ÇUKUROVA UNIVERSITY

INSTITUTE OF NATURAL AND APPLIED SCIENCES

MSc THESIS

Deniz GÖYDENİZ

COMPUTER SIMULATION OF ROLLOVER TEST OF A CATEGORY M3 VEHICLE SUPERSTRUCTURE USING DYNAMIC ANALYSIS SOFTWARE ACCORDING TO UNECE REGULATION NO 66.02

DEPARTMENT OF AUTOMOTIVE ENGINEERING

ADANA, 2022

ABSTRACT

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Year: 2022, Pages: 57
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Rollover is one of the most dangerous and fatal vehicle accident. Therefore, vehicle manufacturers must be sure about the strength of the superstructure of vehicles they produce to guarantee passenger safety. Because of these reasons the regulation UNECE R66 was first released in 1997.

In this study, the strength and structural behavior of a M3 category bus in a rollover accident was simulated to appraise the vehicle superstructure resistance and passenger injury risks. Aforementioned virtual rollover simulation analysis was carried out according to safety regulation of UNECE (The United Nations Economic Commission for Europe) Regulation number 66.02.

Keywords: Vehicle Rollover, UNECE R66, Strength of Vehicle Superstructure, Virtual Rollover Analysis of Vehicle, Category M3 Vehicle Rollover, Bus Rollover, Finite Element Analysis

ÖZ

YÜKSEK LİSANS TEZİ

UNECE R66.02 REGÜLASYONUNA GÖRE DİNAMİK ANALİZ YAZILIMINI KULLANARAK YAPILAN M3 KATEGORİ ARAÇ ÜST YAPISININ DEVRİLME TESTİNİN BİLGİSAYAR SİMÜLASYONU

Deniz GÖYDENİZ

ÇUKUROVA ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ
OTOMOTİV MÜHENDİSLİĞİ ANABİLİM DALI

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Devrilme en tehlikeli ve ölümcül araç kazalarındandır. Bu nedenle araç üreticileri, yolcu güvenliğini garanti altına almak için ürettikleri araçların üst yapısının sağlamlığından emin olmalıdır. Bu nedenlerden dolayı UNECE R66 yönetmeliği ilk olarak 1997 yılında yayınlanmıştır.

Bu çalışmada, aracın üst yapısının direncini ve yolcu yaralanma risklerini değerlendirmek için M3 kategorisindeki bir otobüsün devrilme kazasında mukavemeti ve yapısal davranışı simüle edilmiştir. Söz konusu sanal devrilme simülasyonu analizi, UNECE (Birleşmiş Milletler Avrupa Ekonomik Komisyonu) 66.02 numaralı yönetmeliğinin güvenlik yönetmeliğine göre yapılmıştır.

Anahtar Kelimeler: Araç Devrilmesi, UNECE R66, Araç Üst Yapısının Dayanma Gücü, Sanal Araç Devrilme Analizi, Kategori M3 Araç Devrilmesi, Otobüs Devrilmesi, Sonlu Eleman Analizi

GENİŞLETİLMİŞ ÖZET

Her gün birçok insan, istedikleri yere gitmek için otobüse biner. dünyada birçok devrilme kazası meydana gelmektedir. Araç üreticilerinin yolcuların güvenliği konusunda daha fazla dikkat etmesi gerekmektedir.

Otobüs devrilmeleri hakkında teknik olarak açıklayıcı kayıtları elde etmek çok zor olabilir. Bu olayları inceleme ve bildirme kapasitesine sahip herhangi bir kuruluş yoktur, dolayısıyla kazalar kategorileştirilip yıllık verilere yansıtılmıyor. Yıllık toplanan veriler motorlu araçların tamamı için olup, otobüsler için kaza sütunu ve satırı oluşturulur. Burada, her türlü otobüs kazalarının toplam miktarını ve tüm ölüm ve yaralanma sayılarını gösterir. Dolayısıyla ayda veya yılda kaç otobüs kazasının kaç tanesi devrilme kazası kesin olarak bilinemiyor. Medya raporları, fotoğraflar, polis ve devlet açıklamaları ve bilir kişi açıklamalarına dayanarak veriler toplanmaya çalışılıyor.

Devrilme kazalarında ölüm oranları yüksek olduğu için birçok ülke ve araç üreticisi devrilme kazalarının nasıl azaltılabileceğini araştırmak için üretim süreçlerini ve bu otobüslerin araştırma ve geliştirmelerini daha detaylı değerlendirmeye başlamıştır. Bu değerlendirmelerin bazıları sonucunda UNECE R66 regülasyonu ortaya çıkmıştır (1997).

Otobüs devrilme analizinin araç üreticileri, yerel yönetimler ve toplu taşımada güvenlik denetimi için çok önemli bir değere sahip olmasının birçok nedeni vardır. Her şeyden önce sanal devrilme analizi, aracın devrilme durumunda kendi kendine yardım edip edemeyeceği, bu hasara dayanıp dayanamayacağı, yolculara verilen zararı detaylıca incelemeyi ve bu değerleri araştırıp geliştirmeyi sağlayan en önemli yöntemdir.

Bir otobüsün devrilme boyunca böyle bir etkiye direnme kabiliyetini ve bu tür bir senaryonun meydana gelme olasılığını bilerek, üretici, mevcut tasarımlarda herhangi bir iyileştirme yapılması gerekip gerekmediğine karar verebilir. Bu

geliştirmeler, güvenlik önlemleri artışlarından, yapısal değişikliklerden veya yapısal güçlendirmeden oluşabilir.

Sanal araç devrilme analizlerini gerçekleştirmek için birçok bilgisayar programı mevcuttur. Bu çalışmada araç CATİA V5 programı ile modellenmiştir, geometrik modelleme, geometri kontrolleri ve mesh işlemleri için de MSC Apex program kullanılmıştır.

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1. INTRODUCTION

In this study, a superstructure of a vehicle was modelled with the software CATIA to carry out required inspections and roll over test according to UNECE Regulation No. 66

Every day, many people take the bus to go where they need to go. Simultaneously, many rollover accidents happen in the world. Because of this reason there is a need for increased caution of their safety.

As a result of a great number of rollover accidents with high death amounts in each accident, many countries and vehicle producers have started evaluating production processes and research and development of these buses to search how rollover accidents can be decreased.

It can be very hard to get technically explanatory records regarding to vehicle roll-overs. There isn't any affiliation and/or organization that's handling, which has the capacity to acquire and report those facts. The statistical annuals comprise one column for buses (amongst motor vehicles), which offers the entire quantity of all sorts of bus injuries and the entire quantity of deaths and injuries. These facts do now no longer assist humans to apprehend technical information of a varieties of a coincidence (consisting of rollover, crash etc.), their seriousness.

Table 1.1. Summary of rollover statistics(https://unece.org/DAM/trans/doc/2003/wp29grsg/TRANS-WP29-GRSG-85-inf01r1e.pdf, September 2021)

Summary of rollover statistics	1990-1999	01.01.2000 01.03.2001	01.03.2001 31.07.2002	01.08.2002 31.12.2002	01.01.2003 31.08.2003	**Σ (I –V)**
Number of accidents	23	23	51	20	40	157
Number of countries affected	min.15	min.15	min.26	min.14	min.22	min.48
Total number of:						
- Deaths	238	254	519	170	534	1726
- Serious injuries	103	107	94	56	112	492
- Light injuries	122	123	170	47	59	525
- Injuries without classification	197	122	189	160	360	1028
- Reported “many injuries”	2 times	1 time	6 times	1 time	5 times	15 times
Type of rollover (seriousness)						
- Turned on side	4	2	5	5	4	19
- Rolled over from the road	13	12	18	7	16	67
- Serious rolled over	3	6	9	3	12	33
- Combined accident	3	3	19	5	8	38

Category of the bus rolled over						
- Class I. (city, suburban)	2	2	2	-	1	7
- Class II (intercity, local)	-	2	2	-	4	10
- Class III (tourist, long-distance)	18	10	20	9	14	71
- Small bus	-	2	9	8	11	30
- Double decker	2	2	1	-	3	8
- School bus	-	1	2	-	2	5
- Other (worker, etc.)	-	1	4	-	-	5
- Unknown	1	3	9	3	5	21
Damage of superstructure						
- Serious damage	4	5	6	9	7	31
- Slight damage	5	5	11	7	6	34
- No information	14	13	34	4	27	92

Table 1.2. Examples of rollover accidents (https://unece.org/DAM/trans/doc/2003/wp29grsg/TRANS-WP29-GRSG-85-inf01r1e.pdf, September 2021)

	City, Country	**Bus type, Category, Operator**	**Conditions and reasons (if known) of roll-over**	**Deaths and injuries**
1	Izabella Philippines	School-bus regional operator	The vehicle got out of the road, crash into a three then rolled over into water. Reason: The vehicle was over-loaded	12 deaths, plenty of injuries
2	Catamarca Argentina	Class III coach vehicle, regional operator	The vehicle was drugged from the road and rolled-down into 30 meters deep cliff. There were 62 passengers in the vehicle.	49 deaths, 14 injuries
3	Kirganga India	Class III coach vehicle, regional operator	The vehicle got out of its way and rolled-over into a river	30 deaths, 16 injuries
4	San Vincente Philippines	Class III coach vehicle, regional operator	The vehicle got out of its way then rolled-down into a 30 meters deep canyon. Reason: Driver fell asleep	33 deaths, 6 major injuries
5	Madjha Prades India	Class III coach vehicle, regional operator	The vehicle rolled-over and burned. Backup fuel bottles were positioned behind the driver's seat.	30 deaths, 27 injuries
6	Petronell Bad Austria	Class III coach vehicle, regional operator	Frozen road, the vehicle slid and rolled over to its side	Only minor injuries
7	Taltenango Mexico	Intercity class III bus,	Rocky road, the breaks did not	18 deaths,

		regional operator	function, the fast vehicle changed the lane and then rolled-down into a deep cliff	22 major injuries
8	Morone Santiago, Equator	Class III coach vehicle, regional operator	Rocky road, the vehicle went ahead of another vehicle, but slid on the road then rolled-down into a 200 meters deep cliff	12 deaths 27 injuries
9	Yuunan China	School bus, regional operator	Rocky road, the vehicle drugged in a bend, hit the barriers, rolled-down into a river	17 deaths, 1 major injury, 9 lost people
10	Murau (Steier) Austria	Midibus, regional operator	Midibus slid on the frozen road then rolled-over. There were 3 passengers in the vehicle	2 deaths
11	Poland	Class III vehicle, tourist coach, high decker, regional operator	Normal road, the driver was pensive, the vehicle bumped to rear of a truck, got out of its was and rolled-over.	1 death (driver), few minor injuries
12	Plovdiv-Szófia, Bulgária	Class III vehicle, tourist coach, high decker, Turkish operator	Vehicle hit the barriers of motorway and rolled-down into a 40 meters deep canyon.	5 deaths, plenty of injuries
13	Fagersta, Sweden		Vehicle slid, got out of its way and rolled-over	6 deaths, 4 major injuries, 23 minor injuries
14	Katmandu, Nepal	Class III Coach vehicle, regional operator	Vehicle got out of its way then rolled-down into a canyon.	13 deaths, 30 injuries

15	Near to Vietnam borderline, China	Midibus, regional operator	There were 34 passengers in the midibus (the maximum capacity of the midibus was 12) The driver lost the control of the vehicle and then the midibus rolled-into 40 meters deep valley	18 deaths, 16 injuries
16	Goré, Hungary	Class II vehicle	Frozen road, the vehicle slid then rolled-down into a trench on its side.	3 major injuries, 4 minor injuries
17	Himalaja, Nepal		Vehicle rolled-down into a cliff.	23 deaths, 31 injuries, 20 passengers lost
18	Saloniki, Greece	Class III Coach vehicle, high decker, regional operator	Vehicle rolled-down from a viaduct into a river nearly 10 meters height. There were 23 people in the vehicle.	13 deaths, 6 injuries, 4 passengers lost
19	Kaplice, Czech Republic	Class III vehicle, tourist coach, high decker, regional operator	There were 70 passengers in the vehicle. Firstly, the vehicle hit the right barriers, rolled down on its left side.	19 deaths, 27 major injuries, 10 minor injuries
20	Miskolc, Hungary	Minibus (ambulance), regional operator	Minibus with patients, slid then rolled-over.	2 major injuries, 5 minor injuries
21	Nyírpozsony, Hungary	Minibus (ambulance), regional operator	Slippy way because of snow, the vehicle rolled-over.	2 injuries
22	Quito, Alog Equador		Vehicle got out of the rocky road then rolled-down into a	26 deaths, 17 injuries

			150 meters deep canyon.	
23	Nagybátony, Hungary	Class II vehicle	The driver was fainted. The bus rolled over on its side because of the sidewalk	2 major injuries, 6 minor injuries
24	Mezőkövesd, Hungary	Minibus, Ukrainian operator	The vehicle hit the barriers of highway. There were 4 passengers in the vehicle. Reason: Driver fell asleep.	1 death 2 injuries
25	Tembi valley, Greece	Class III vehicle, tourist coach, high decker, regional operator	Highway with hills, logs of wood fell down from a truck, the vehicle hit a log and then hit other vehicles before rolled over	24 deaths 30 injuries



Figure 1.1. Rollover Accident

To guarantee passenger safety, bus producer companies are being required to meet hard bus rollover standards with careful tests and analysis.



