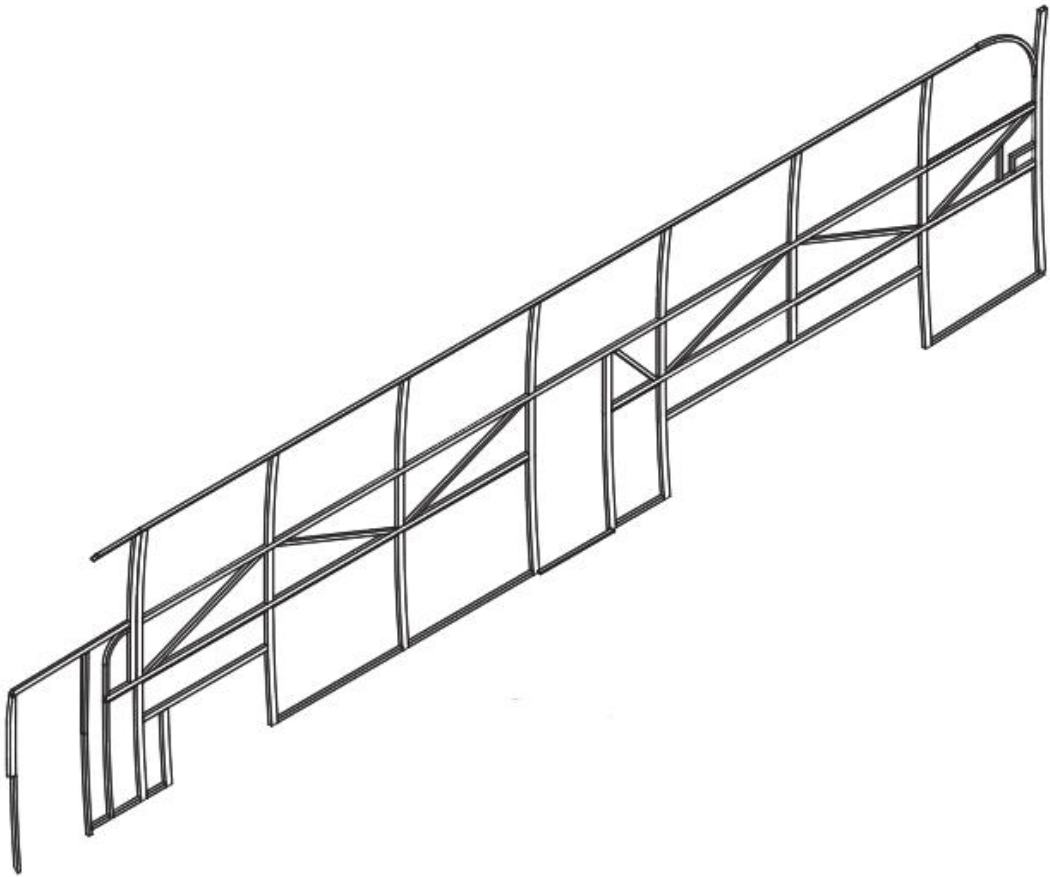


Figure 3.4. Right side wall design with CATIA(Model-1).

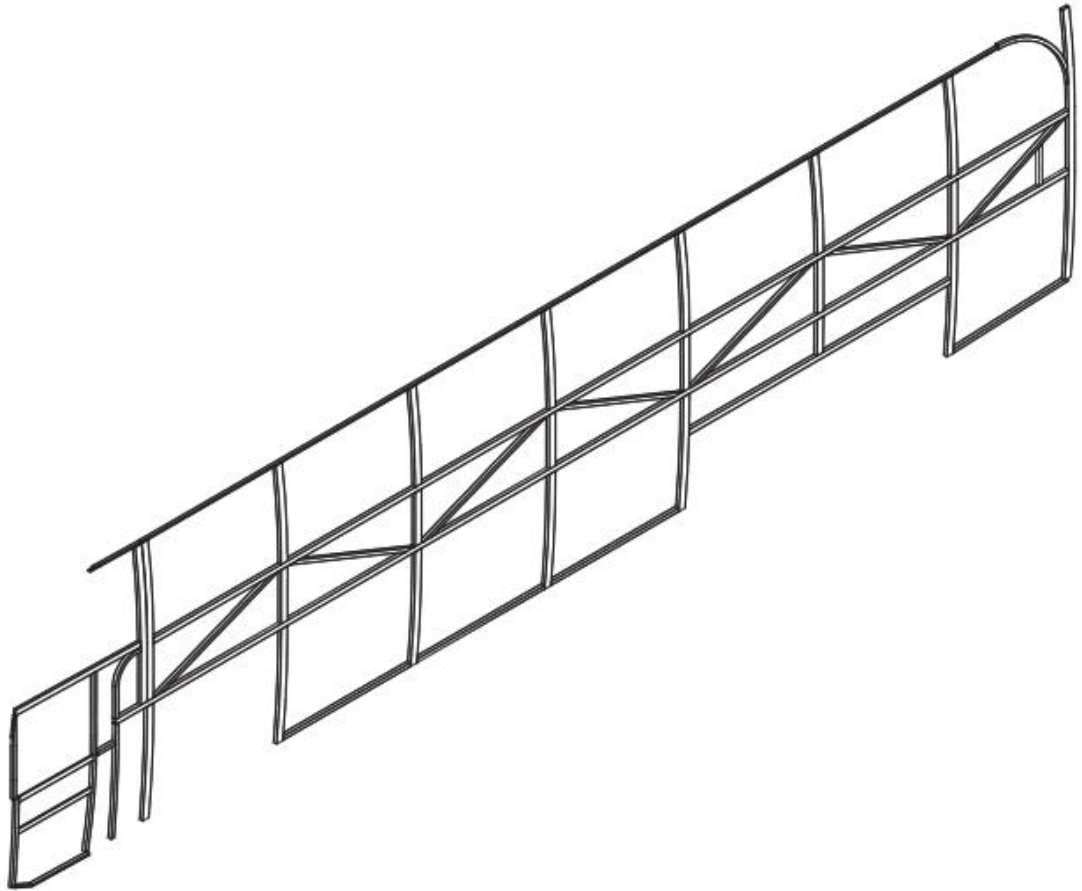


Figure 3.5. Left side wall design with CATIA(Model-1).

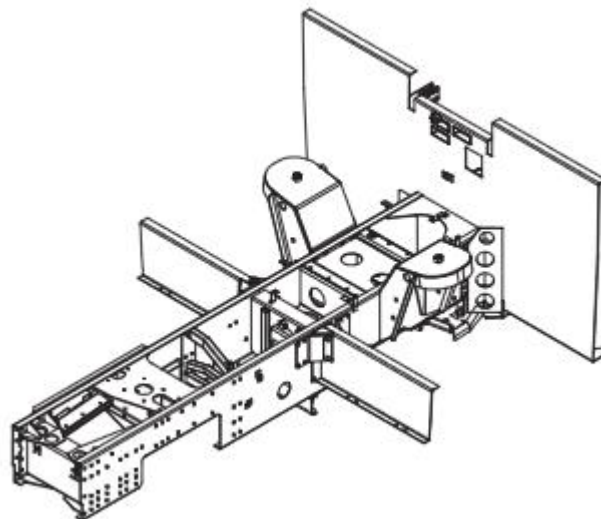


Figure 3.6. Front frame design with CATIA(Model-1).

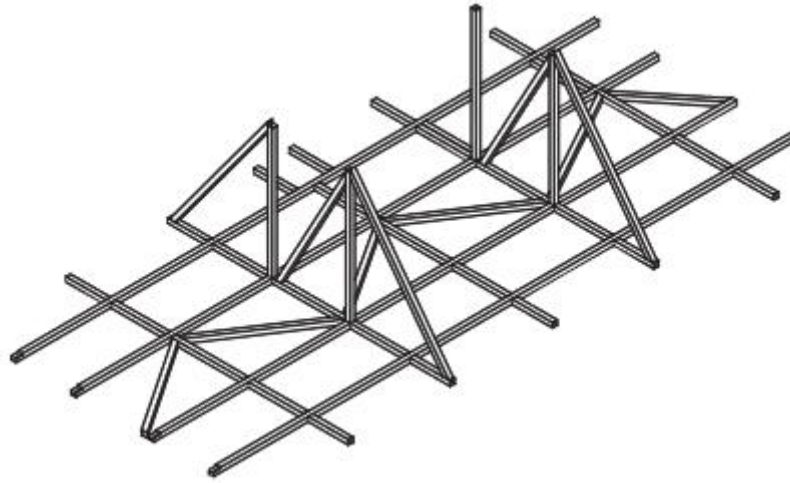


Figure 3.7. Center frame design with CATIA(Model-1).

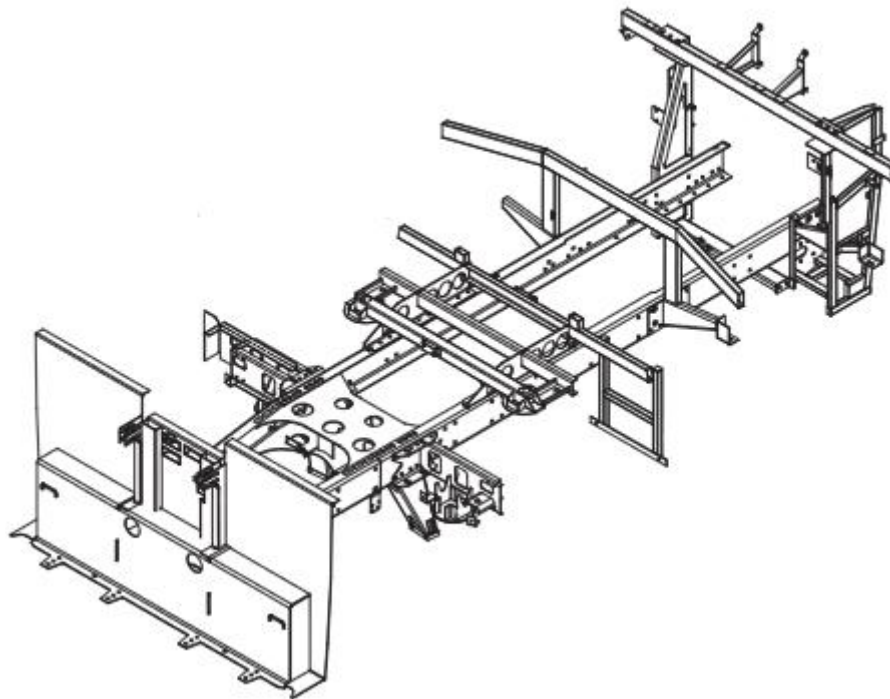


Figure 3.8. Rear frame design with CATIA(Model-1).

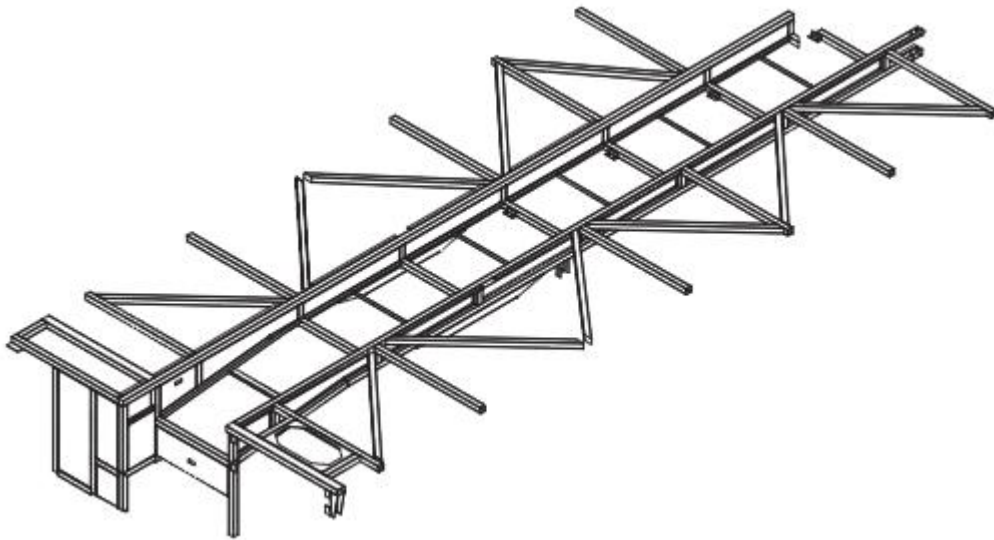


Figure 3.9. Front sill design with CATIA(Model-1).

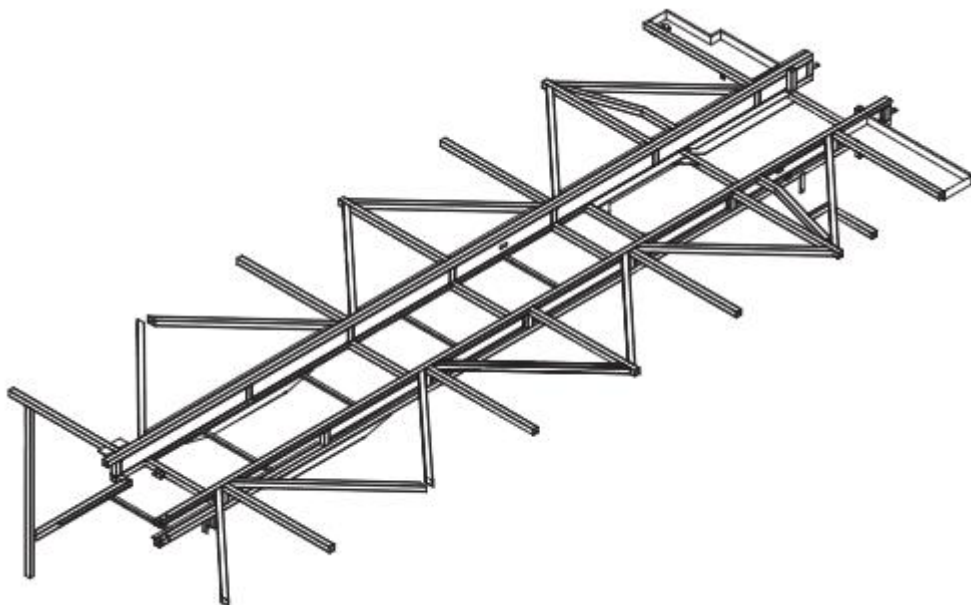


Figure 3.10. Rear sill design with CATIA(Model-1).