Figure 1.2. Rollover Accident 2



Figure 1.3. Rollover Accident 3

There are many reasons why bus rollover analysis has crucial value for vehicle manufacturers, local governments, and safety oversight in public transportation. First of all, it allows to determine whether the vehicle might be capable of help itself withinside the case of rollover or not.

By knowing the ability of a bus to resist such an effect all through the rollover, and the possibility that this kind of scenario might occur, the producer could make a decision if there are any enhancements are required to existing designs. These enhancements may consist of safety measures increases, structural changes, or structural strengthen.



Figure 1.4. Rollover Accident 4



Figure 1.5. Rollover Accident 5

The main goals of this test are reducing the quantity of accidents the ones arise every year, saving lives, and enhancing entire passenger protection. Vehicle producers will be able to incorporate safety measures they recognize will work primarily based totally on those tests, enhancing overall performance and protection whilst keeping operational costs. This test facilitates vehicle producers with saving money and time which each are very important for them.

The superstructure of the vehicle must have enough strength to guarantee that the residual area during and after the rollover test on the complete vehicle is undamaged. According to this explanation;

Parts which are outside of the residual area at the beginning of the test (e.g. pillars) should not penetrate into the residual area during the test. Any structural parts, which are already in the residual area (e.g. handholds, partitions) should be ignored while calculating the penetration into the residual area.



Figure 1.6. Physical rollover Test

No part of the residual area should project outside of the damaged body. The outline of the damaged body should be determined separately, among every neighboring windows and door pillars.

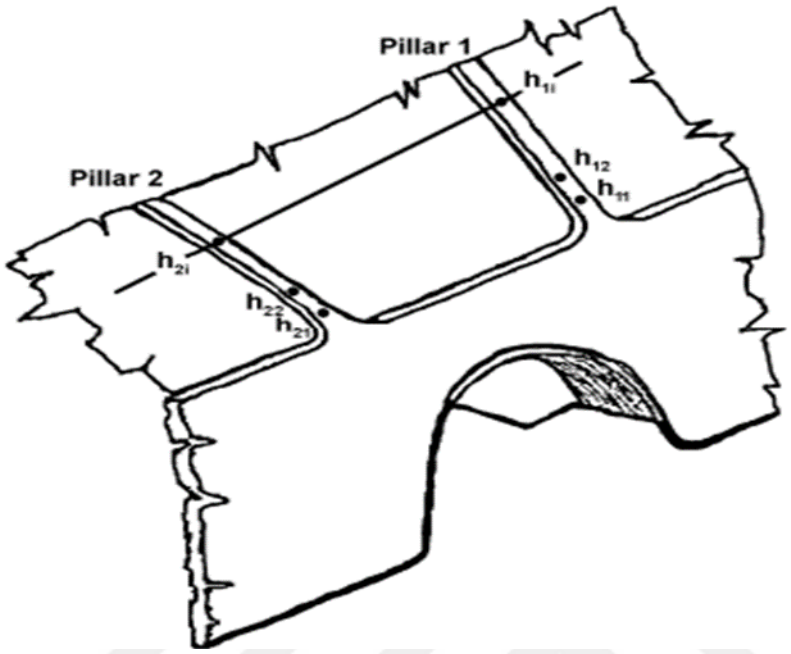


Figure 1.7. Pillars

The regulation ECE R66 must be applied to single deck rigid or articulated, incomplete, complete and completed vehicles these are designed and used for the transporting of greater than twenty-two passengers, either seated and/or standing, besides the driver and crew.

In different words; In accordance with the scope of this regulation must be applied to single deck rigid or articulated vehicles belonging to vehicle categories M2, M3, classes II, III, B having greater than sixteen passengers.

On demand of the vehicle producers, this regulation can be also applied to any other classes of M2 or M3 category vehicles which is not specified withinside the paragraph above.

2. TERMS AND DEFINITIONS:

Articulated vehicle: Is a motor vehicle which contains 2 or greater rigid sections which articulate to one another, the passenger compartments of every section intercommunicate so people can pass freely amongst them; the rigid sections are permanently connected so they can only be separated via an operation a workshop.

Residual area: Is an area in the passenger, crew and driver's compartments to provide better survival possibility for them in case of a roll-over accident.

Incomplete vehicle: Is a motor vehicle that must be processed at least 1 more stage of production in order to fit the necessary technical requirements of regulations.

Complete vehicle: Is a motor vehicle that does not need to be completed in order to fit the necessary technical requirements of regulations.

Completed vehicle: Is a motor vehicle resulting from the multi-stage type-approval that fits the necessary technical requirements of regulations.

Category M1: Motor vehicles with not greater than 8 seats besides the driver's seat and without area for standing people.

Category M2: Motor vehicles with greater than 8 seats besides the driver's seat and having a maximum weight not overrunning five tons, disregarding of whether those motor vehicles have area for standing people.

Category M3: Motor vehicles with greater than 8 seats besides the driver's seat and having a maximum weight overrunning five tons, disregarding of whether those motor vehicles have area for standing people.

Class I: Motor vehicles produced with area for standing people, to permit them to move.

Class II: Motor vehicles produced in particular for the transportation of seated passengers, and designed to permit the transportation of standing people withinside the gangway and/or in a place that does not exceed the area supplied for 2 double-seats.

Class III: Motor vehicles produced only for the transportation of seated people.

• For motor vehicles having capacity not greater than 22 people besides the driver, there are two classes of these vehicles:

Class A: Motor vehicles designed to transport standing people; a vehicle of this class has seats and should have provision for standing people.

Class B: Motor vehicles not designed to transport standing people; a vehicle of this class has no provision for standing people.

3. MATERIALS AND METHODS

LS-DYNA software was used to perform the virtual simulation analysis.
Vehicle rollover simulation test processes:

– Tensile tests

– Preparation of Test Vehicle

– Test methods

– Vehicle selection (Worst Case)

– Residual area

– Geometric modeling (Geometry Check)

– Meshing

– Load and material assignments, determining CoG (Centre of Gravity)

– Run process in LS-DYNA

– Obtaining value

Deformable body is assigned as “MAT Type 24, piecewise linear isotropic plasticity model”. This is an elastic plastic material model which uses the youngs modulus if stresses are below the yield stress and the measured stress – strain curve.

Rigid parts are assigned as “MAT Type 20, rigid material”. This material has no contribution to the stiffness.

Passenger masses (Element Point Mass) are connected on the structure by the rigid truss elements according to screw holes. There is no connection between side walls. So, they are not additional reinforcements to the strength of the superstructure.

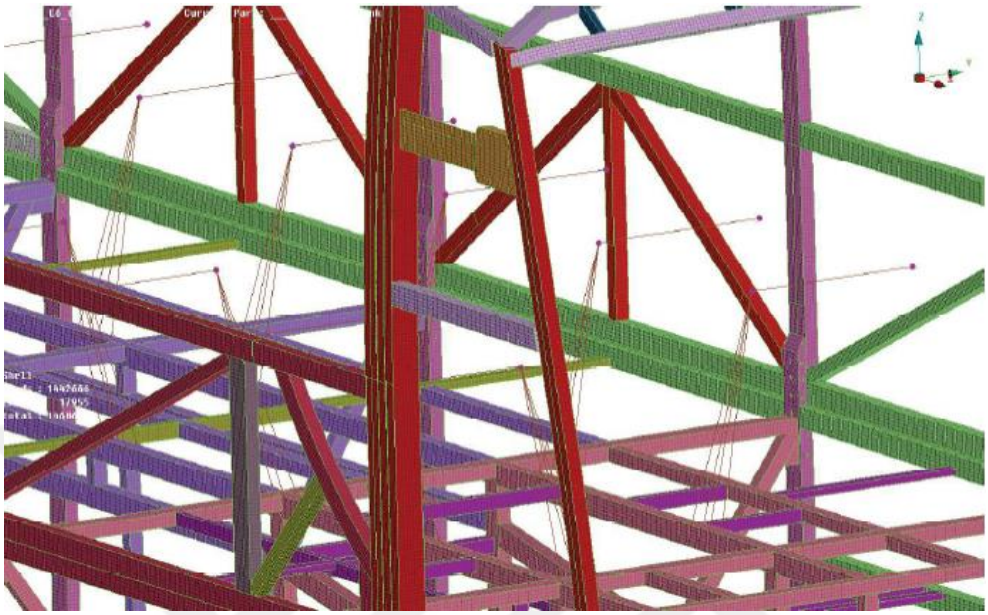


Figure 3.1. Passenger mass nodes (points)

3.1. Tensile Tests

Tensile tests are one of the most important and useful mechanical tests due to its capability to measure many material characteristics in a single test. The obtained values from tensile tests are usually used for; determining properties for developing new materials, certifying the quality of materials, referencing material properties and giving ideas to designers. This test is used along the various fields of manufacturing and industries, from metal manufacturers to plastic or composite manufacturers in industries such as automotive, iron and steel and more.

The tensile test is mostly carried out of a bone and dumbbell shaped metal sample that is either flat or round. The sample must be produced with the suitable ends to avoid any slippage of the tensile test device. After all, the sample will be ready to be mounted to the test device, pulled from the both ends with a constant rate until the sample is fractured into two pieces. Sudden stress which means load divided by the original cross sectional area, and strain (tension) which means post test sample length divided by the pre test sample length are recorded nonstop. A load cell device

is used to measure the load, an extensometer device fixed to the sample is used to measure the length.

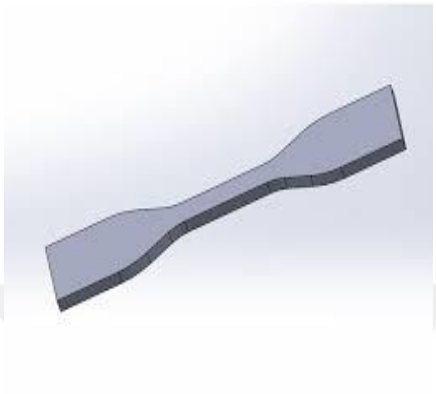


Figure 3.2. Flat sample



Figure 3.3. Round sample

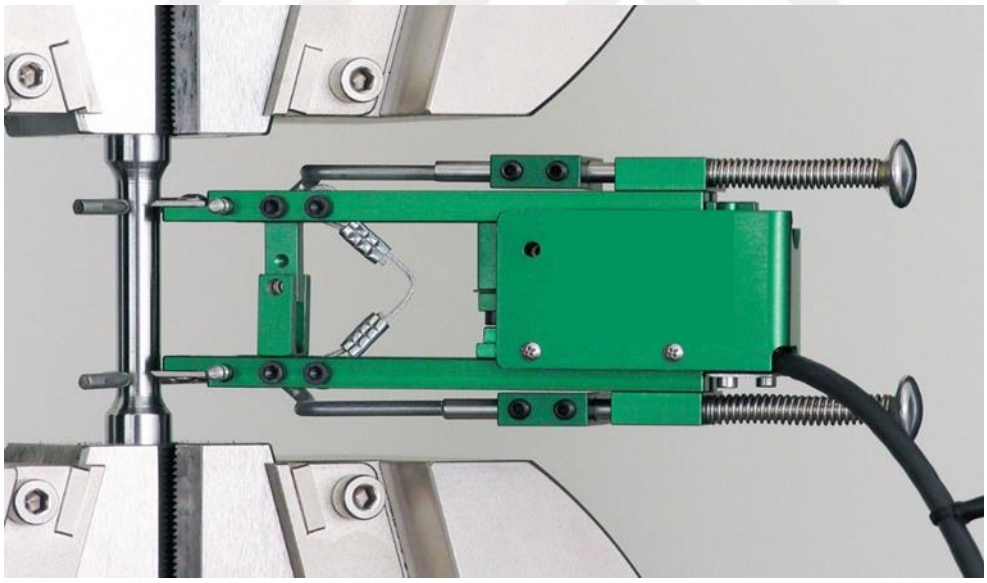


Figure 3.4. Example of tensile test setup (Epsilon)

At first, stress and strain change at rates that are proportional to each other, producing a linear graph when plotted on X and Y axes. The slope of the linear section of the tensile curve is called as stiffness or modulus of that material.

At a point, strain starts to rise faster than stress; at that point, the material has achieved to its corresponding limit. If the sample were unloaded, it would be found to be longer than its pre test length. When the change in length achieves a specific point (i.e., 0.2% of its pre test length), the test has achieved to its offset yield strength. The test continues until the sample breaks. (https://rtilab.com/analytical-services/materials-testing-division/tensile-testing/, November 2021)

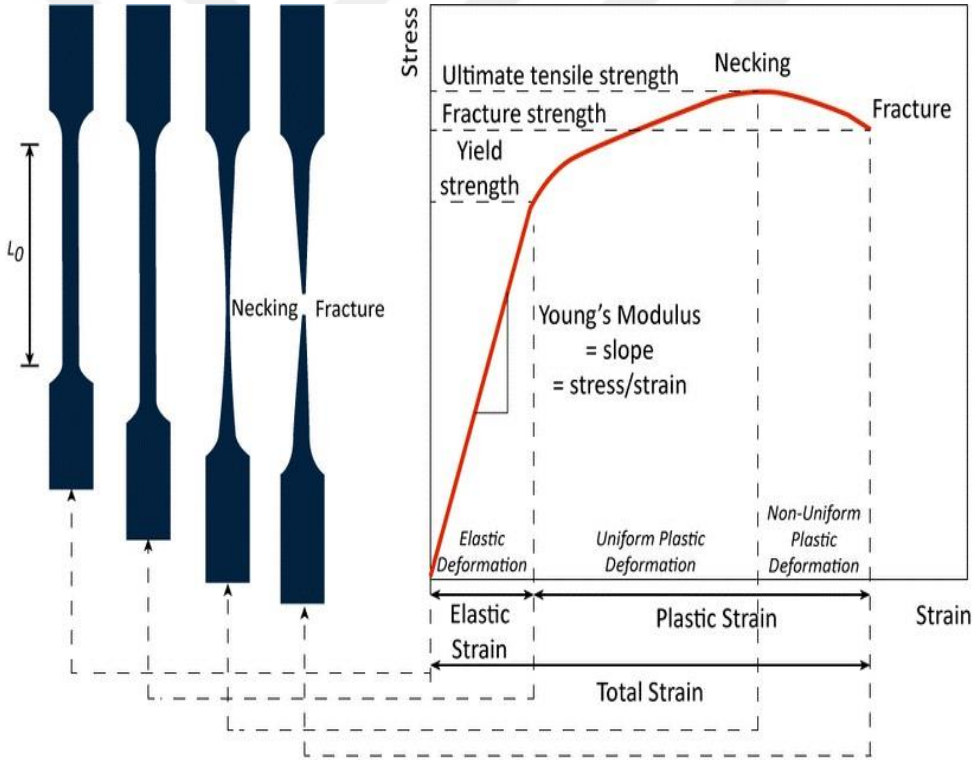


Figure 3.5. Graphic of tensile test (https://imechanica.org/node/21939, November 2021)

The maximum stress obtained during the test is the material's ultimate tensile strength. The elongation is the permanent change in length or deformation of the sample as measured from notches or punch signs located in the middle of sample before the test or from the extensometer's data for plastic strain at break. The change in cross sectional area from the pre test area to the area after break is called as the reduction in the area. Elongation and reduction in areas are a measure of a softness of material.

Material specification values obtained from tensile test was assigned one by one to vehicle's body profiles and plates. S420 steel material was used for this bus. Properties of S420 steel, for profiles and plates are given in the table below, obtained from the tension test results (True stress – true strain, strength – position).

Material curves used for the body steel were calibrated towards the physical joint test. The yield stress used for tube parts in the FE-model (Finite elements model) is σy = 516 Mpa (yield stress). The yield stress used for plate parts is σy = 120,16 MPa. Tube parts have Young's Modulus (E) value is 19500 MPa, this value is 12870 MPa for plate parts.

Ultimate tensile strength values are quite close; for tube parts this value is 566 Mpa, for plate parts this value is 562,42 Mpa. Both material models are linear with υ= 0,3 (Poisson's ratio in elastic range) up to this point.

Table 3.1.. Material data used for the complete bus

Part	**Material**	**E [GPa]**	**υ**	**σ_y [MPa]**	**σ_{UTS} [MPa]**
Tube (Profile)	S420	19,50	0,3	516	566
Plate (Sheet metal)	S420	12,87	0,3	120,16	562,42

Table 3.2. Material specifications used in the finite elements model (FEM)

Part	**Material**	**ρ [kg/m^3]**	**Young's modulus [GPa]**	**υ**	**Yield stress [MPa]**
Body steel (40x40x3 mm and 40x60x2 mm tube profiles)	Steel	7850-57000	19,50	0,3	516
Body steel (5 mm plate)	Steel	7800	12,87	0,3	120,16
Residual area	Steel	7850	21	0,3	-

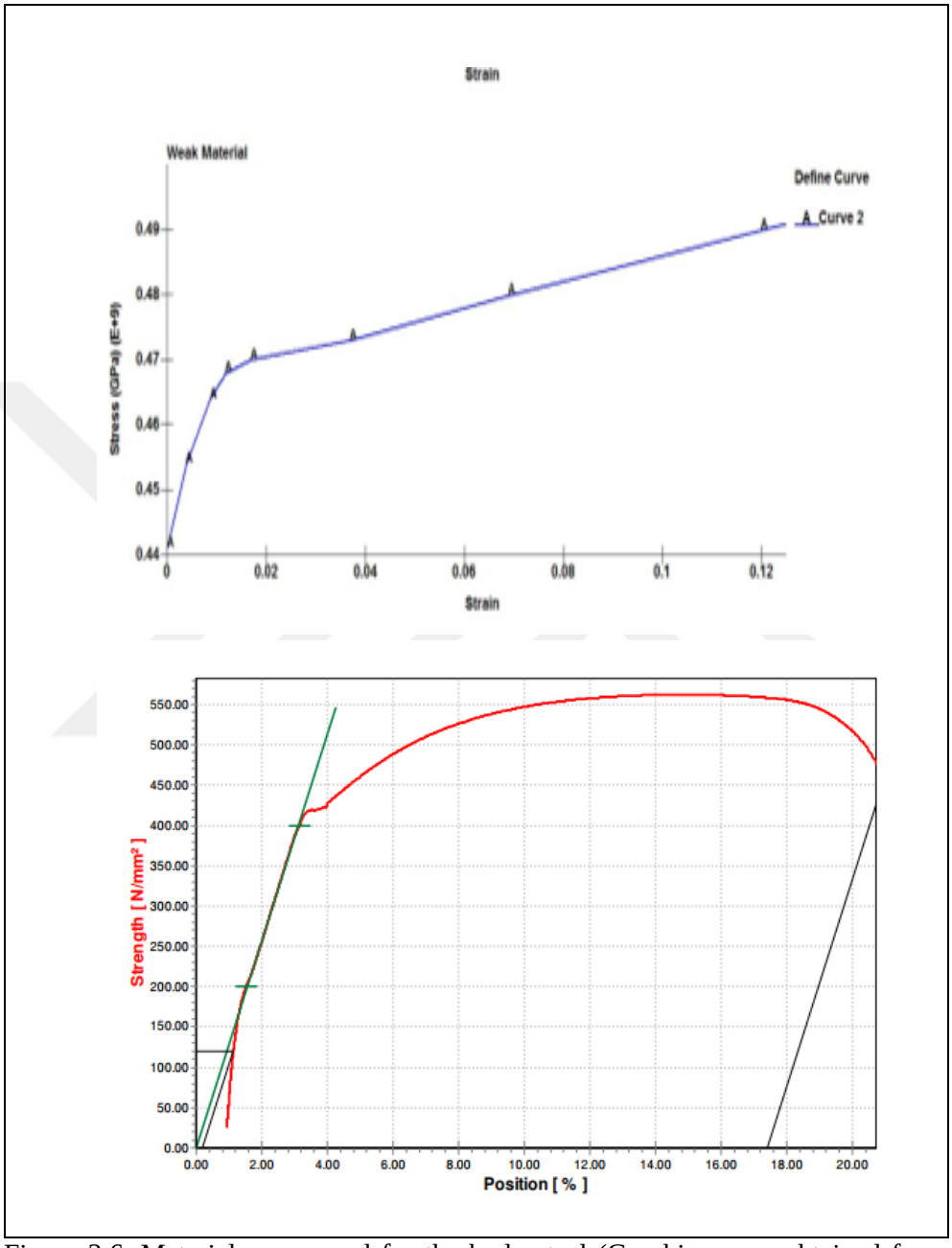


Figure 3.6. Material curve used for the body steel (Graphics were obtained from tensile test)

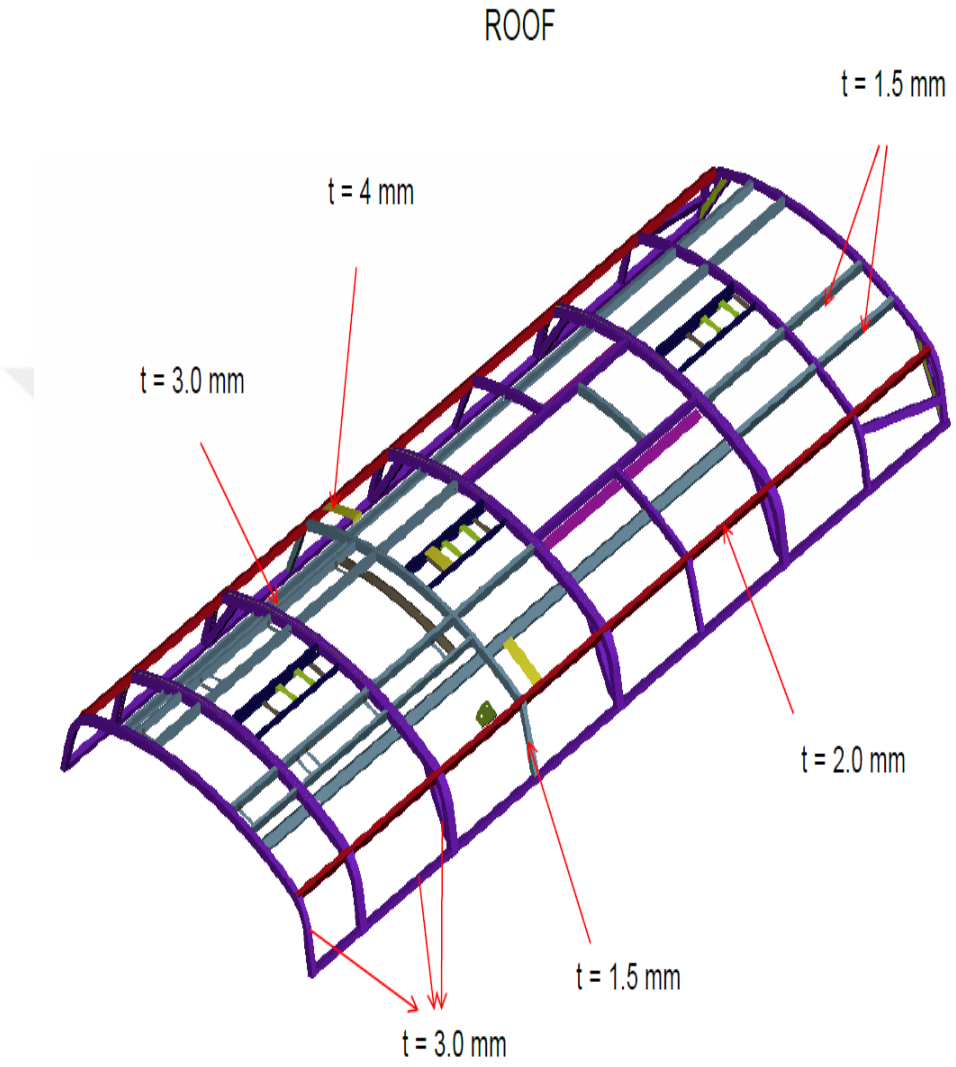


Figure 3.7. Thicknesses of the roof (sample)