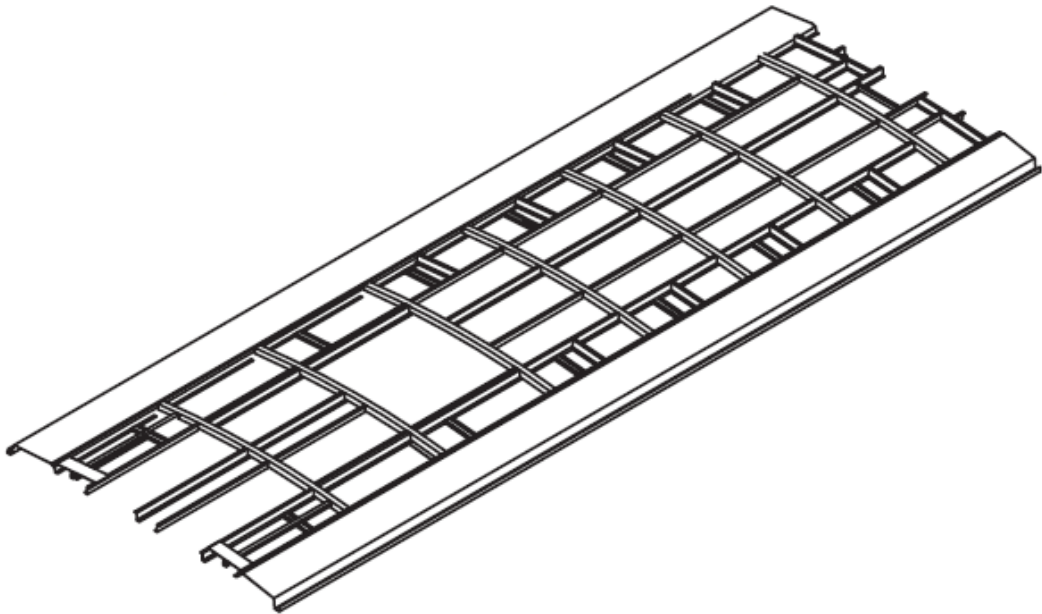


Figure 3.11. Roof design with CATIA(Model-2).

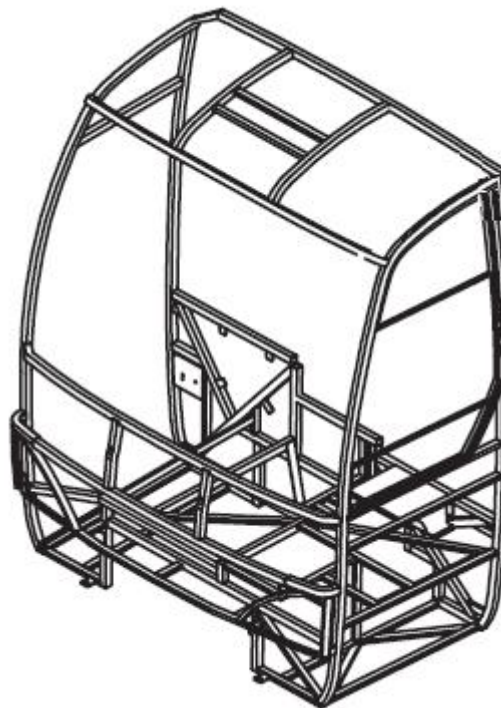


Figure 3.12. Front body design with CATIA(Model-2).



Figure 3.13. Rear body design with CATIA(Model-2).

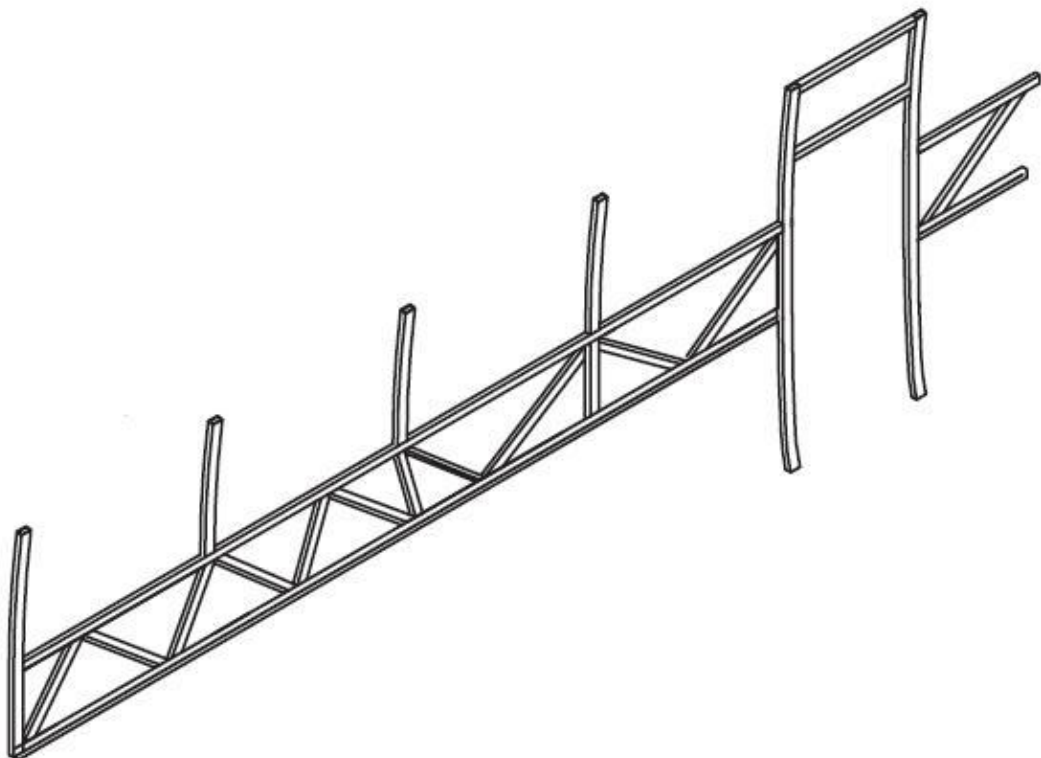


Figure 3.14. Right side wall design with CATIA(Model-2).

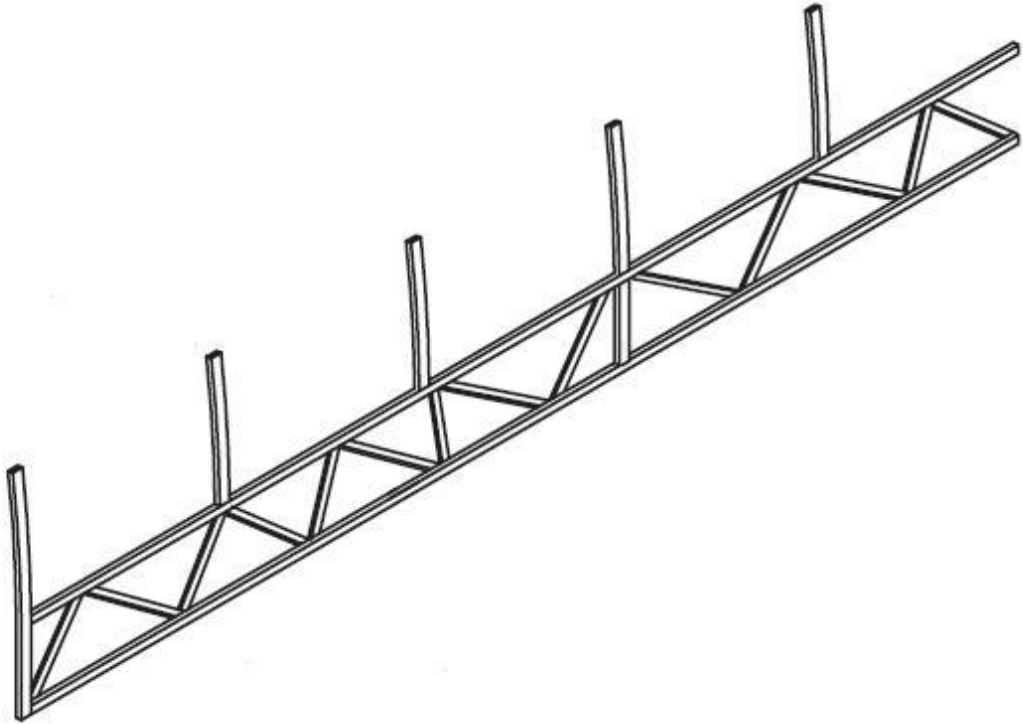


Figure 3.15. Left side wall design with CATIA(Model-2).

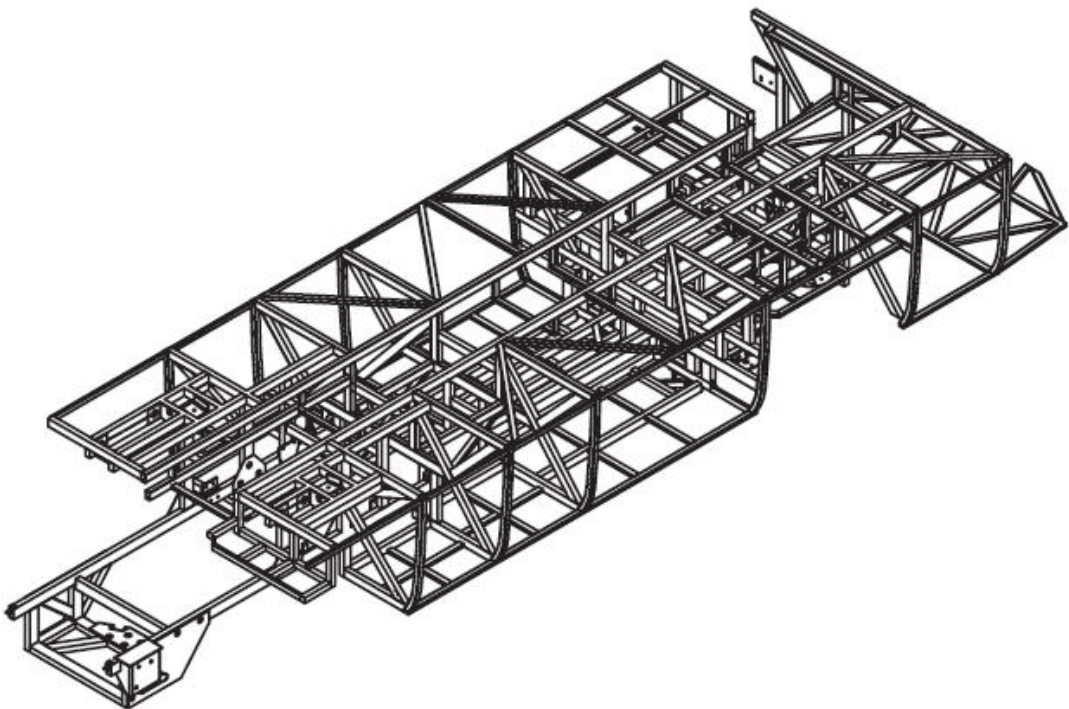


Figure 3.16. Frame design with CATIA (Model-2).

3.2. Finite Element Modeling

Engineering analysis of mechanical systems have been addressed by deriving differential equations relating the variables of through basic physical principles such as equilibrium, conservation of energy, conservation of mass, the laws of thermodynamics, Maxwell's equations and Newton's laws of motion. However, once formulated, solving the resulting mathematical models is often impossible, especially when the resulting models are nonlinear partial differential equations. Only very simple problems of regular geometry such as a rectangular of a circle with the simplest boundary conditions were tractable.

The finite element method (FEM) is the dominant discretization technique in structural mechanics. The basic concept in the physical interpretation of the FEM is the subdivision of the mathematical model into disjoint (non-overlapping) components of simple geometry called finite elements or elements for short. The response of each element is expressed in terms of a finite number of degrees of freedom characterized as the value of an unknown function, or functions, at a set of nodal points.

The response of the mathematical model is then considered to be approximated by that of the discrete model obtained by connecting or assembling the collection of all elements. The disconnection-assembly concept occurs naturally when examining many artificial and natural systems.

3.2.1 ANSA Software

ANSA is an advanced multidisciplinary CAE pre-processing tool that provides all the necessary functionality for full-model build up, from CAD data to ready-to-run solver input file, in a single integrated environment. ANSA is the users' favorite due to its wide range of features and tools that meet their needs. The list of productive and versatile features is long and the alternative tasks and processes to be completed using them are countless (ANSA,2008).

Following the versatile mesh area idealization, geometry can be meshed according to modeling requirements by its cutting edge, fully integrated surface and

volume meshing algorithms. The numerous proprietary shell meshing algorithms, the high performance and quality volume meshing algorithms, the versatile boundary-layers elements deployment, the Hexa-Interior meshing algorithm, the Acoustic Cavity mesher and the straight forward Wrapping tool, compose a unique mesh generation environment. Further more, the integrated Batch Meshing tool leads to controllable and effortless optimal results, for both shell and volume meshing.