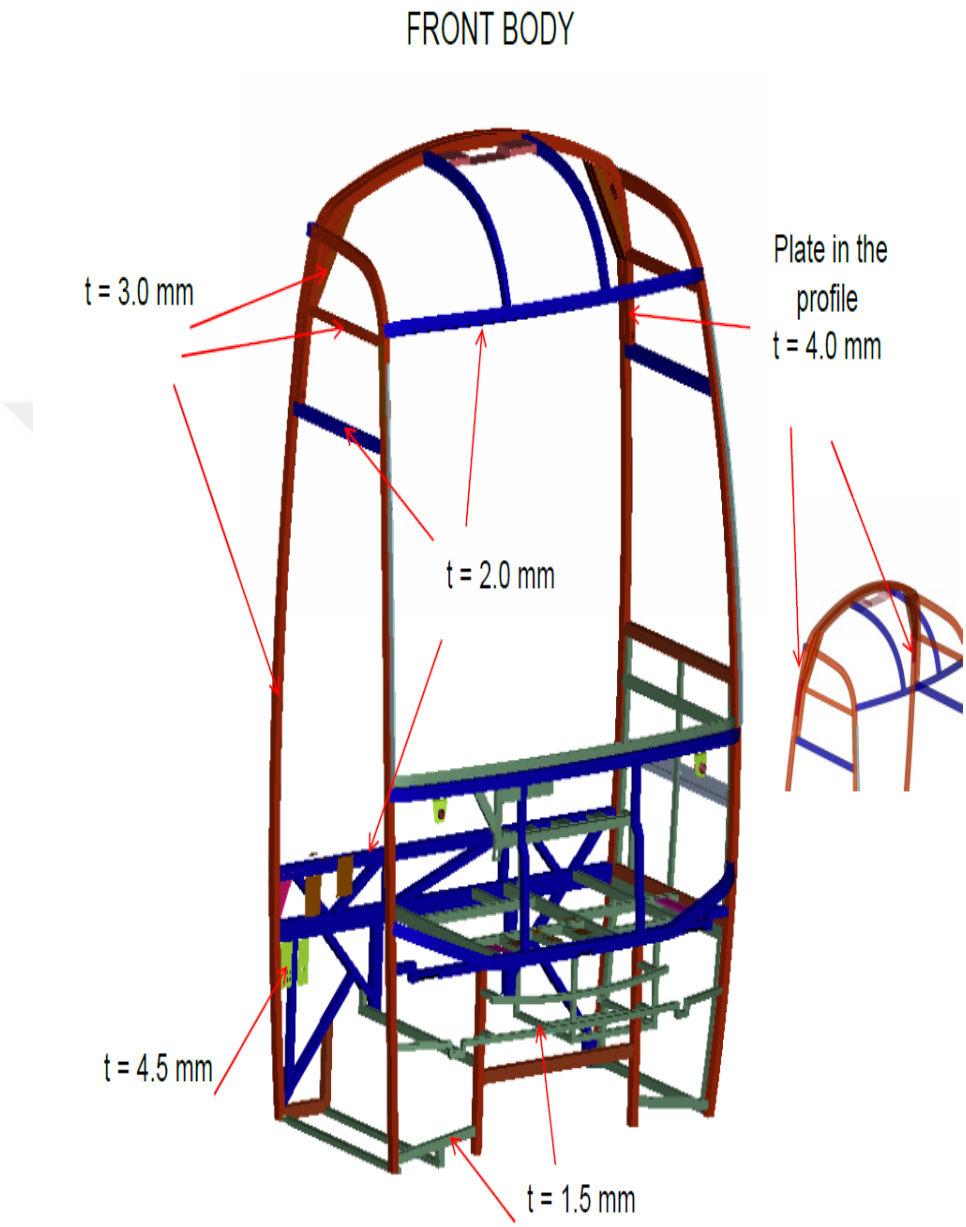


Figure 3.8. Thicknesses of the front body (sample)

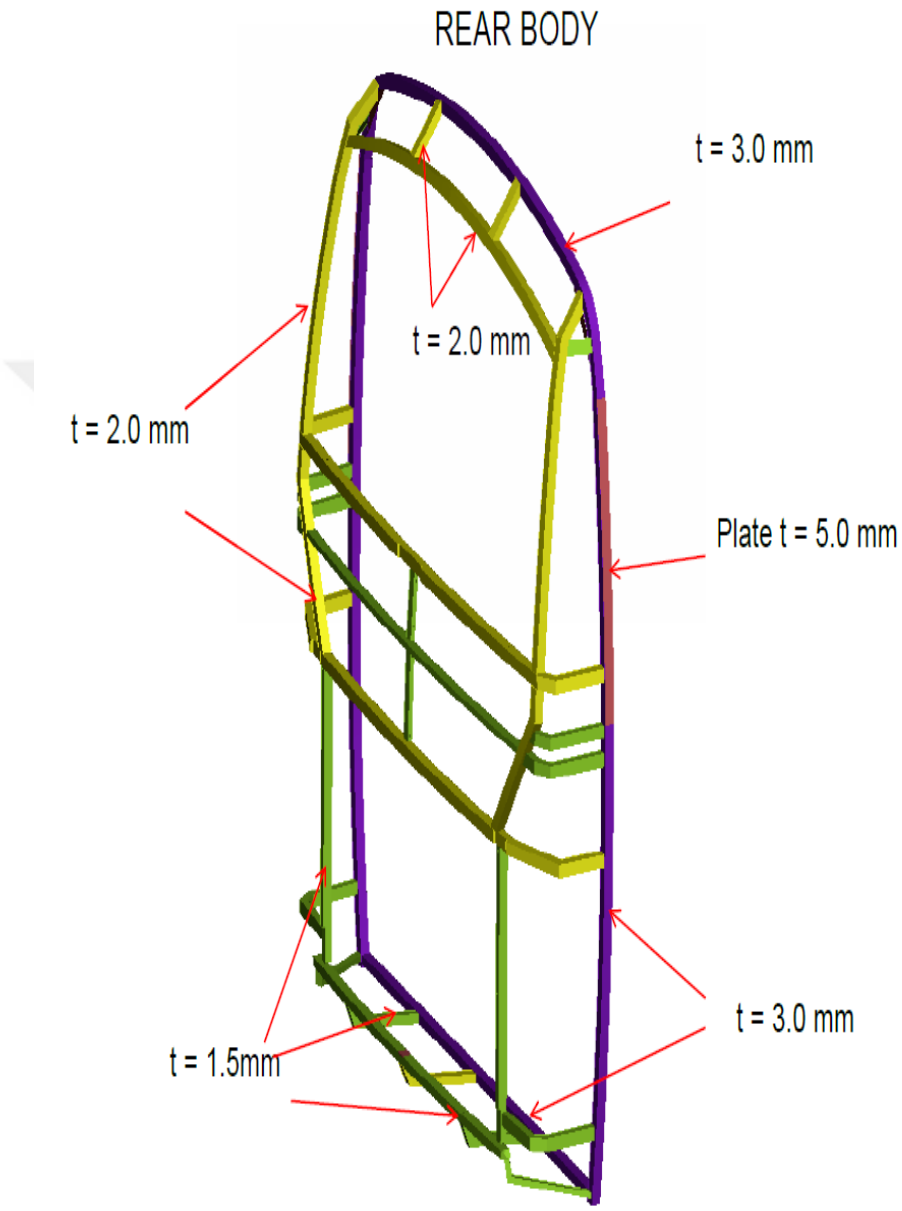


Figure 3.9. Thicknesses of the rear body (sample)

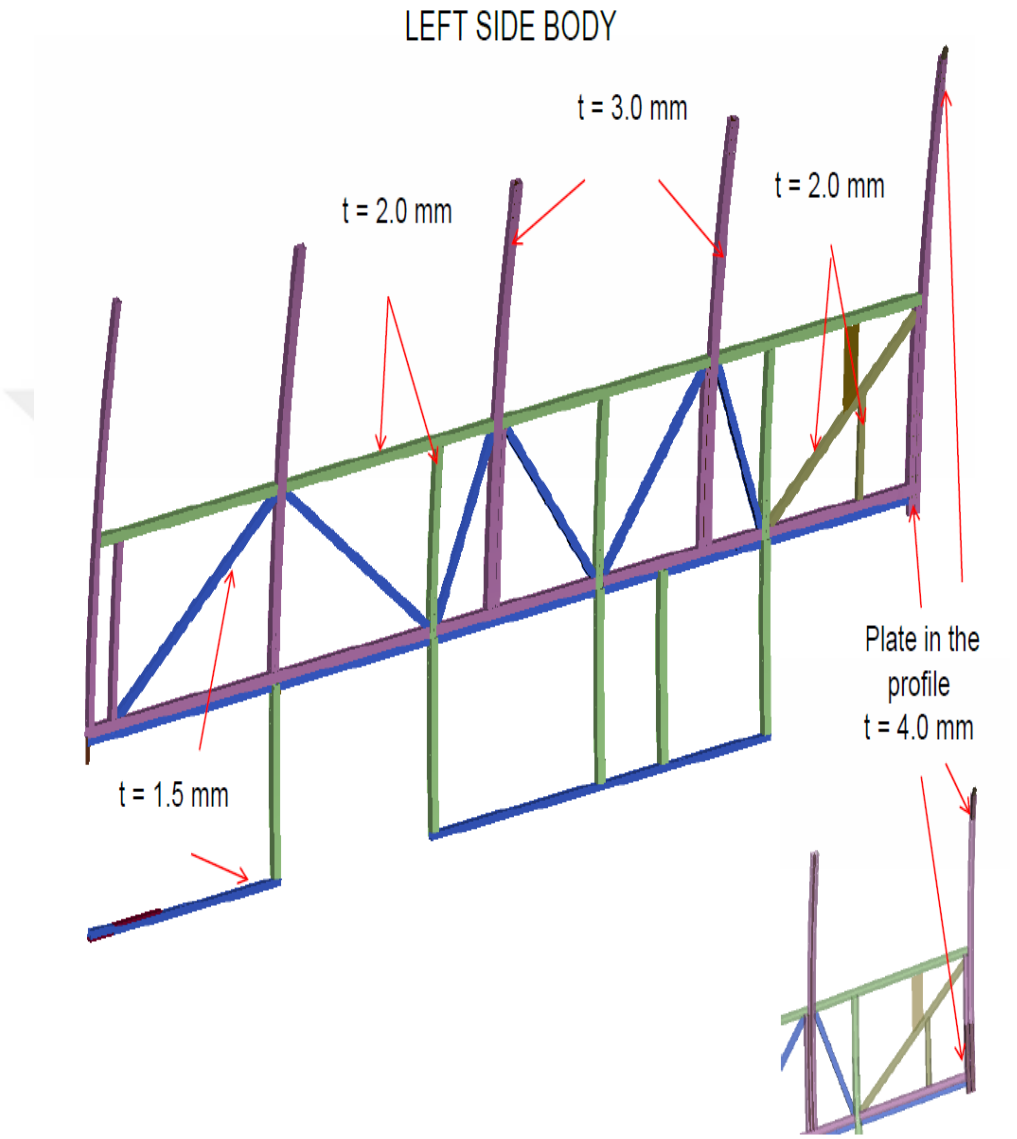


Figure 3.10. Thicknesses of the left side body (sample)

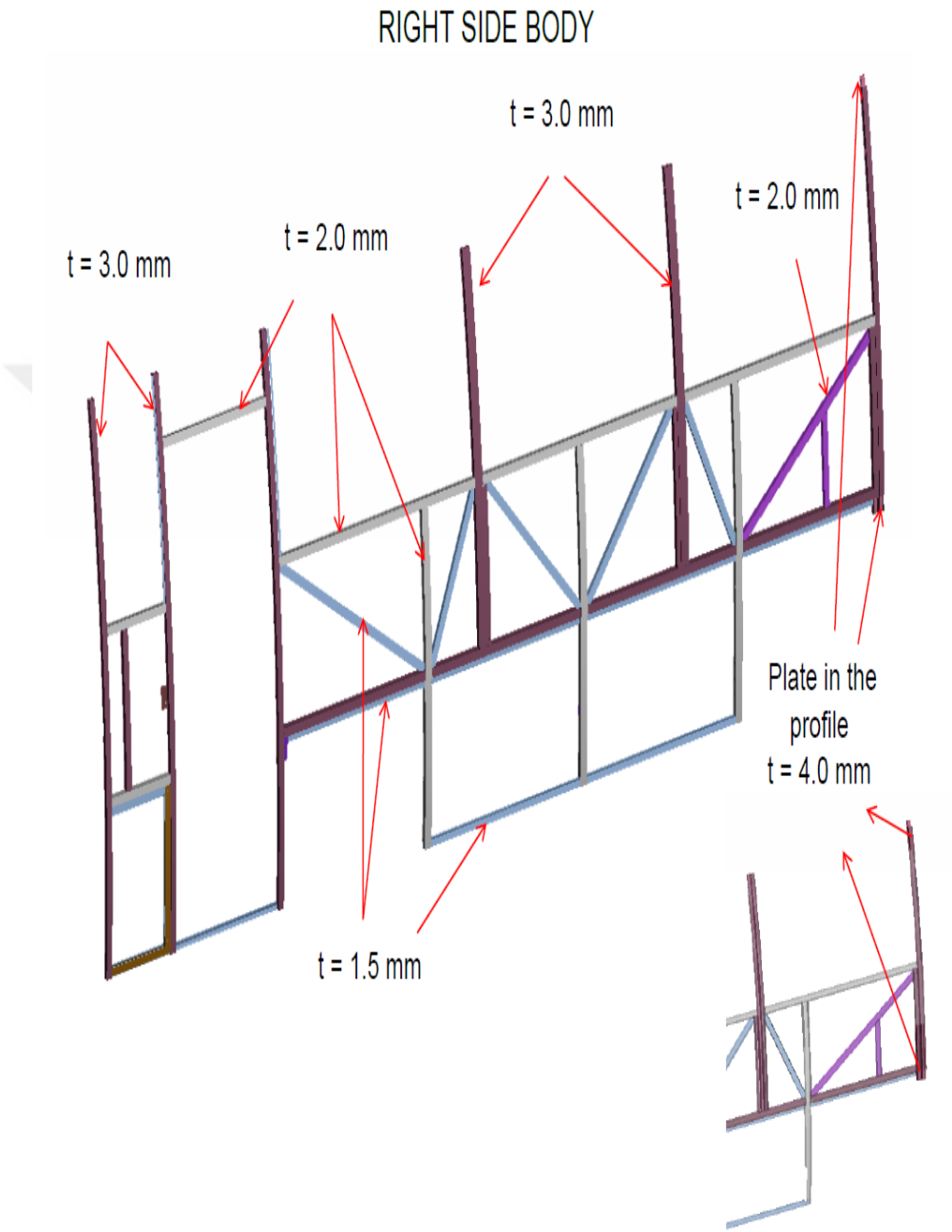


Figure 3.11. Thicknesses of the right side body (sample)

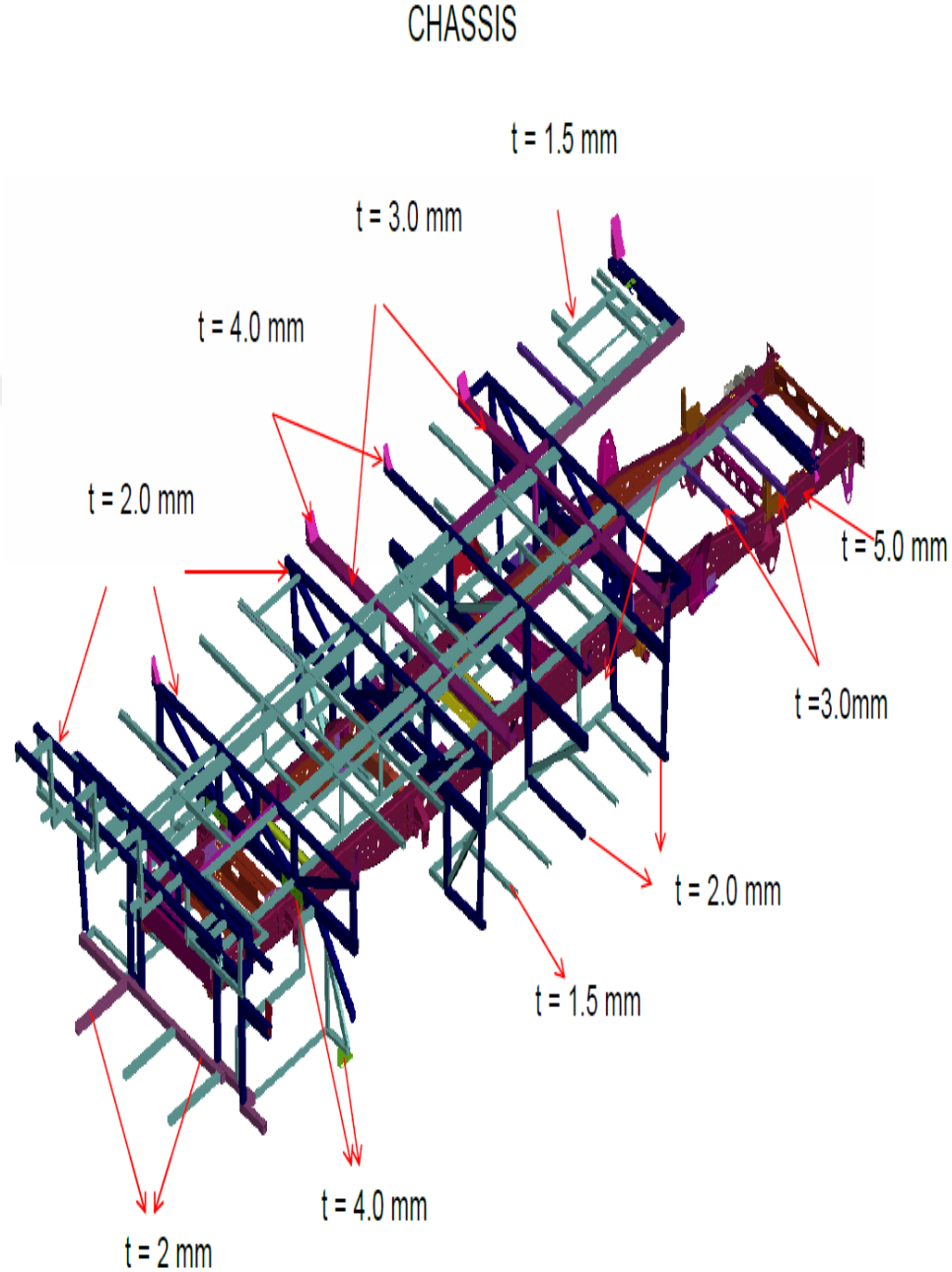


Figure 3.12. Thicknesses of the chassis (sample)

3.2. Preparation of Test Vehicle:

The test vehicle does not need be completed. Usually, any modification from the fully finished condition is acceptable if the general specifications and action of the superstructure are not affected by that. The vehicle to be tested should be the same as its completely finished model relating to following conditions:

The position of the center of gravity, the total mass of the vehicle (unladen kerb mass, or total effective vehicle mass where restraints are fitted) and the distribution of masses.

All the specifications mentioned above which take a part to the strength of the superstructure should be installed to their original location.

Parts or elements, which do not take a part to the strength of the superstructure – are too worthy to risk damage (e.g., drive chain, driver's seat, etc.) – can be changed with additional parts or elements which are equal in mass and the installation way. These additional parts or elements must not have strengthen affects on the superstructure.

Passenger weight is normally 68 kg for each but according to ECE regulation no. 66, half of this value that is 34 kg should be used for each passenger with center of gravity of the weight will be located to 100 mm above and 100 mm ahead of the R point of the seat.

Seats must be fixed rigid and secure so it does not break off during the test. (In the case of a real test, non computer simulation)

Note: In this study same weight was added to nodes located 100 mm above and ahead of the R point of each seat.

Tires should be inflated to the pressure declared by the manufacturer.

Vehicle’s suspension system should be blocked, such as the axles, the springs and the other suspension elements of the vehicle should be fixed according to the superstructure.

Every door and windows -which can be opened- of the vehicle should be closed and not locked.

3.3. Test Methods:

Instead of the roll-over test on a complete vehicle, at the discretion of the manufacturer, one of the following equivalent approval test methods can be chosen:

3.3.1. Roll over test on body sections[1] which are representative of the complete vehicle

All the different bay[2] configurations which are part of the whole body should be tested in at least one body section.

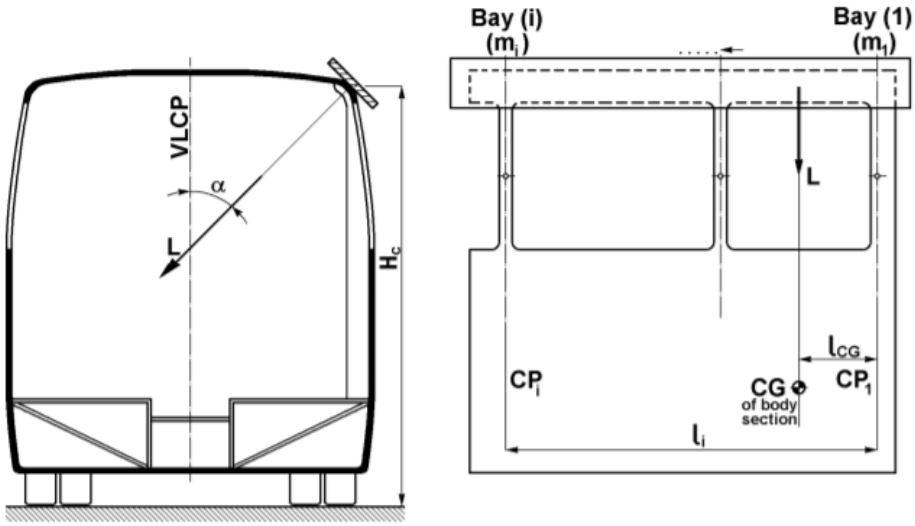


Figure 3.13. Body section

[1] "Body section" means a structural unit, which represents one part of the superstructure for the purposes of an approval test. A body section contains at least two bays connected by representative connecting elements (side, roof, and underfloor, structures).

[2] "Bay" means a structural section of the superstructure forming a closed loop between two planes which are perpendicular to the vertical longitudinal central plane of the vehicle. A bay contains one window (or door) pillar on each side of the vehicle as well as side wall elements, a section of the roof structure and a section of the floor and underfloor structure.

Every body sections should have at least two bays. The bays of the body section should be completely the same structurally as they are indicated in the superstructure, according to its shape, geometry, material, joints.