Powered with fully comprehensive parts and welding management tools, accommodates parts assembly, with alternative nodedependent or independent connections types, appropriate to various disciplines. Interfaces to numerous connections data file formats allow the completion of a single stage assembly. New concepts introduced, including model hierarchy input, multiple part instances handling, alternative part representations management, model assembly and build up using Generic Entities such as Connectors, Boundary Conditions and Output Requests.

3.2.2 Meshing

ANSA has seven different algorithms for generating surface mesh along with 4 unique algorithms for volume meshing. These algorithms can be used individually or a combination of them can be used for modeling a complex geometry. All these algorithms are available as both manual and batch – mesh options. The algorithms can be applied to generate a combination of elements across different mesh types and mesh order. These proprietary algorithms enhance the speed and accuracy of geometry meshing.

-Batch meshing: Batch meshing tool integrates all actions needed to generate a high – quality mesh for any analysis on both geometric and FE data through its customizable meshing sessions. In addition, this tool can also be fully controlled and executed through scripts, as an integral part of the pre – processing job. Advanced inbuilt filtering options allow for easy mesh criterion based part sorting and organization. Batch mesh tool is capable of automatic detection and treatment of holes, flanges, fillets, tubes and logos among other features. Automatic detection and

treatment of unnecessary face edges, features, holes, flanges, fillets, tubes and logos gives the user tight control over every aspect of the resulting mesh. Input/output of ASCII parameter files provide easy saving and loading of sessions, making the batch mesher a simple and straightforward "plug and play" operation thus is an effective way to maintain modeling guidelines. A final report can be generated at the end of the session documenting the batch mesh result on part basis.

-Reconstruct / Reshape: A frequent requirement that arises during modeling is the need for disfeaturing the model for optimizing mesh quality. Most pre processor will force you to disfeature the geometry and run new meshing job. ANSA provide a simple solution to such scenarios by introducing the RECONSTRUCT & RESHAPE algorithms. These mesh improvement tools give the user batch mesh-like capability solutions for local mesh problems on geometric mesh and FE data. Optimizing quality, changing density, changing mesh types, and feature treatments can all be accomplished through these tools wherever needed. This capability allows for fast local changes without the need to remesh the whole part.

-Wrap: ANSA's variable-density wrapping tool provides very tight adherence to detail in convex as well as concave feature situations. Inner and outer wraps are possible, with auto detection of multiple "volumes" for the user to choose which to wrap. The original assembly's zone/property changes can be matched in the wrap mesh, with very close alignment of the wrap zones to the originals. The wrap tool also houses useful functions to identify leaks, identify and fix duplicate elements, and automatic fixes for such scenarios.

-Layers Generation: The layer generation interface in ANSA offers the user lot of control to generate the required layers off of the surface mesh. Along with the control for height and growth factors, user can provide direction to the algorithm for layers from adjacent surfaces and also auto – create skins on them. The tool use HEXA, PENTA or a combination of these element types depending on what the scenario dictates.

-Volume Mesh: ANSA has a fully automatically generations for TETRA meshes for both CFD and structural application. It also has the capability of creating DELAUNAY type of TETRA elements. Some fluid flow applications and even in

structural there is often a need for HEXA – CORE, this can be easily be achieved in a automatic method, with control over defining specific coordinates for the HEXA element generation. These HEXAs are connected to the surface elements through a transition of PENTAs or TETRAs. To support ‘100% HEXA’ model, ANSA has developed advanced functionalities to indulge user in semi – automatic process.

-Connections manager: Welds and Bolts in ANSA are based on geometric entities in a group of entities known as Connections. ANSA incorporates a very comprehensive connections manager tool which is geared towards managing various types of welds, adhesives, bolts through a single user friendly interface. The tool is capable of handling both mesh – dependent & independent welds, catering for discipline specific representation of the connection entities. Some of the connections that it handles are:

- Spot welds
- Seam welds
- Hemlines
- Adhesive Lines and faces
- Gumdrops
- Bolts

It is also capable of interfacing with numerous connections data file-formats allow the completion of a single stage assembly.

-Bolt Tool: This is a specialized tool for BOLT construction. The interface supplies the user with a variety of element types for head and body of the bolt. This tool is common for all the structural solver decks in ANSA. Entities created from this tool are interoperable and map to the respective solver entities when user switches decks.

The models were called into ANSA. In this software geometry cleaning was done by geometry manipulation tools. And the models were checked by a geometry check tool. The models were meshed with batch meshing tool as shown in Figure 3.17 and Figure 3.18.



Figure 3.17. Meshed Model (Model-1).

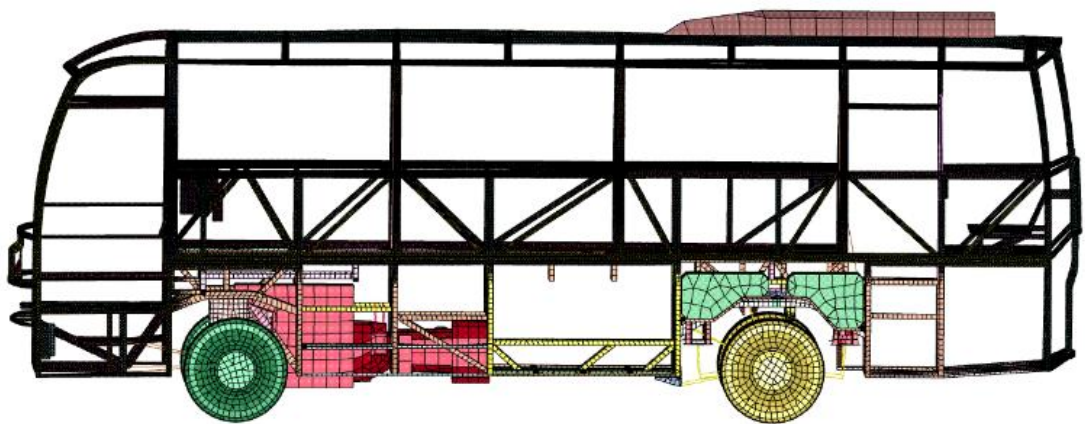


Figure 3.18. Meshed Model (Model-2).

3.2.3 Mesh Quality

Some default quality criteria are available in ANSA including the following:

- Min Side Length: Length of the smallest side of an element.
- Max Side Length: Length of the largest side of the element.
- Aspect Ratio: Ratio of the longest side to the shortest side of an element.
- Warpage: Deviation of an element or element face from being planar.
- Min/Max Quad Internal Angle: The minimum/maximum angle of a quad element.
- Min/Max Tria Integral Angle: The minimum/maximum angle of a triangle element.

- Percent of Triangular Elements: Ratio of the number of triangular elements to the total number of elements.

Mesh quality criteria was listed in the Table 3.1

Table 3.1. Mesh quality criteria.

No	Quality Parameter	Allowable Min / Max
1	Minimum Side Length	5
2	Maximum Side Length	100
3	Maximum Aspect Ratio	5
4	Maximum Warpge Angle	15
5	Minimum Quad Internal Angle	45
6	Maximum Quad Internal Angle	135
7	Minimum Tria Internal Angle	15
8	Maximum Tria Internal Angle	120
9	Percent of Triangular Elements	5

3.3. Non Linear Structural Analysis

Nonlinear analysis of structures has become increasingly important in the study of structural response to hazardous loads. Such analyses should include the effects of significant material and geometric nonlinearities, various phenomenological models of structural components and the energy and momentum transfer to different parts of the structure when structural components fracture.

Computer analysis of structures has traditionally been carried out using the displacement method, wherein the displacements in the structure are treated as the primary unknowns, combined with an incremental iterative scheme for nonlinear problems.

3.3.1. LS-DYNA Software

LS-DYNA was developed by LSTC (Livermore Software Technology Cooperation). LS-DYNA is a multifunctional applicable explicit and implicit FE program to simulate and analyse highly non-linear physical phenomena pertaining to real-world problems. Usually those phenomena are subjected to large deformations within a short time duration, 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 implementation for the automobile industry.

The numerical study is based on the LS-DYNA FEA. The LS-DYNA software contains a pre-processing FE builder, 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 perform solutions. The output results such as stress and strain of elements, displacement, velocity and acceleration of nodes, and energy distribution, etc., can be shown clearly through the user interface. The main solution is based on explicit time integration.

The explicit method was originally developed, and is primarily used, to solve dynamic problems involving deformable bodies. Accelerations and velocities at a particular point in time are assumed to be constant during a time increment and are used to solve for the next point in time. For the explicit method, a central difference time integration method is used. The word 'implicit' here refers to the method by which the state of an FE model is updated from time t to $t + \Delta t$. A fully implicit procedure means that the state at $t + \Delta t$ is determined according to information at time $t + \Delta t$, while the explicit method solves for $t + \Delta t$ according to information at time t .

With the explicit FE method, the solver equations can be solved directly to determine the solution without iteration, thus providing an alternative, more robust method. In the case of loading conditions involving contact, the explicit method proved to be the preferred choice. Moreover, the explicit method displayed constantly high levels of parallelisation efficiency compared with the implicit method for analyses solved with multiple processors.

3.3.2. Tilting Platform

According to ECE Regulation 66, the tilting table geometry is shown in Figure 3.19. The tilting table shall be sufficiently rigid and the rotation sufficiently

controlled to ensure simultaneous lifting of the axles of the vehicle with a difference of less than one degree in the platform's tilt angles measured below the axles. The height difference between the horizontal lower plane of the ditch and the plane of the tilting platform on which the bus is standing, shall be 800 ± 20 mm. The axis of its rotation is 100 mm maximum from the vertical wall of the ditch and 100 mm maximum below the plane of the horizontal tilting platform. Wheel supports shall be applied at the wheels being close to the axis of rotation against sliding of the vehicle sideways when tilting it. The tilting platform shall be constructed to prevent the vehicle moving along its longitudinal axis. The impact area of the ditch shall have a horizontal, uniform, dry and smooth concrete surface.

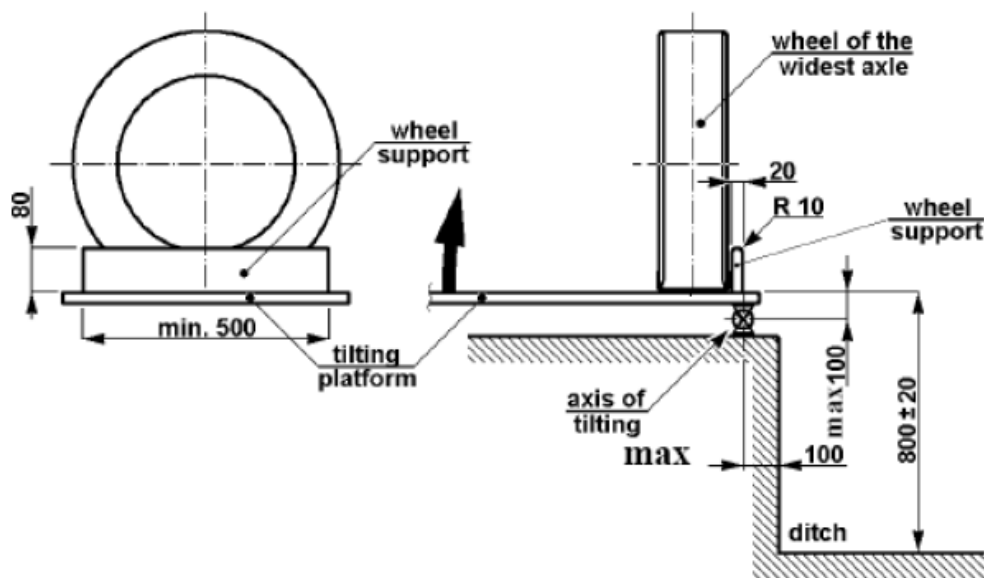


Figure 3.19. Geometry of tilting platform.

3.3.3. Rollover Simulation

The ground was simulated a rigid plane (MAT_RIGID) with all degrees of freedom constrained. For the contact between the bus and the ground, the AUTOMATIC_SURFACE_TO_SURFACE card was used. Static and dynamic coefficient of frictions was kept at 0.7 because of the hard nature of the concrete

ground used for the rollover test. Contact was given between all parts of the bus by using the CONTACT_AUTOMATIC_SINGLE_SURFACE_ID card.

The total energy according to the formula indicated in the ECE R66 regulation:

$$E^* = 0.75Mgh \quad (1)$$

where ‘M’ is the unladen kerb mass of the bus structure, ‘g’ is the gravitational acceleration and ‘h’ is the vertical distance between the CoG of the vehicle at free fall position (z_2) and the CoG of the vehicle which is kinematically rotated up to the ground contact position (z_3). (see Figure 3.20 for z_2 and z_3).

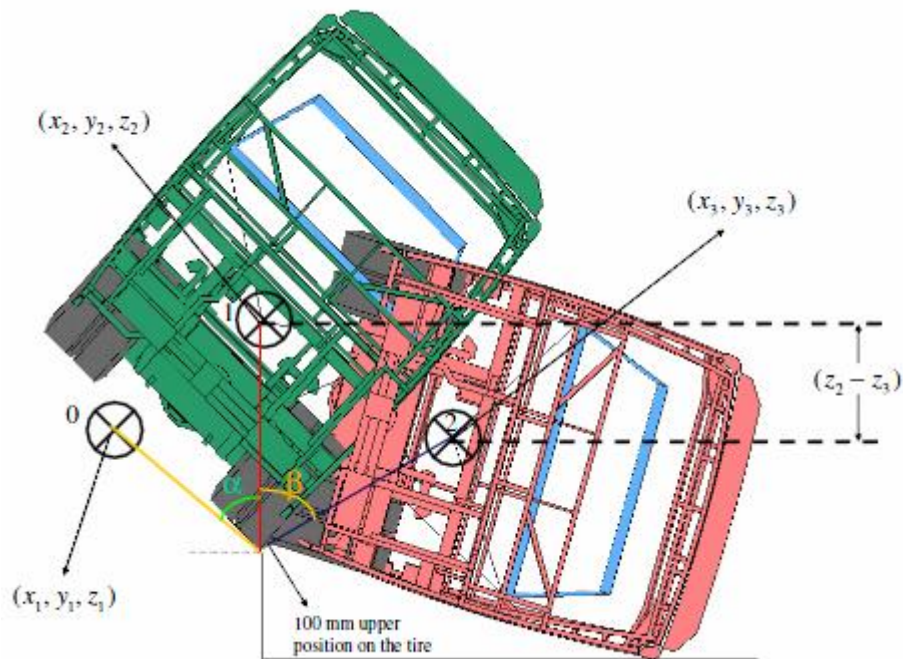


Figure 3.20. Rotation of the non-commercial vehicle during rollover.

“h” is determined by rotating the model around its axis until the mass center of the whole vehicle reaches its highest position. At this point the coordinate of the CoG in the direction is recorded. Then the bus is rotated around the 100mm obstacle until the vehicle contacts the ground. The coordinate of the CoG at this position is

recorded as well. Then the vertical distance between these two points is determined (h).

The total energy E^* is applied to the structure by applying a rotational velocity to all of the parts of the vehicle. Initial velocity generation is done with LS-DYNA keyword INITIAL_VELOCITY_GENERATION. Figure 3.21 shows the energy calculation for initial velocity generation.

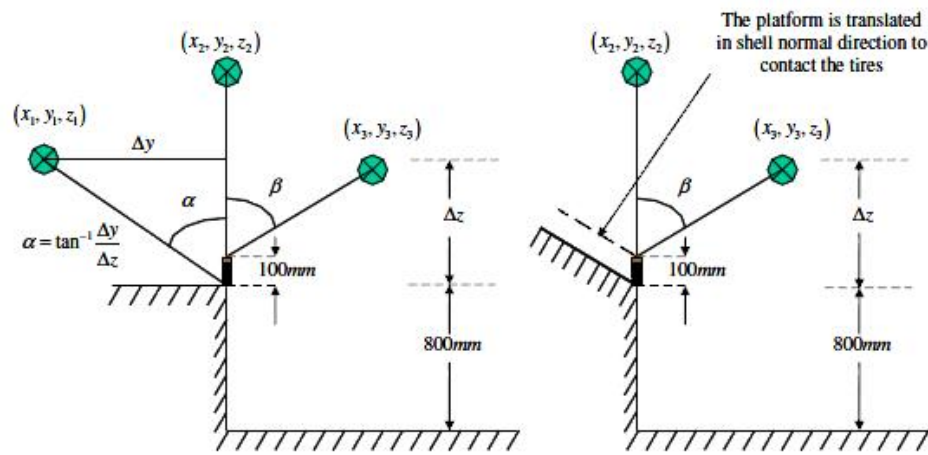


Figure 3.21. Energy calculation for initial velocity generation.

All surfaces of the model were defined as one contact group, thus, effectively accounting for multiple self-contacting regimes during computational impact analyses. The static friction coefficient between all parts was set to 0.1 and the dynamic friction coefficient was set to default which assumes that it is dependent on the relative velocity 'v-rel' of the surfaces in contact.

Mass scaling was applied to the smallest 100 element which resulted in negligible change in overall mass and a good time saving in the total elapsed time.

Objective Stress Update (OSU) option which is generally applied in explicit calculations for only those parts undergoing large rotations is turned on.

Shell thickness change option in CONTROL_SHELL is enabled assuming that membrane straining causes thickness change during the deformation.

The solutions are performed with SMP (Shared Memory Parallel) version of LS-DYNA. The analysis time interval was set to 300 ms, with results output required after every 5000 timesteps.

4. RESULTS AND DISCUSSION

4.1. Effects of Using Different Type of Materials on Vehicle Rollover Analysis

4.1.1. Using ST-37 Grade Steel on Side Walls of Model-1

Side walls of the vehicles has an important role for the rollover analysis results. In the first analyse ST-37 grade steel will be used on the side walls as shown in Figure 4.1.

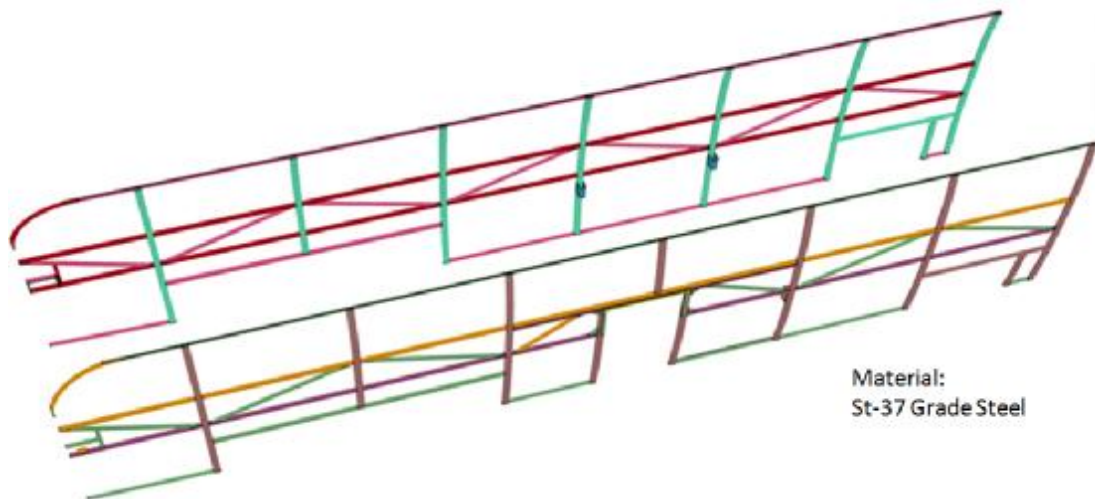


Figure 4.1. Side walls of Model-1.

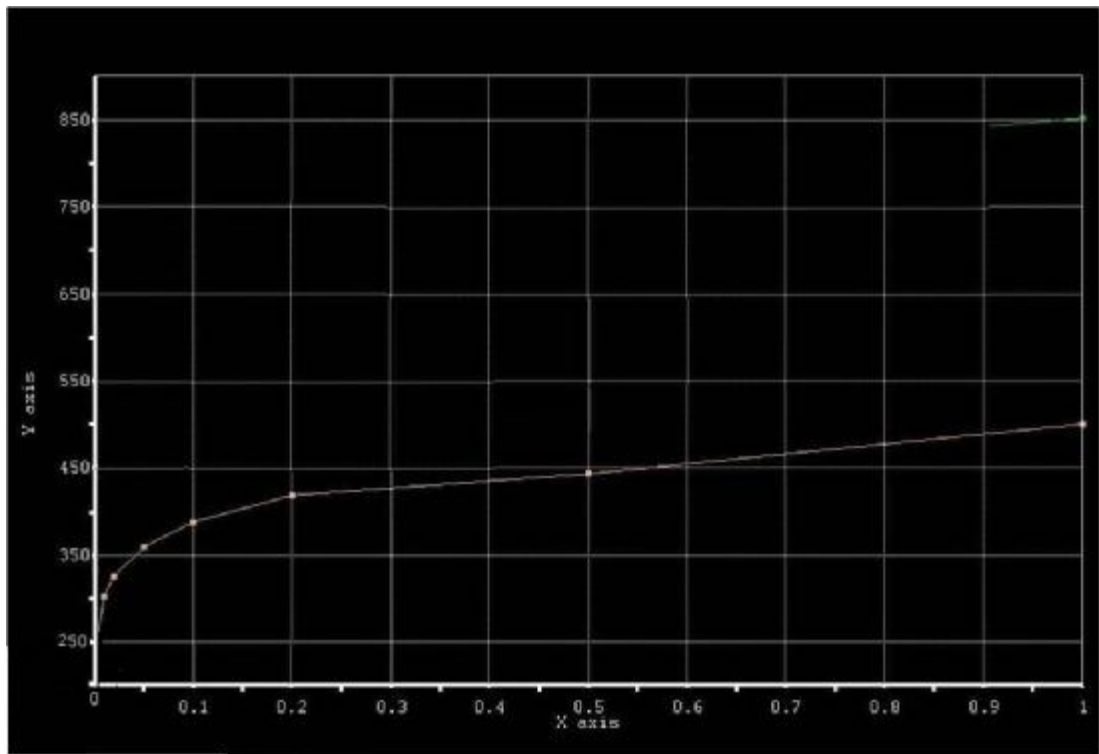


Figure 4.2. Stress-Strain curve for St-37 grade steel.

Rollover analyse has been runned for Model-1 by using SMP (Shared Memory Parallel) version of LS-DYNA. The sections which results were collected were shown in Figure 4.3.

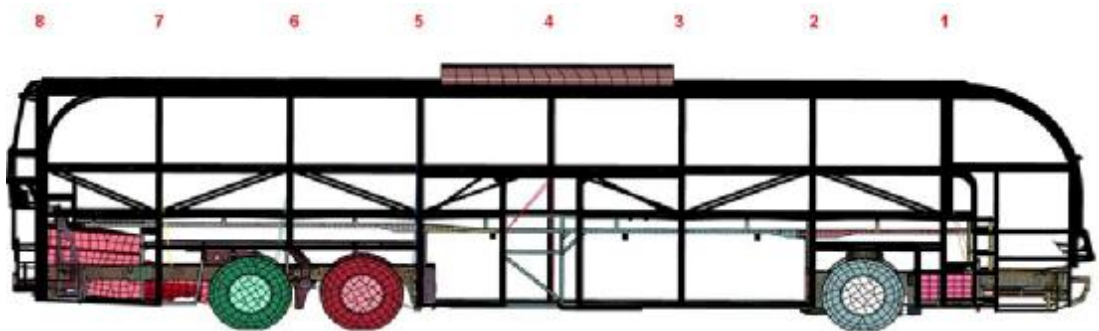


Figure 4.3. Model-1 Sections.

Closest distance between the residual space and the side wall profile has been measured as 1,81mm. from Section-1 of the Model-1 as shown in Figure 4.4.

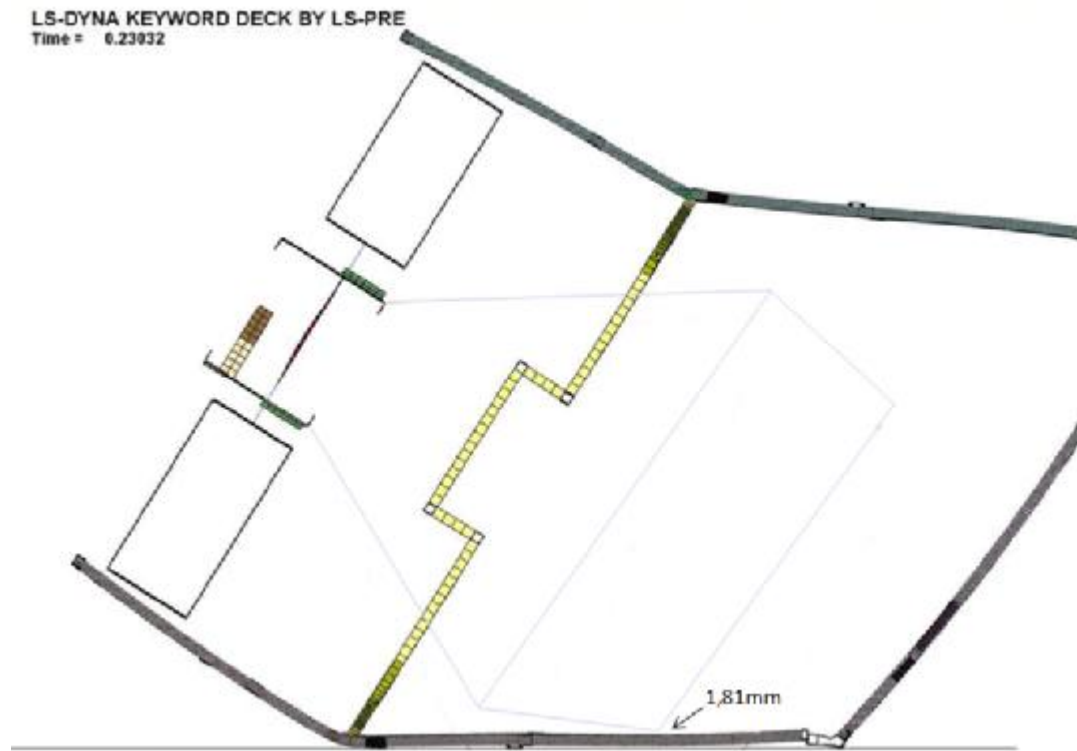


Figure 4.4. Section-1 Result.

Closest distance between the residual space and the side wall profile has been measured as 1,65mm. from Section-2 of the Model-1 as shown in Figure 4.5.