The residual area should be fitted in the body sections, including all special combinations of the vehicle's bodywork configuration. If there are local specialties such as air condition installation, gas tanks, etc. the whole roof should be together with the body sections.

The bays of the body section should be exactly the same structurally as they are indicated in the whole body, with regard to shape, geometry, type of material, joints.

3.3.2. Physical rollover test

3.3.3. Computer simulation – with dynamic calculations − of the basic rollover test on a complete vehicle in accordance with the specifications of Annex 9 of the ECE regulation no.66.

3.4. Vehicle Selection (Worst Case):

"Worst case" means the vehicle type, among a group of vehicle types, least likely to withstand the requirements of this regulation according to the strength of superstructure.
(https://unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/r066r1e.pdf, September 2021)

The three parameters which define the worst case are: structural strength, reference energy and the residual area.

If a manufacturer submits more than one vehicle variant in the same type for this test, the worst case should be chosen for this test due to vehicle's maximum safety. To carry out the rollover simulation test, there are several situations that will affect the worst case.

These are maximum mass capacity, vehicle length, vehicle height, maximum CoG, pillar numbers on each side of the vehicle. Firstly, seat number is

important to reach maximum mass. Vehicle with maximum mass capacity is the worst case, for this reason vehicle with maximum seat number should be chosen.

The longest and the highest vehicle is the worst case to get maximum CoG. Afterall the rollover test should be carried out on that side of the vehicle which is more dangerous with respect to the residual area, rollover direction should be chosen with regard to number of pillars on each side of the vehicle, the side with the minimum pillar number is the worst case, that is usually doors side.

The different, asymmetrical constructional features of the two sides of the vehicle, and the support given by partitions or inner boxes (e.g., wardrobe, toilet, kitchenette). The side with the lesser support should be chosen as the direction of the rollover test.

3.5. Residual Area

The cover of the vehicle's residual area is defined by creating a vertical transverse plane within the vehicle which has the outline and moving this plane through the length of the vehicle.

The S_R point shown in figure 3.14 is located on the back of the seat of each outer forward or rearward facing seat, 500 mm above the floor under the seat, 150 mm from the inside surface of the side wall of the vehicle. Wheel arches and other variations of the floor height will not be considered. Mentioned dimensions can also be applied in the case of inward facing seats in their center planes.

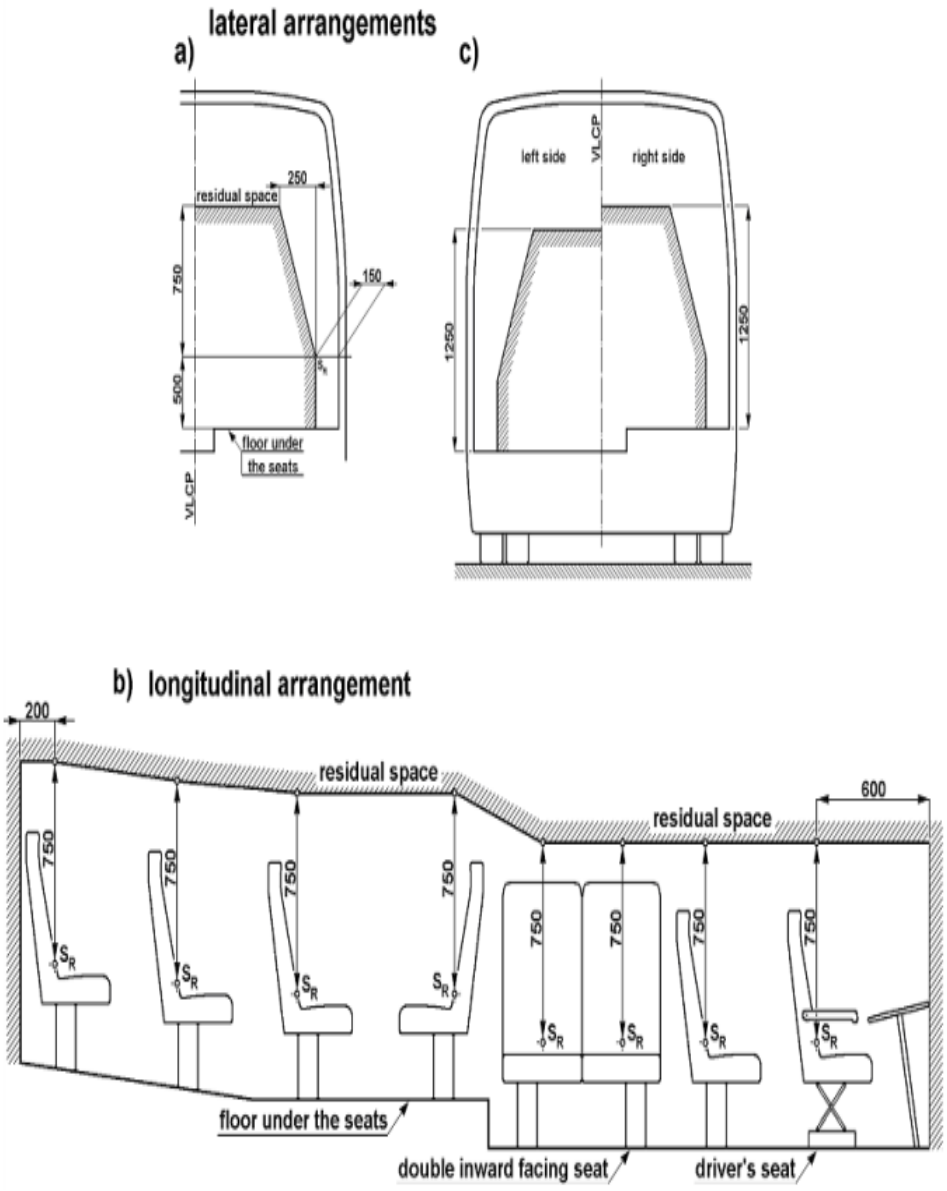


Figure 3.14. Specifications of Residual Area

If the two sides of the vehicle are not symmetrical according to arrangement of the floor of the vehicle, for this reason, the height of the S_R points are dissimilar, the step between the two floor lines of the residual area should be taken as the longitudinal vertical center plane of the vehicle.

The hindmost location of the residual area is a perpendicular surface 200 mm behind the S_R point of the hindmost outer seat, or the inner face of the rear wall of the vehicle if this is less than 200 mm behind that S_R point. The foremost location of the residual area is a perpendicular surface 600 mm in front of the S_R point of the foremost seat (whether passenger, crew, or driver) in the vehicle set at its fully forward adjustment. If the hindmost and foremost seats on the two sides of the vehicle are not in the same transversal surfaces, the length of the residual area on each side will not be similar.

The residual area is continual in the passenger, crew and driver compartment between its hindmost and foremost surface and is described by moving the defined perpendicular transverse surface through the length of the vehicle along straight lines through the S_R points on both sides of the vehicle. Behind the hindmost and in front of the foremost seat's S_R point the straight lines are horizontal.

The producer can describe a bigger residual area than required to simulate a worst case in order to improve the design.
(https://unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/r066r1e.pdf, September 2021)

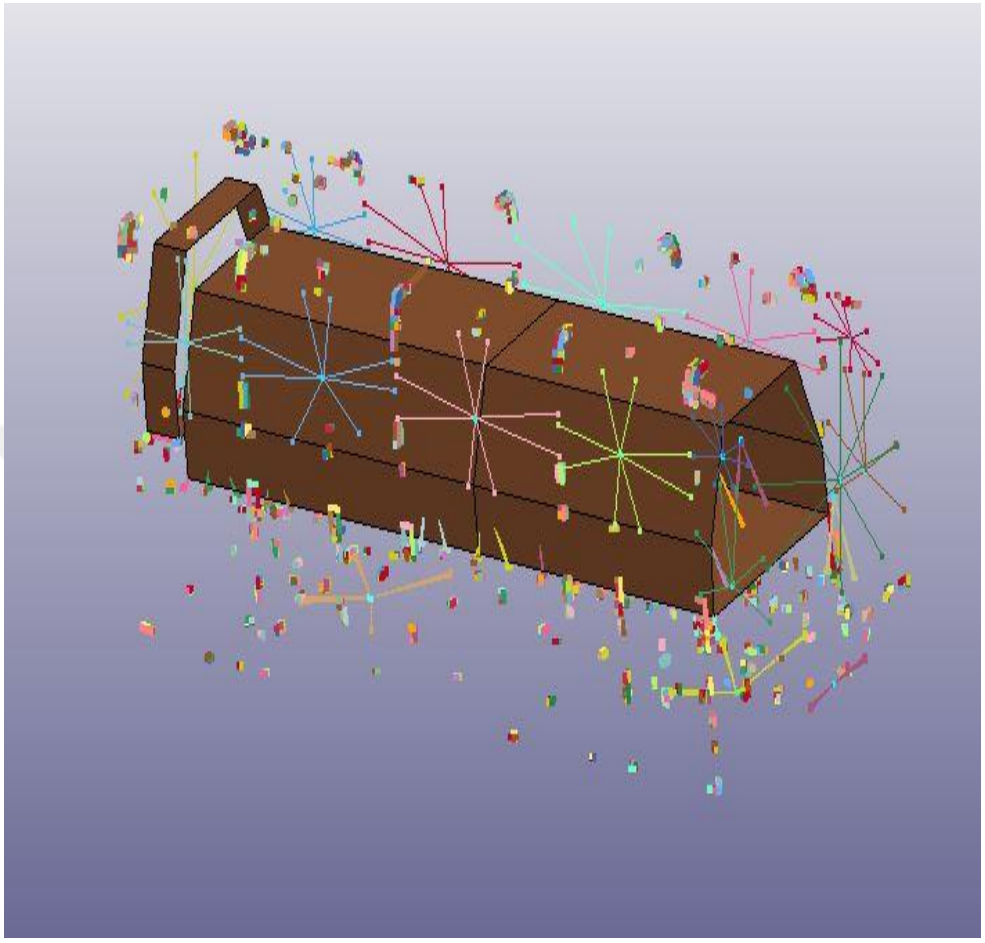


Figure 3.15. Residual Area

Note: The model of the survival area consists rigid beam frames in each section, rigidly mounted to stiff regions under the floor and connected to each other by shell elements. Connecting shells are for visualization only, there is no affect to the stiffness.

3.6. The tilting bench

The tilting platform should be sufficiently rigid and the turning sufficiently controlled to provide simultaneous lifting of the axles of the vehicle with a difference of less than 1° 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, should be 800 ± 20 mm. (https://unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/r066r1e.pdf, September 2021)

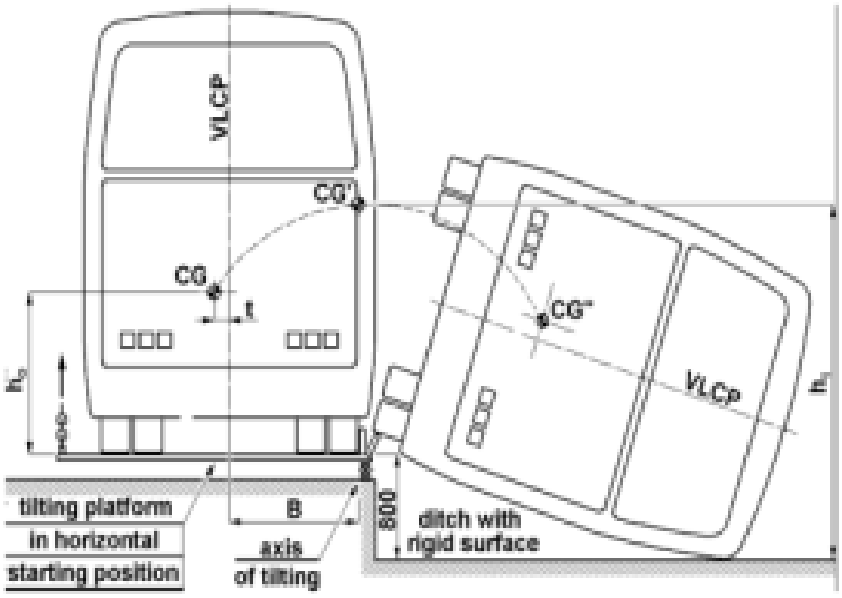


Figure 3.16. Specifications of the rollover test on a complete vehicle showing the path of the center of gravity through the starting, unstable position

3.7. Geometric Modelling (Geometry Check):

After the model is ready (designed in CAD programs), geometry check for profiles and plates is performed to see if there is any failure about the model.