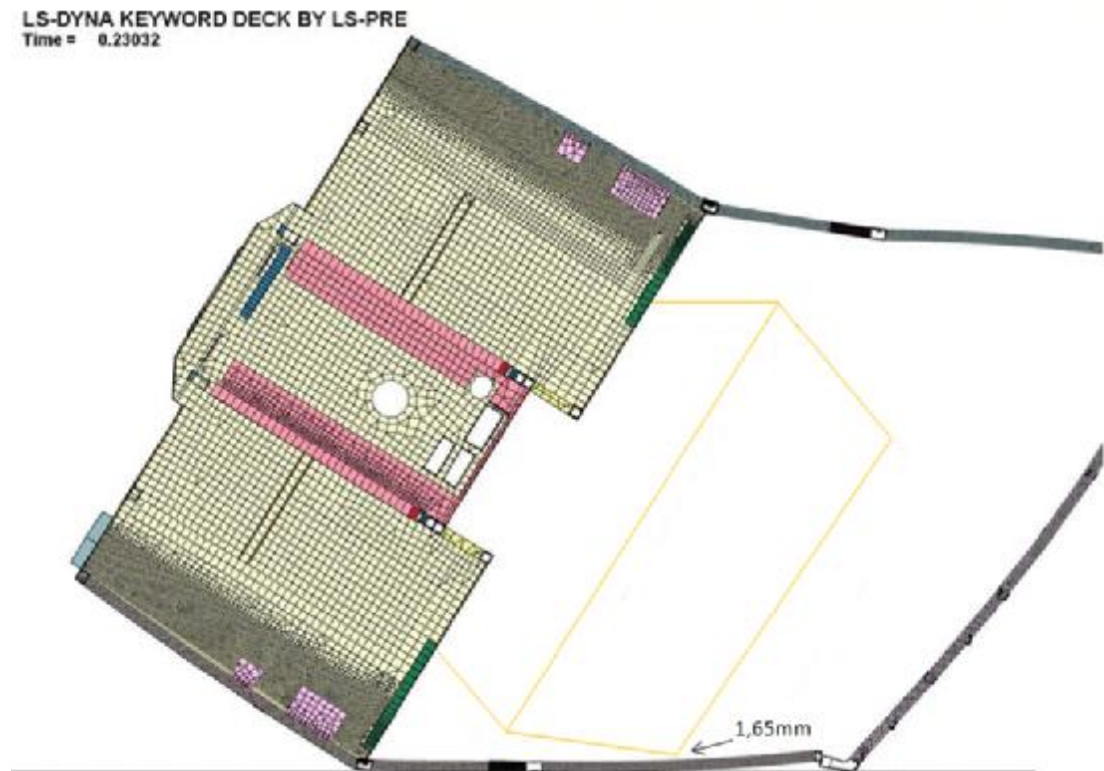


Figure 4.5. Section-2 Result.

Closest distance between the residual space and the side wall profile has been measured as 2,95mm. from Section-3 of the Model-1 as shown in Figure 4.6.

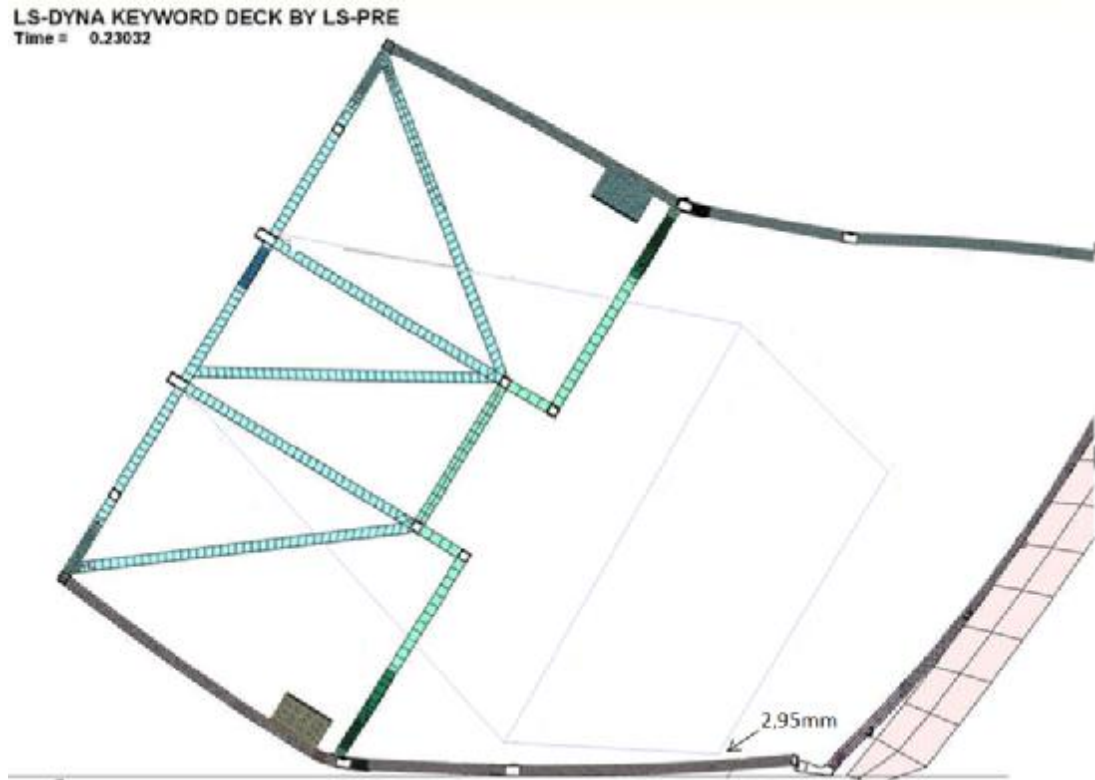


Figure 4.6. Section-3 Result.

Closest distance between the residual space and the side wall profile has been measured as 3,02mm. from Section-4 of the Model-1 as shown in Figure 4.7.

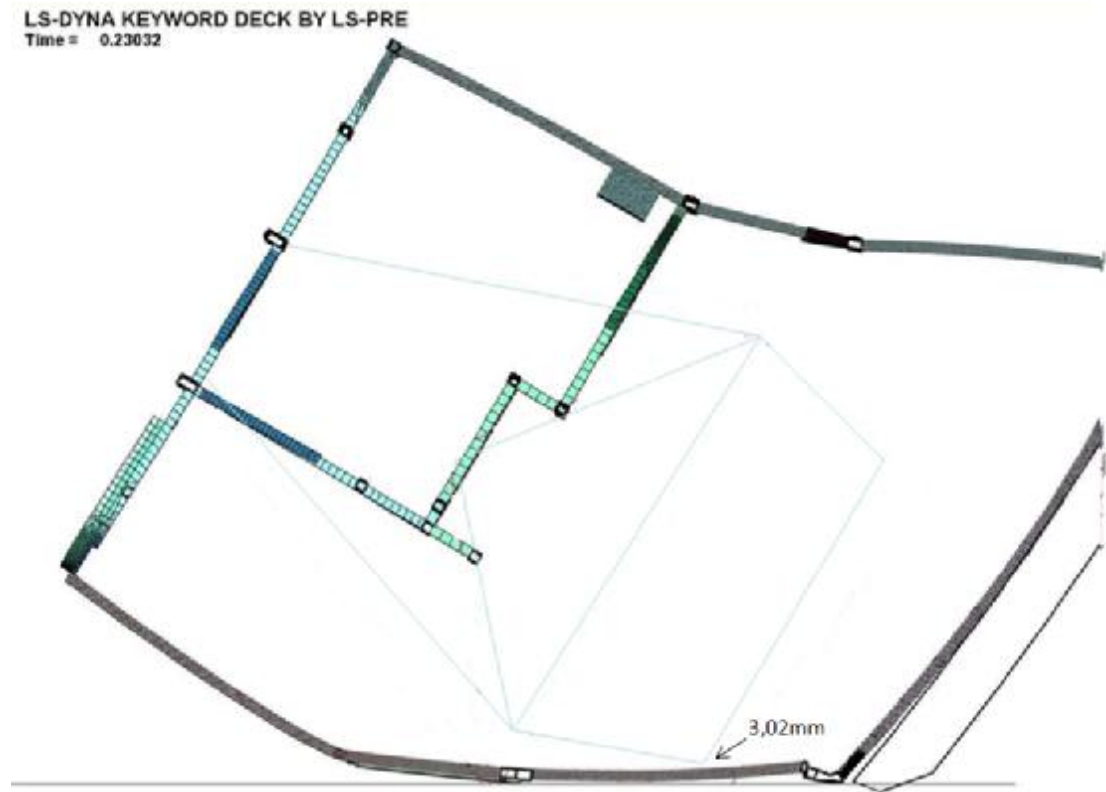


Figure 4.7. Section-4 Result.

Closest distance between the residual space and the side wall profile has been measured as 4,23mm. from Section-5 of the Model-1 as shown in Figure 4.8.



Figure 4.8. Section-5 Result.

Closest distance between the residual space and the side wall profile has been measured as 4,81mm. from Section-6 of the Model-1 as shown in Figure 4.9.

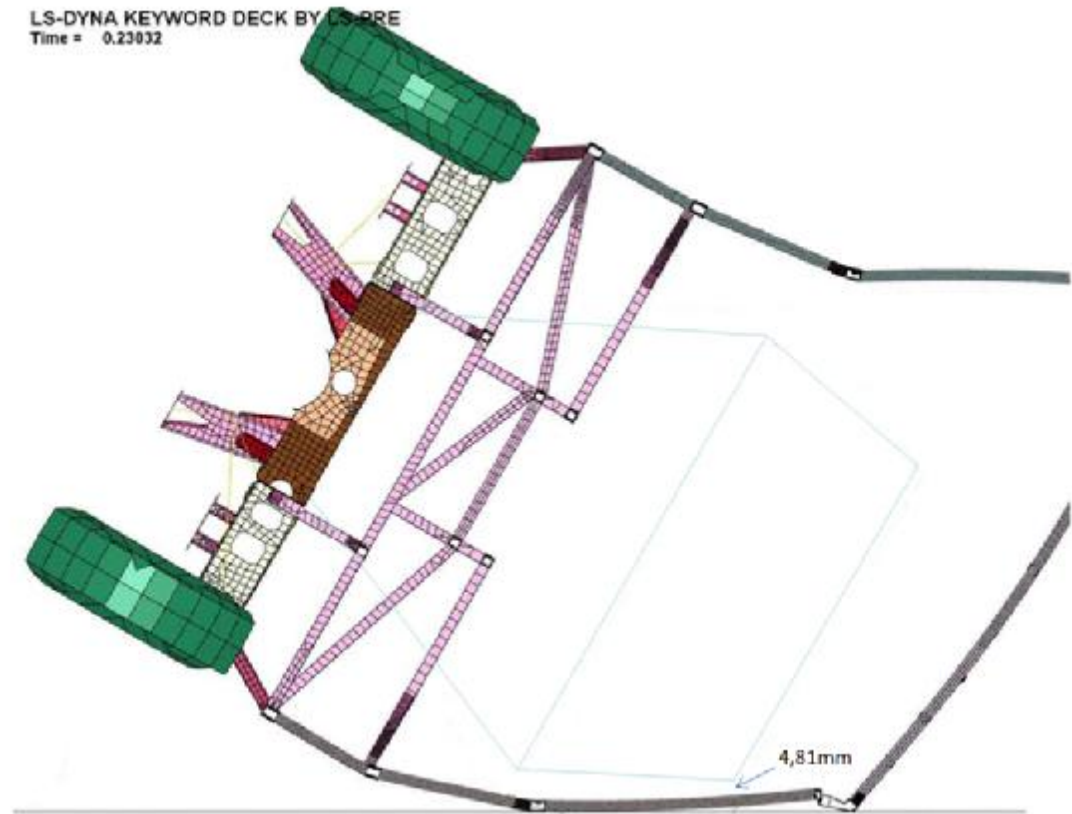


Figure 4.9. Section-6 Result.

Closest distance between the residual space and the side wall profile has been measured as 5,33mm. from Section-7 of the Model-1 as shown in Figure 4.10.

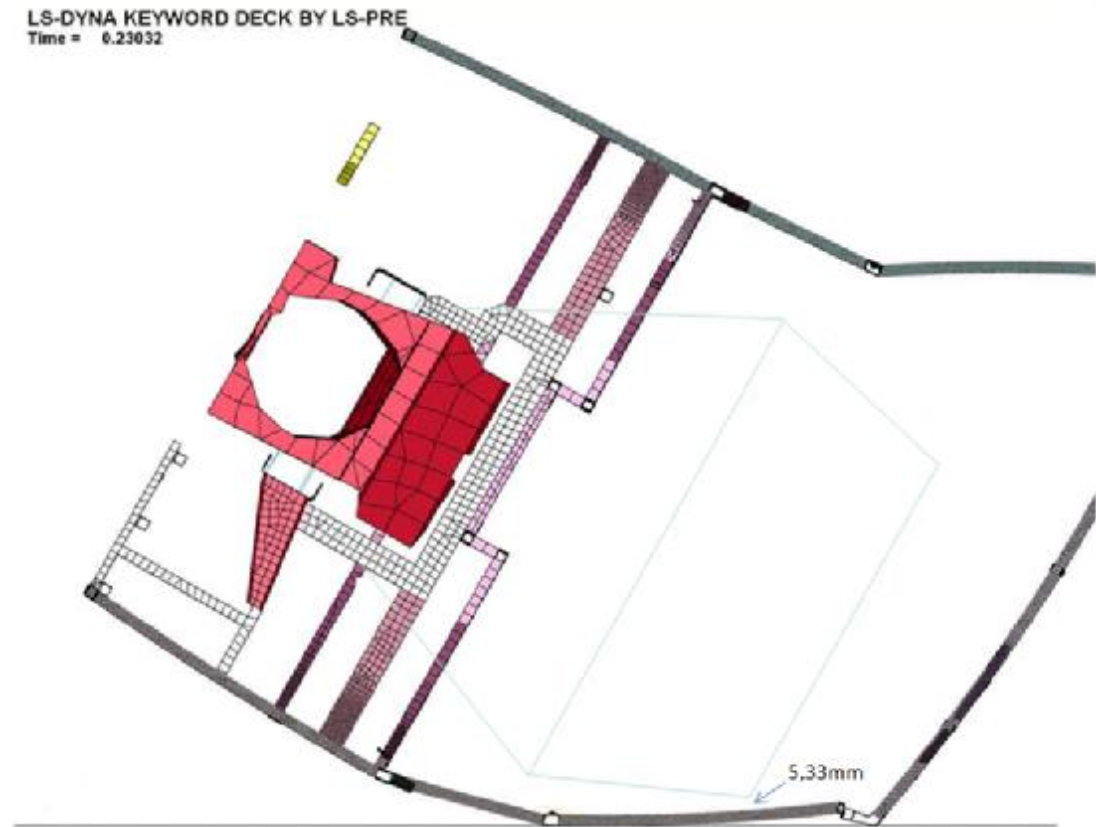


Figure 4.10. Section-7 Result.

Closest distance between the residual space and the side wall profile has been measured as 6,20mm. from Section-8 of the Model-1 as shown in Figure 4.11.



Figure 4.11. Section-8 Result.

4.1.2. Using ST-44 Grade Steel on Side Walls of Model-1

In the second analyse ST-44 grade steel will be used on the side walls as shown in Figure 4.12.

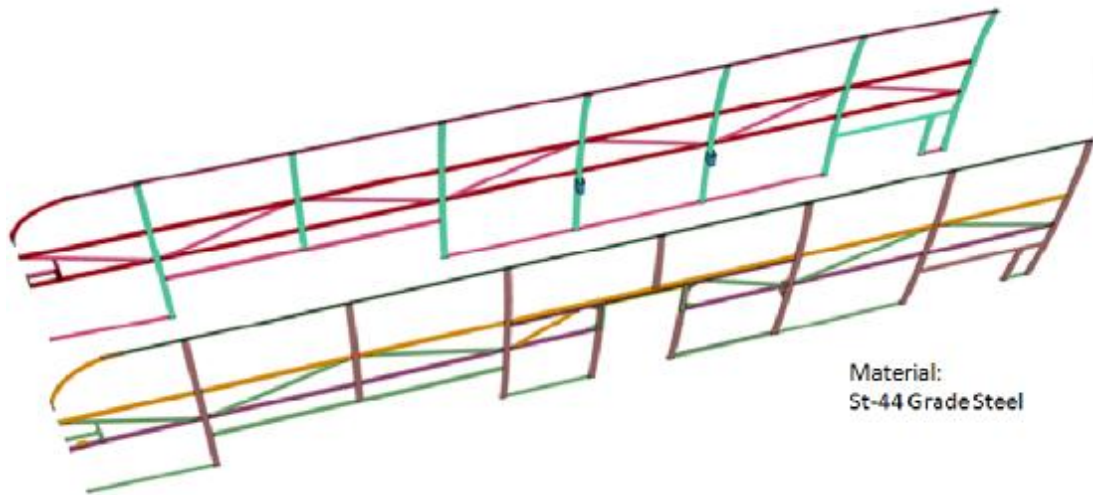


Figure 4.12. Side walls of Model-1.

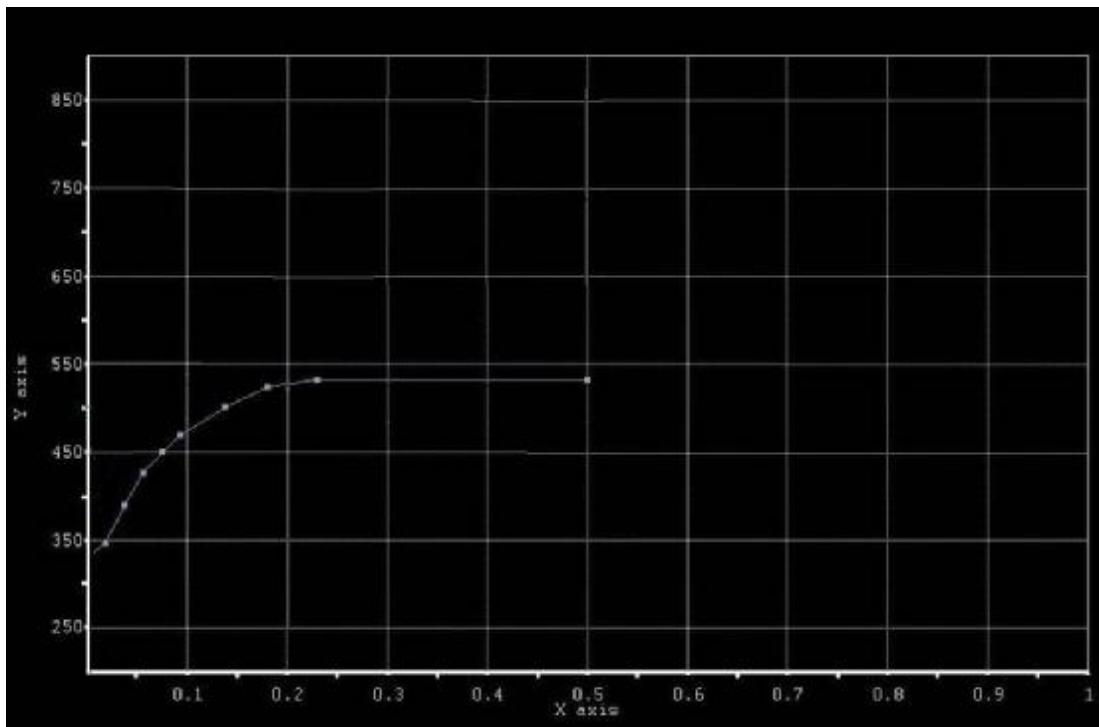


Figure 4.13. Stress-Strain curve for St-44 grade steel.

Rollover analyse has been runned for Model-1 by using SMP (Shared Memory Parallel) version of LS-DYNA. The sections which results were collected were shown in Figure 4.14.

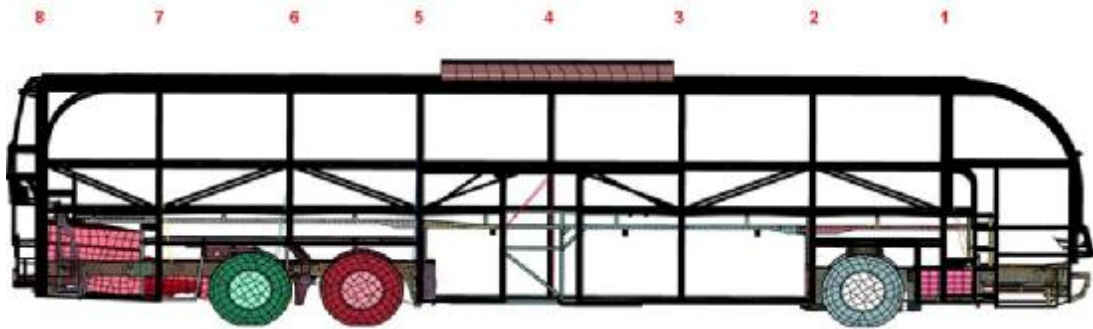


Figure 4.14. Model-1 Sections.

Closest distance between the residual space and the side wall profile has been measured as 4,52mm. from Section-1 of the Model-1 as shown in Figure 4.15.

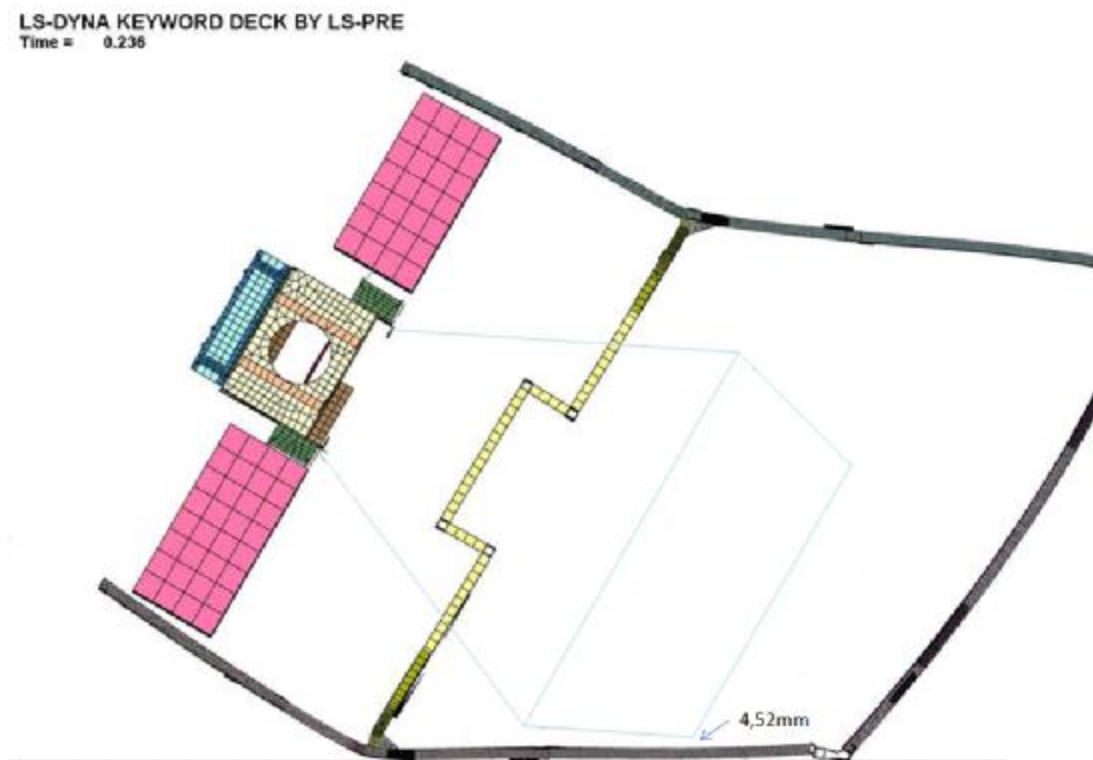


Figure 4.15. Section-1 Result.

Closest distance between the residual space and the side wall profile has been measured as 4,38mm. from Section-2 of the Model-1 as shown in Figure 4.16.



Figure 4.16. Section-2 Result.

Closest distance between the residual space and the side wall profile has been measured as 5,45mm. from Section-3 of the Model-1 as shown in Figure 4.17.

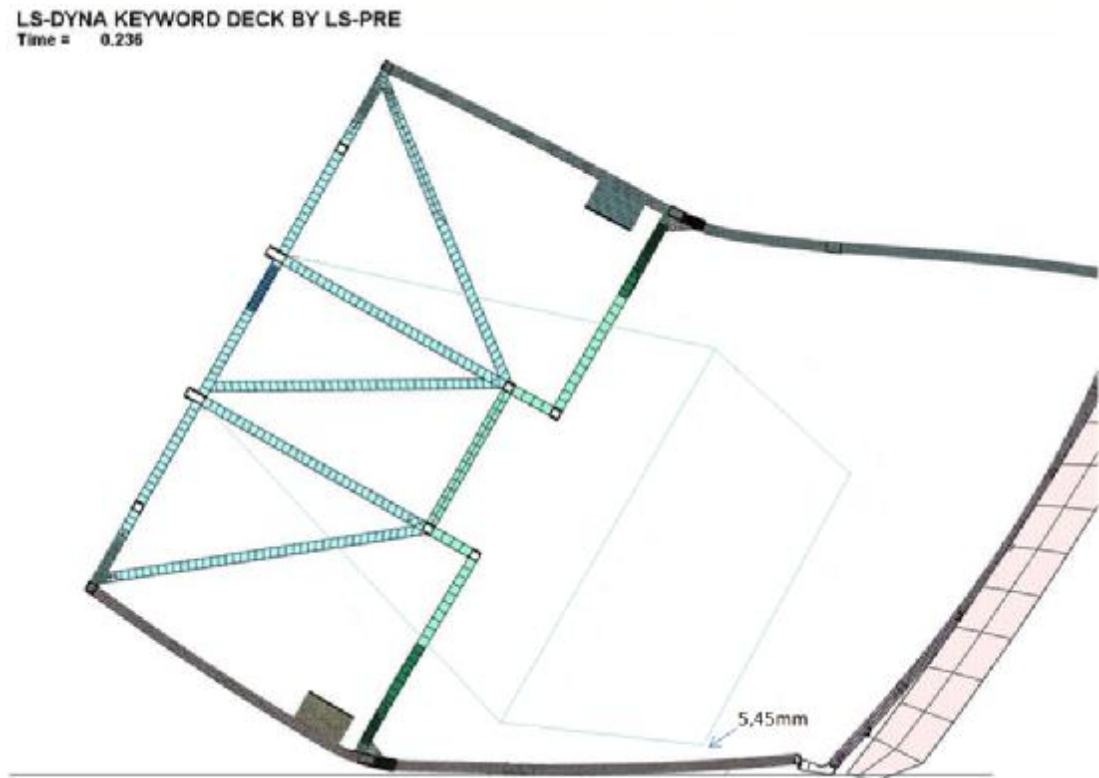


Figure 4.17. Section-3 Result.

Closest distance between the residual space and the side wall profile has been measured as 6,12mm. from Section-4 of the Model-1 as shown in Figure 4.18.