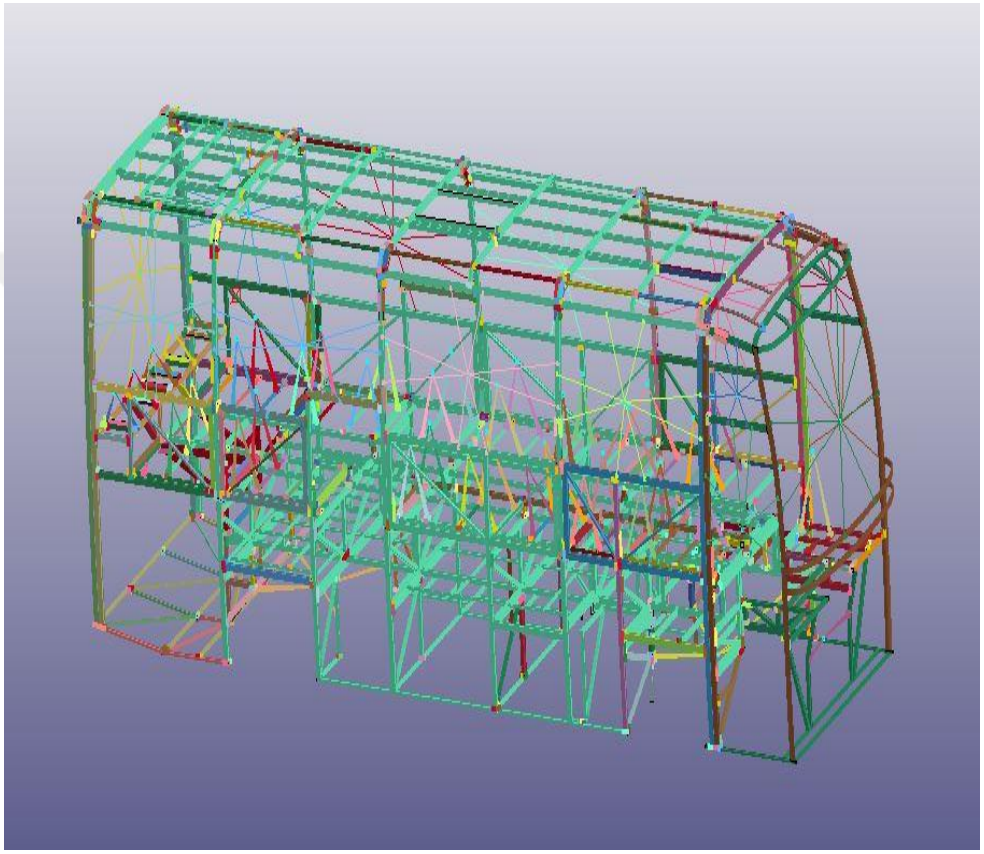


Figure 3.17. Geometry of the vehicle body

3.8. Meshing

The whole vehicle body should be meshed by using square mesh option between 5 mm and 20 mm depending on the shape and dimension of the parts. The reason of using square mesh option is; in LS-DYNA triangle meshes give errors and decrease quality of calculation sensitivities.

Shell element type: Reduced integration element with Belytschko-Tsay formulation

Element length: 5 mm in critical areas (pillars, roof corners)

10 mm, 15 mm, 20 mm other areas

MSC Apex software was used to perform this meshing process.

3.9. Masses and determining CoG (Center of Gravity)

Added masses are; air conditioner, driver mass, seat masses, glass masses, engine and axle masses, etc. (Table 3.3.).

Table 3.3. Component masses that added to lumped mass

Components	**Mass**
Glasses (in total)	425 kg
Passenger seat	30 x 19,5 = 585 kg
Rear passenger seat	5 x 19,5 = 97,5 kg
Driver seat	47 kg
Crew seat	20 kg
Driver	75 kg
Crew	75 kg
Passengers	1190 kg
Air conditioner	50 kg
Air conditioner compressor	20 kg
Engine (including oil)	550 kg
Gearbox (including oil)	136 kg
Shaft	20 kg

Cooling water	40 kg
Engine room pipes	20 kg
Engine sub cover	10 kg
Rear axle (including wheels and rims)	850 kg
Front axle (including wheels and rims)	650 kg
Fuel tank	100 kg
Air tanks	20 kg
Battery	25 kg
Exhaust system	85 kg
FRP (front)	35 kg
FRP (rear)	27 kg
FRP (roof)	60 kg
Doors (front+rear)	100 kg
Steering gear box + Steering pump + Steering pipe + hydraulic oil	47 kg
Front body (interior and exterior coating materials, lamps mirrors)	68 kg
Left side wall (interior and exterior coating materials, isolation materials, brackets)	79 kg
Right side wall (interior and exterior coating materials, isolation materials, brackets)	79 kg
Rear body (interior and exterior coating materials, lamps)	59 kg
Roof (interior and exterior coating materials, isolation materials)	138 kg
Chassis (all profiles, sheet metals)	4248,9 kg

Afterall, total calculations were performed as given in the table below:

Table 3.4. Total mass calculation and center of gravity

Part	Mass (Kg)	COG (mm)		
		XM	YM	ZM
Chasis + Body + Driver	8766,4	-11	2878	1226
50% of mass of passengers	1190 + 75 (crew)	-	-	-
Total	10031,4	3	2604	1714

Table 3.5. Worse case table

Length	8872,82 mm
Width	2351,31 mm
Height	3030,73 mm
Effective mass	10031,4 kg
Centre of gravity	1714 mm above the front axle
Seat layout	35+1+1

4. RESULTS AND DISCUSSIONS

The value of reference energy (E_R) which is the product of the vehicle mass (M), the gravity constant (g) and the height (h_1) of centre of gravity with the vehicle in its unstable equilibrium position when starting the rollover test

$$E_R = M.g.h_1 = M.g\left[0.8 + \sqrt{h_0^2 + (B \pm t)^2}\right]$$

where:

M	=	M_k, the unladen kerb mass of the vehicle type if there are no occupant restraints, or, M_t, total effective vehicle mass when occupant restraints are fitted, and
M_t	=	$M_k + k.M_m$, where k = 0.5
h_0	=	the height (in metres) of the vehicle centre of gravity for the value of mass (M) chosen
t	=	perpendicular distance (in metres) of the vehicle centre of gravity from its longitudinal vertical central plane.
B	=	perpendicular distance (in metres) of the vehicle's longitudinal vertical central plane to the axis of rotation in the rollover test
g	=	gravitational constant
h_1	=	the height (in metres) of the vehicle centre of gravity in its starting, unstable position related to the horizontal lower plane of the ditch

Figure 3.18. Abbreviations of formula

Where M is the unladen kerb mass[3] described in the regulation, g is the gravitational acceleration, and Δh is the vertical movement of vehicle center of gravity from the unsteady position to the first impact on the ground. (Figure 3.18., 3.19)

According to formula given above, reference energy is calculated as:

t = 1452 mm = 1,452 m

B = 735 mm = 0,735 m

h_0 = 1452 mm = 1,452 m

[3] "Unladen kerb mass" (Mk) is the weight of the vehicle in running order, without any passenger weight and unladen. Unladen kerb mass includes 75 kg for the mass of the driver, driver seat weight, passenger seats weight, glasses, the mass of 90% fuel of the capacity of the fuel tank, tyres, the masses of coolant, lubricant, tools and spare wheel, if any.

g = 9,81 m/s^2 (This value is given in the ECE Regulation no. 66)

M = 10031,4 kg

10031,4 kg x 9,81 m/s^2 x 3,422393 m =336790,96 Joule

E_R = 336790,96 Joule

Initial energy: $M.g.h_1$

= 10031,4 kg x 9,81 m/s^2 x (1,452 – 0,735)

= 70558,56 Joule

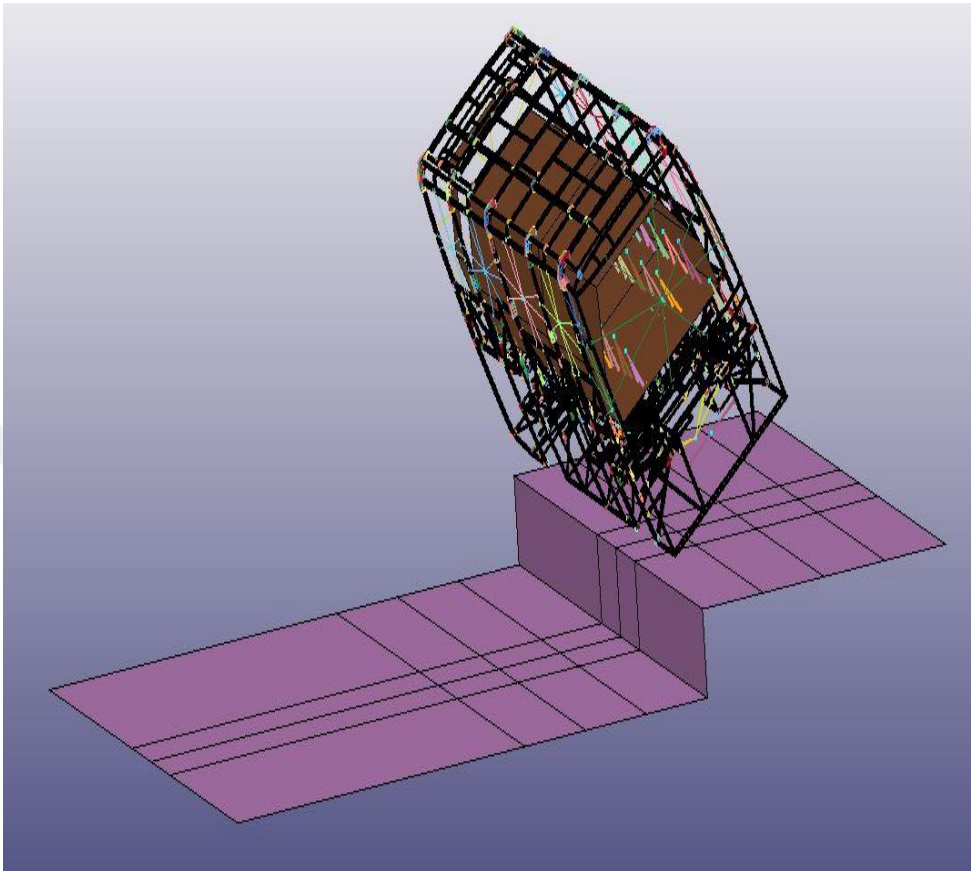


Figure 3.19. The initial position for the FE-model

After the run process was performed by LS-DYNA, the distance values between residual area and each pillar will give the result. In the case of any contact occurrence to the residual area, the virtual analysis is going to be unsuccessful.