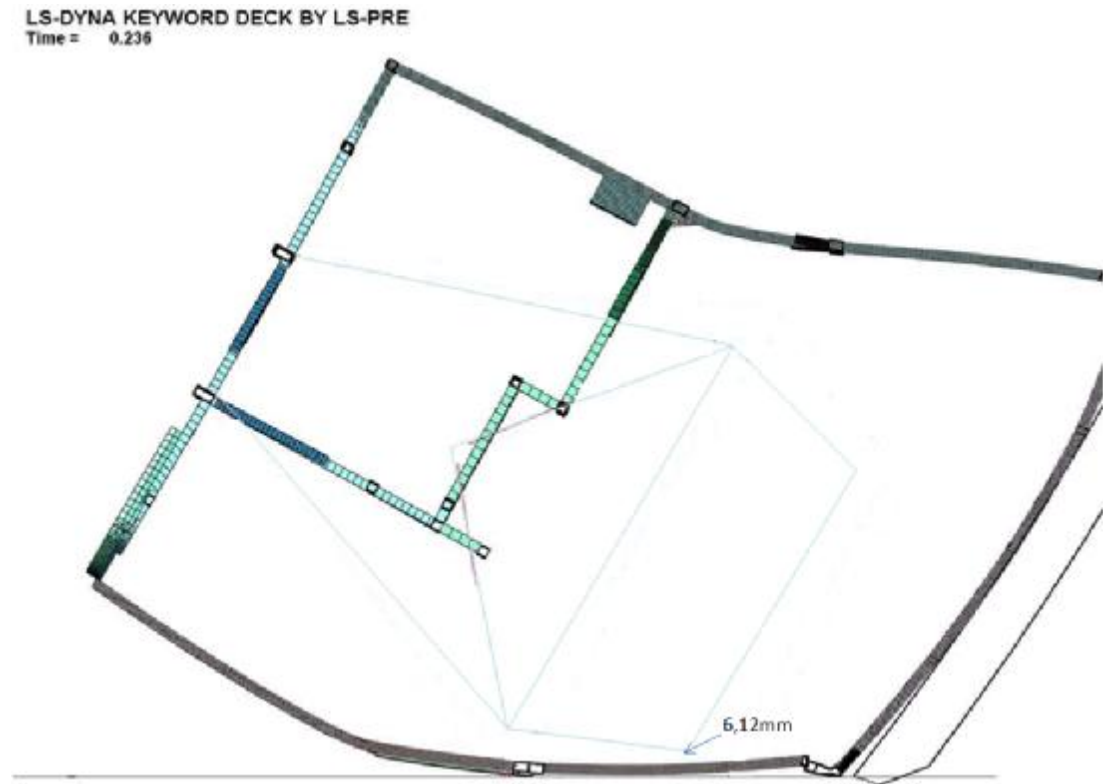


Figure 4.18. Section-4 Result.

Closest distance between the residual space and the side wall profile has been measured as 8,28mm. from Section-5 of the Model-1 as shown in Figure 4.19.



Figure 4.19. Section-5 Result.

Closest distance between the residual space and the side wall profile has been measured as 9,01mm. from Section-6 of the Model-1 as shown in Figure 4.20.



Figure 4.20. Section-6 Result.

Closest distance between the residual space and the side wall profile has been measured as 9,89mm. from Section-7 of the Model-1 as shown in Figure 4.21.

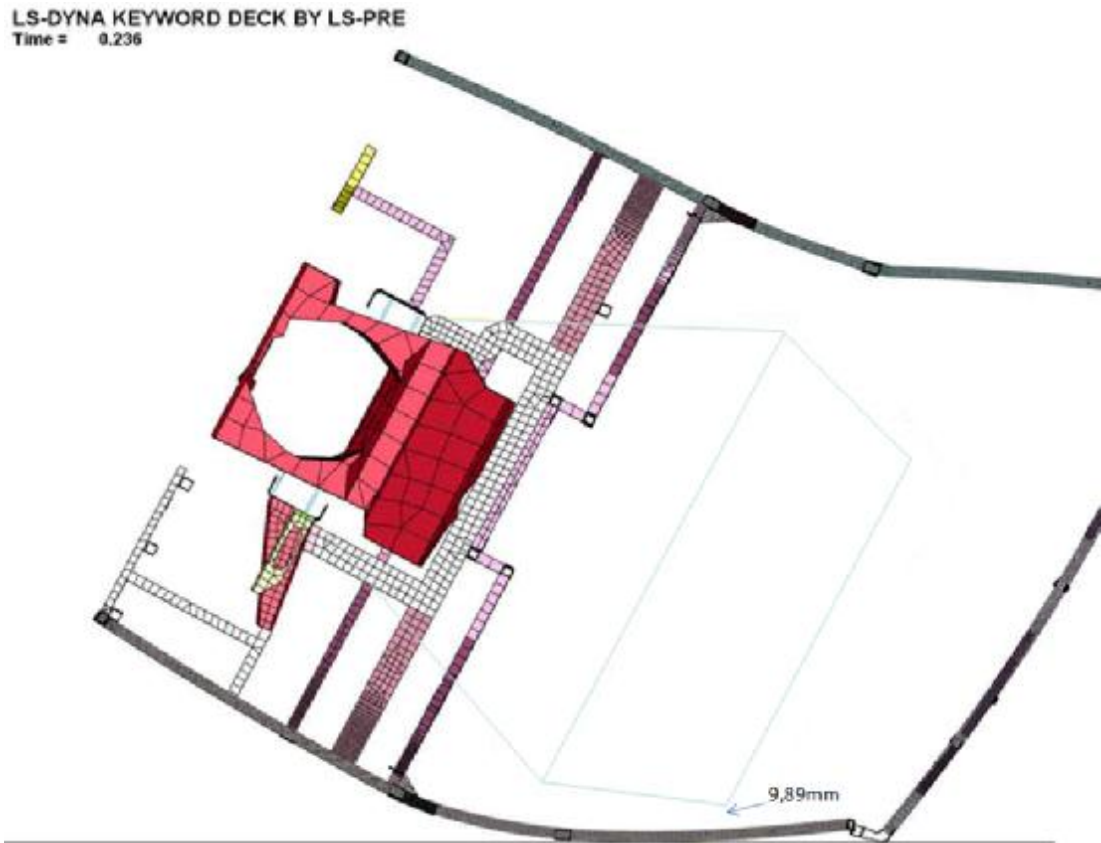


Figure 4.21. Section-7 Result.

Closest distance between the residual space and the side wall profile has been measured as 10,47mm. from Section-8 of the Model-1 as shown in Figure 4.22.



Figure 4.22. Section-8 Result.

4.2. Effects of Foam Application on Vehicle Rollover Analysis

Model-2 will be used for analysing the effects of foam application on vehicle rollover analysis in compliance with ECE-R66 regulation.

4.2.1. Vehicle Rollover Analyse Without Foam Application

In the first analyse the non-commercial vehicle Model-2 will be used without foam application. Rollover analyse has been runned for Model-2 by using SMP

(Shared Memory Parallel) version of LS-DYNA. The sections which results were collected were shown in Figure 4.23.

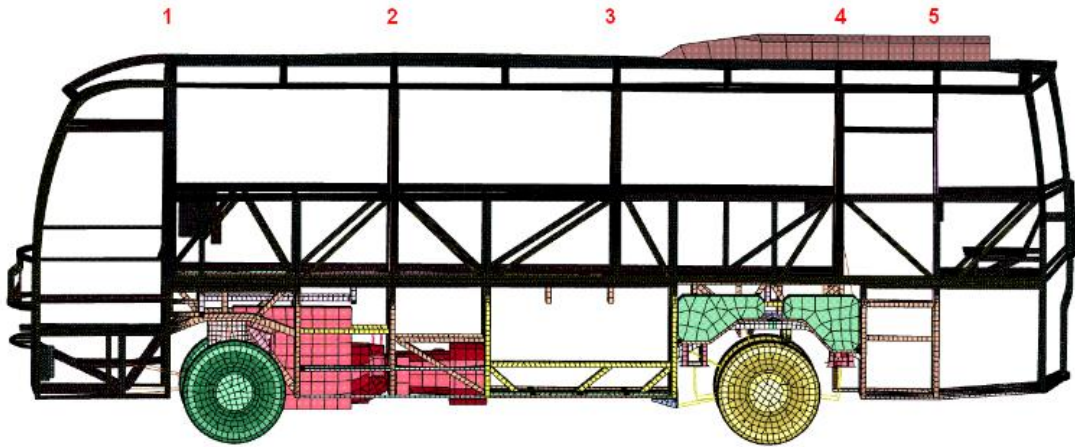


Figure 4.23. Model-2 Sections.

Closest distance between the residual space and the side wall profile has been measured as 2,12mm. from Section-1 of the Model-2 as shown in Figure 4.24.

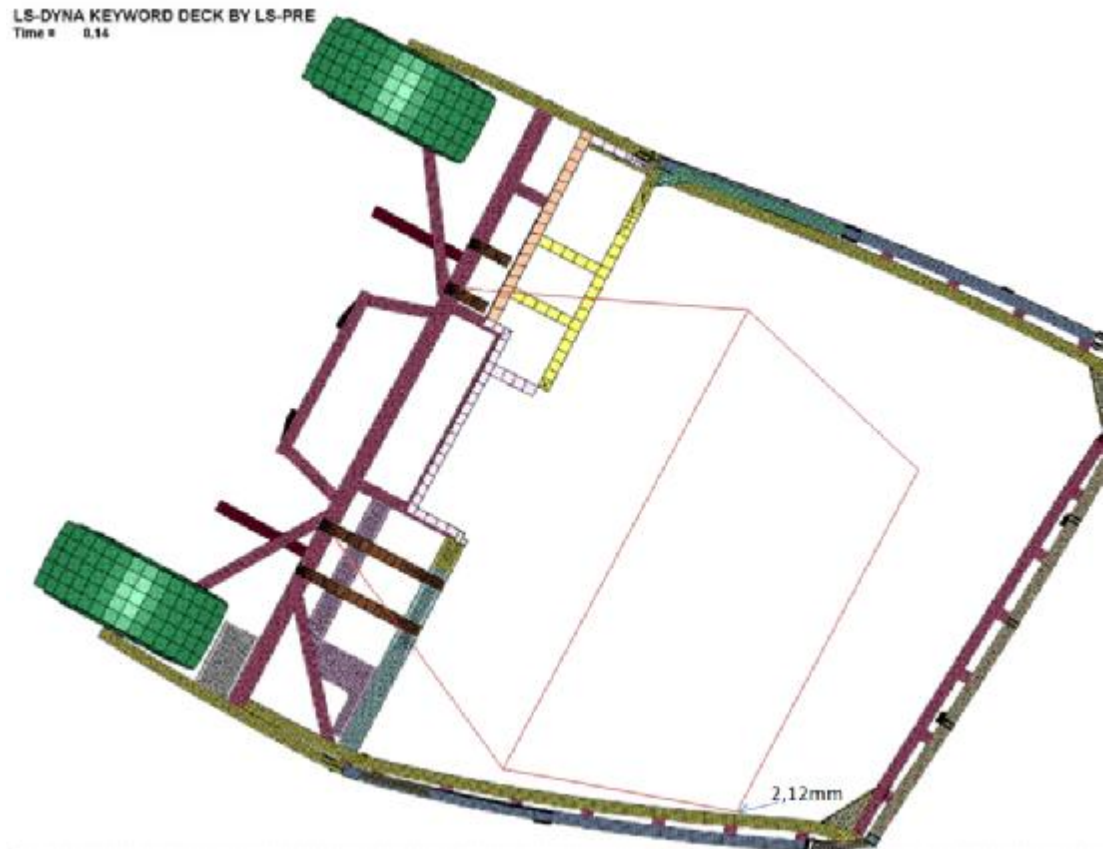


Figure 4.24. Section-1 Result.

Closest distance between the residual space and the side wall profile has been measured as 5,31mm. from Section-2 of the Model-2 as shown in Figure 4.25.

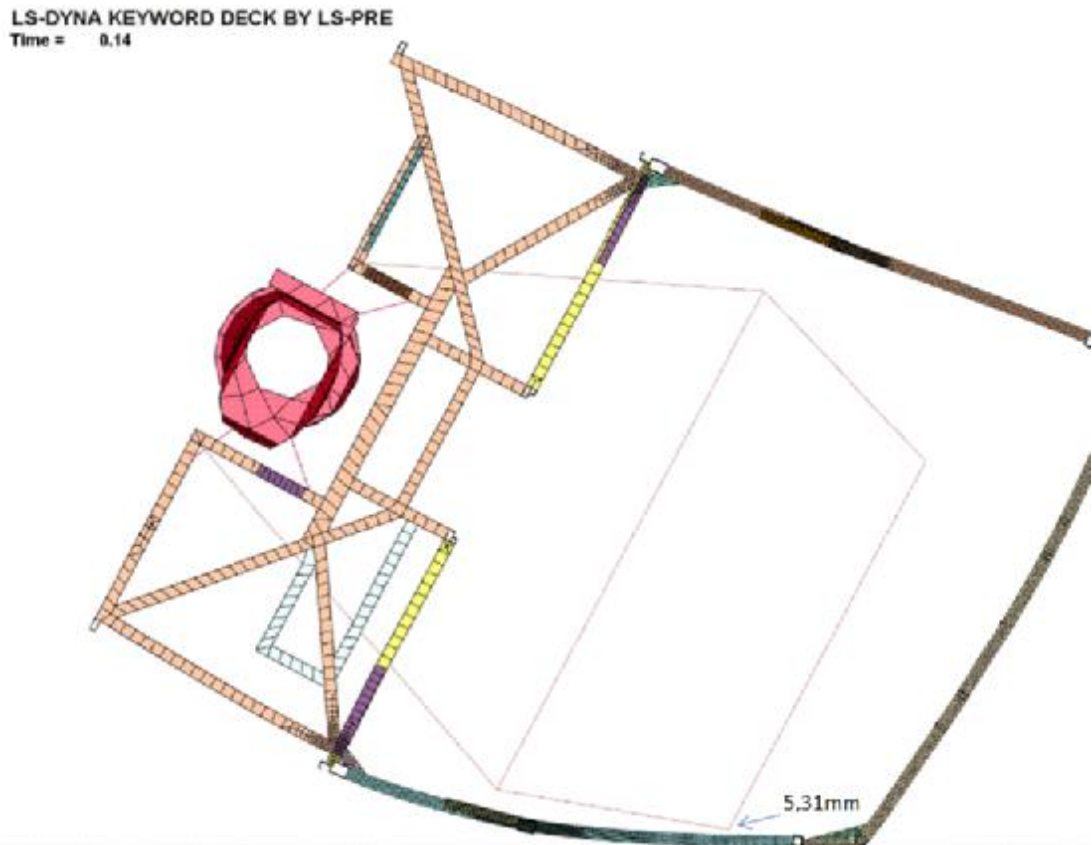


Figure 4.25. Section-2 Result.

Closest distance between the residual space and the side wall profile has been measured as 4,88mm. from Section-3 of the Model-2 as shown in Figure 4.26.

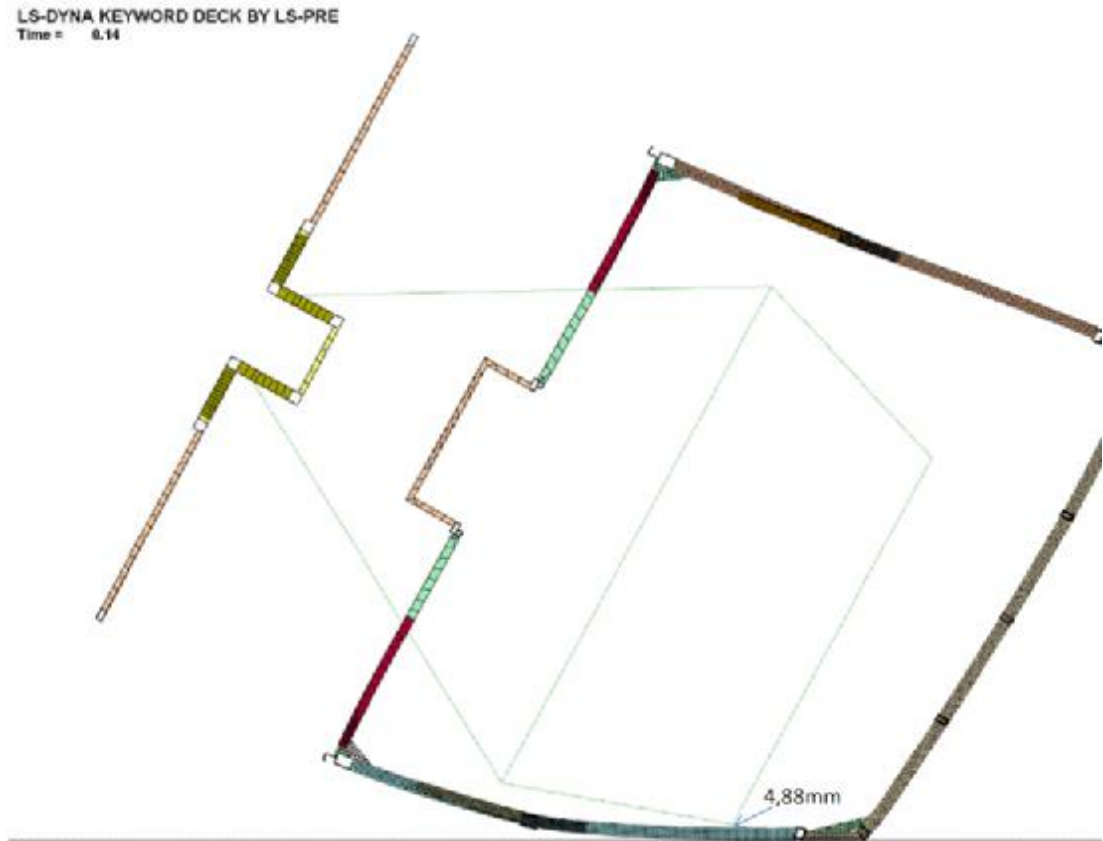


Figure 4.26. Section-3 Result.

Closest distance between the residual space and the side wall profile has been measured as 4,52mm. from Section-4 of the Model-2 as shown in Figure 4.27.



Figure 4.27. Section-4 Result.

Closest distance between the residual space and the side wall profile has been measured as 3,04mm. from Section-5 of the Model-2 as shown in Figure 4.28.



Figure 4.28. Section-5 Result.

4.2.2. Vehicle Rollover Analyse With Foam Application

Non-commercial foam is applied for establishing improvements for the ECE-R66 rollover regulation. Foam has been applied to red sections as shown in Figure 4.29.

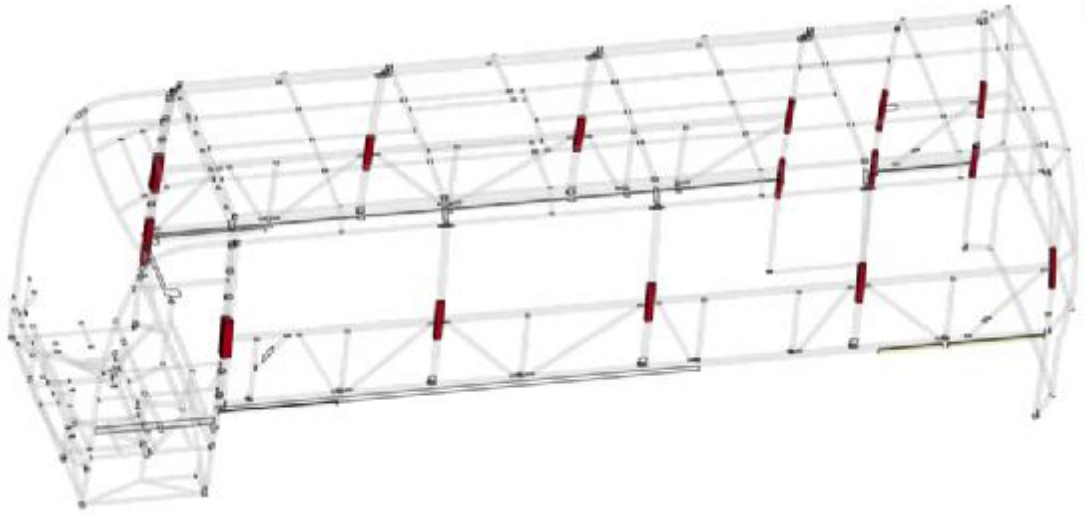


Figure 4.29. Foam application sections.

In the second analyse the non-commercial vehicle Model-2 will be used with foam application. Rollover analyse has been runned for Model-2 by using SMP (Shared Memory Parallel) version of LS-DYNA. The sections which results were collected were shown in Figure 4.30.

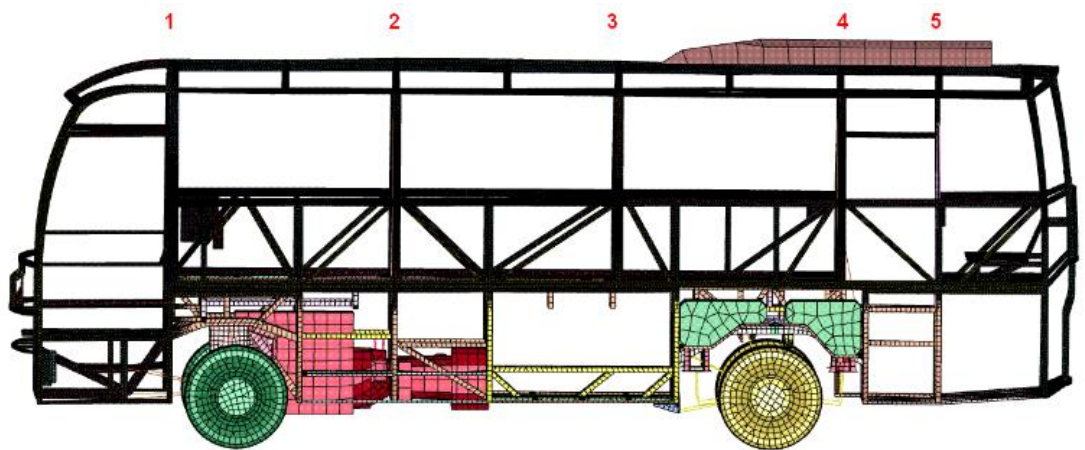


Figure 4.30. Model-2 Sections.

Closest distance between the residual space and the side wall profile has been measured as 3,05mm. from Section-1 of the Model-2 as shown in Figure 4.31.



Figure 4.31. Section-1 Result.

Closest distance between the residual space and the side wall profile has been measured as 6,58mm. from Section-2 of the Model-2 as shown in Figure 4.32.

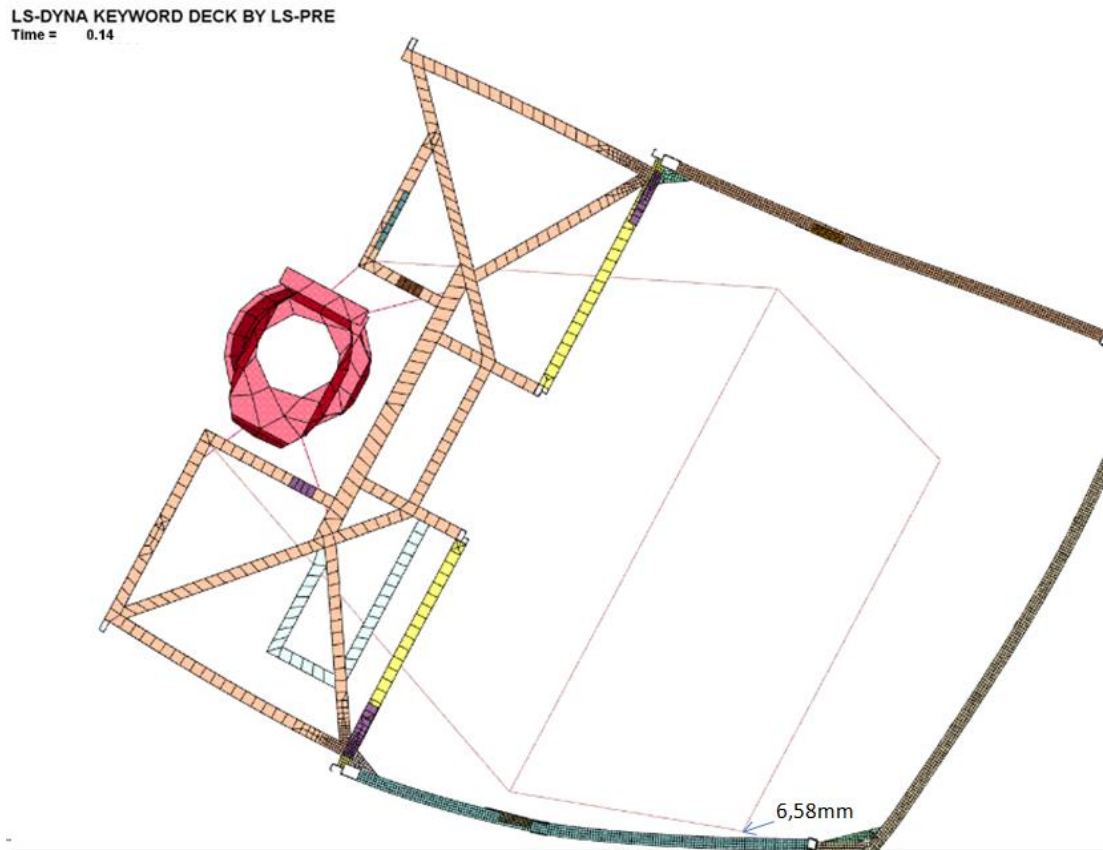


Figure 4.32. Section-2 Result.

Closest distance between the residual space and the side wall profile has been measured as 5,95mm. from Section-3 of the Model-2 as shown in Figure 4.33.



Figure 4.33. Section-3 Result.

Closest distance between the residual space and the side wall profile has been measured as 5,12mm. from Section-4 of the Model-2 as shown in Figure 4.34.



Figure 4.34. Section-4 Result.

Closest distance between the residual space and the side wall profile has been measured as 4,65mm. from Section-5 of the Model-2 as shown in Figure 4.35.



Figure 4.35. Section-5 Result.

5. CONCLUSIONS AND RECOMMENDATIONS

There are two main objectives in this thesis. The first one is analysing the effects of using different types of materials on vehicle rollover analysis. And the second one is analysing the effects of foam application on the vehicle rollover analysis.

For analysing the effects of using different materials on vehicle rollover analysis two analyse has been made with Model-1. In the first analyse St-37 grade steel has been used on side walls of the non-commercial vehicle. And in the second analyse St-44 grade steel has been used on side walls of the same non-commercial vehicle. St-44 grade steel has better mechanical properties than St-37 grade steel which means St-44 grade steel is stronger then St-37 grade steel. This difference directly effects on the rollover analyse results as shown in Table 5.1. The vehicle which St-44 grade steel used on side walls is safer than the vehicle which St-37 grade steel used on side walls during rollover crashes.

Table5.1. Comparison of analyse results for Model-1.

Model-1	Closest Distance Between Residual Space and Side Wall Profile	
	St-37 used on Side Walls	St-44 used on Side Walls
1	1,81mm	4,52mm
2	1,65mm	4,38mm
3	2.95mm	5,45mm
4	3.02mm	6,12mm
5	4,23mm	8,28mm
6	4,81mm	9,01mm
7	5,33mm	9,89mm
8	6,20mm	10,47mm

For analysing the effects of foam application on vehicle rollover analysis two analyse has been made with Model-2. In the first analyse no foam applied on the steel sections of the non-commercial vehicle. And in the second analyse foam application made on the specified sections. Foam application increases the impact absorption of the steels which they applied. This property directly effects on the rollover analyse results as shown in Table 5.2. The vehicle which foam applied on the specified sections is safer than the vehicle without foam application.

Table5.2. Comparison of analyse results for Model-2.

Model-2 Section	Closest Distance Between Residual Space and Side Wall Profile	
	Without Foam Application	With Foam Application
1	2,12mm	3,05mm
2	5,31mm	6,58mm
3	4,88mm	5,95mm
4	4,52mm	5,12mm
5	3,04mm	4,65mm

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