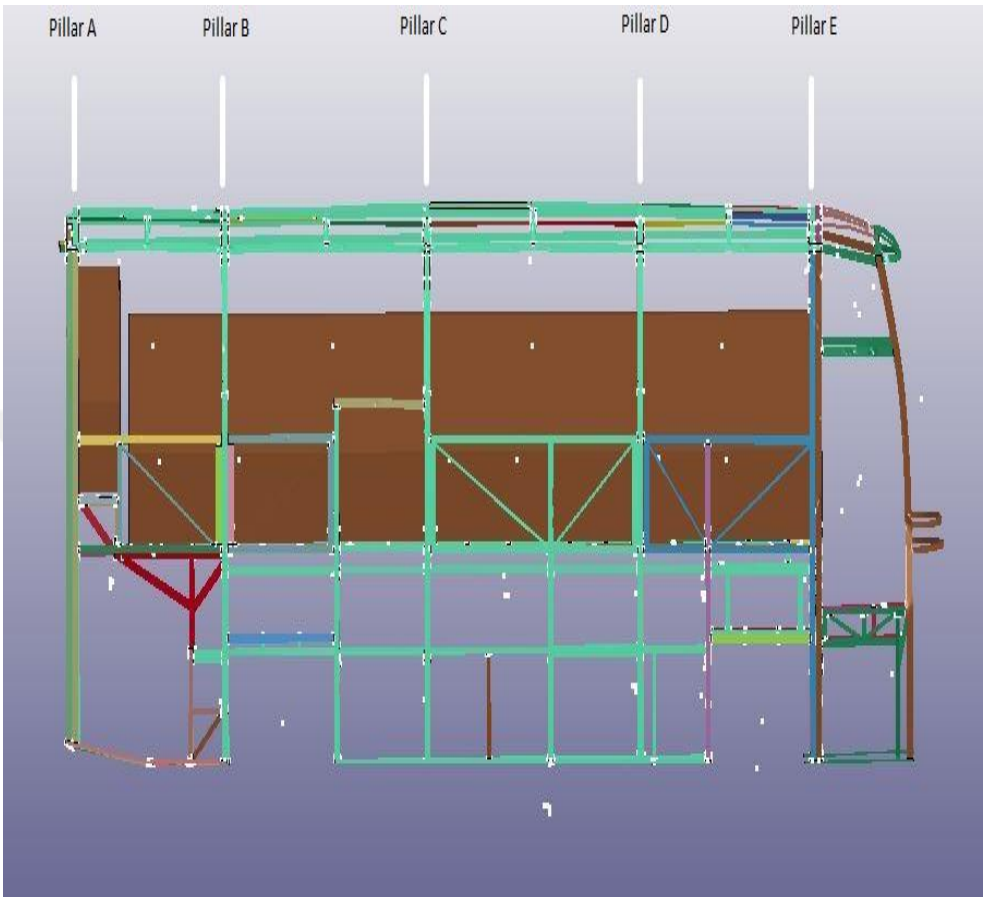


Figure 3.20. Numbering of the pillars

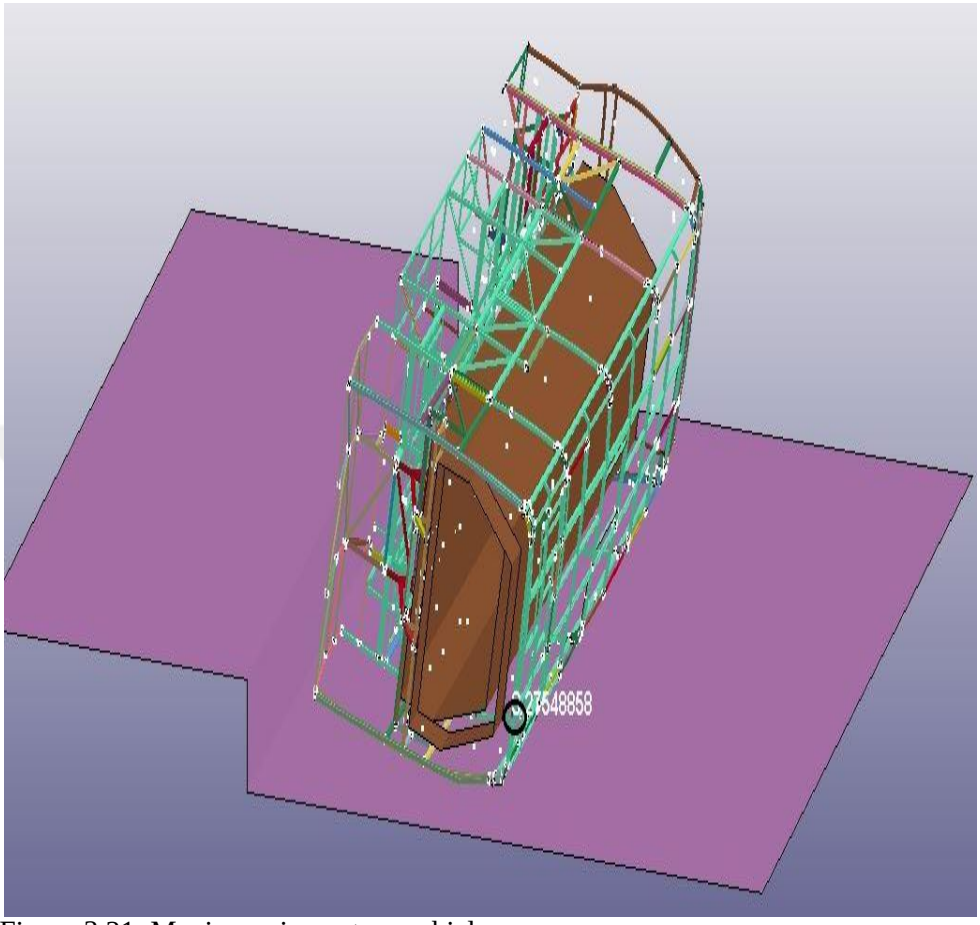


Figure 3.21. Maximum impact on vehicle

Table 3.6. Distances between residual area and each pillar

Pillars		Point 1 (mm) (down side of residual area)	Point 2 (mm) (Up side of residual area)
Pillar A	Before the test	**143**	**412**
	After the test	**116**	**282**
Pillar B	Before the test	**154**	**446**
	After the test	**148**	**290**
Pillar C	Before the test	**154**	**450**
	After the test	**143**	**284**
Pillar D	Before the test	**153**	**450**
	After the test	**110**	**238**
Pillar E	Before the test	**153**	**453**
	After the test	**78**	**210**

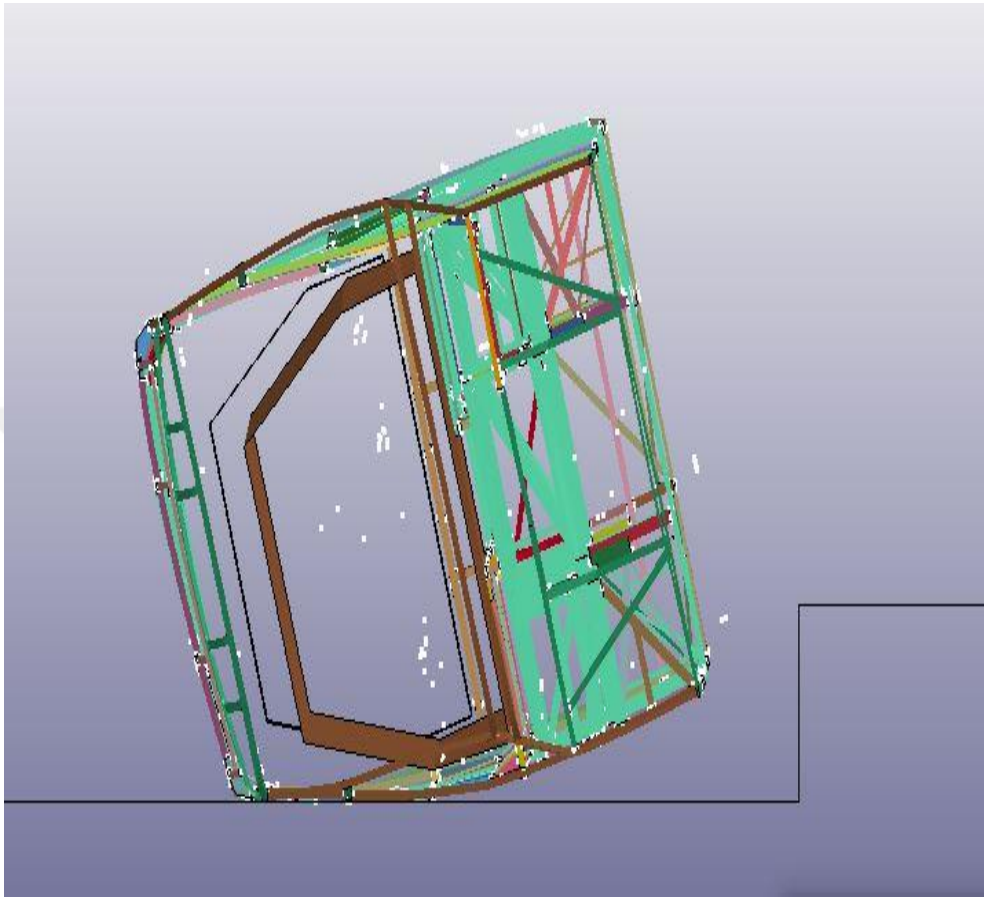


Figure 3.22. Vehicle body at maximum impact

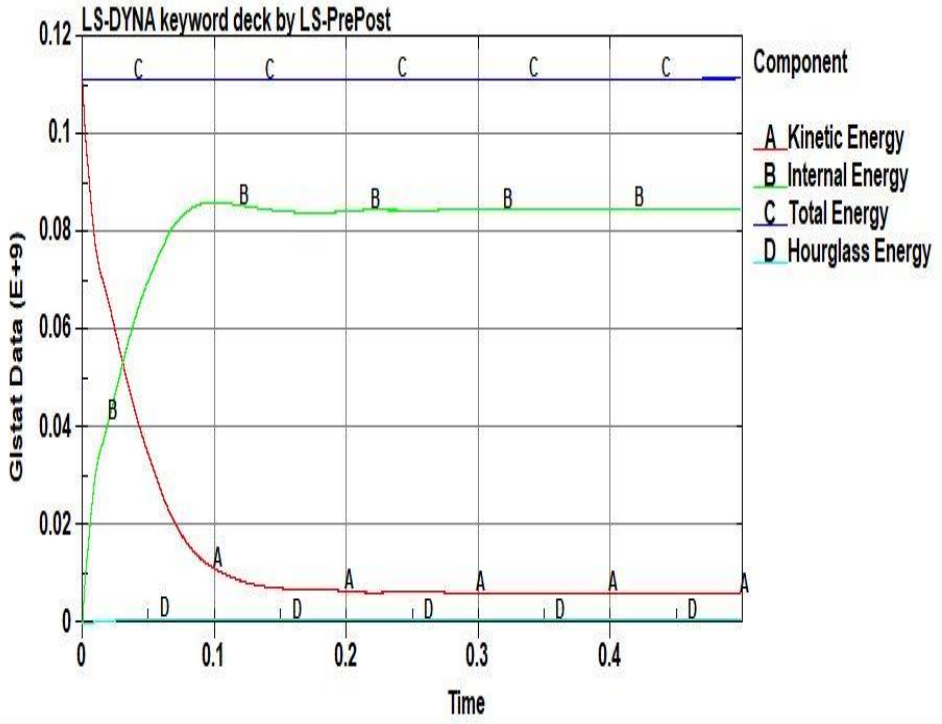


Figure 3.23. Energy balances from the moment of impact

Total Energy (Joule) **:** 111000 J

Kinetic Energy (Joule) **:** 7200 J

Internal Energy (Joule) **:** 86300 J

Figure 3.22 shows the vehicle at maximum impact. The most critical position is at the pillar E. **There is no penetration to the residual area but the distance at upper side of pillar E is near to 210 mm and at lower side is 78 mm**. All other points have more distance to the residual area. The numbering of the pillars can be seen in Figure 3.21.

The distance to the superstructure is **78 mm** for the seat positioned on the higher floor level in the front of the bus (Distance between superstructure and crew seat). The driver position in this vehicle is under floor level and the deformation of the structure in this area is limited.

5. CONCLUSIONS

In the calculations, the roll over test is simulated by positioning the bus on an 800 mm high ramp, see figure 3.16. In figure 3.16 the bus rolls over the edge of the ramp with the edge as rolling center after which the bus falls on the ground. The analysis starts by applying a prescribed rotation velocity to the ramp which makes the bus roll over the edge of the ramp structure. Before the ramp starts to move the bus is at a stable condition. Contact is defined between the wheels and the ramp where the bus is standing on
(CONTACT_AUTOMATIC_SINGLE_SURFACE).

The coefficient of friction between the bus body and the ground is $\mu = 0.4$ (This value was obtained from a comparison of real and simulation test of a body section of the vehicle). Coefficient of friction value was increased in LS-Dyna until the exact real test values was obtained, $\mu = 0.4$ was the most realistic coefficient of friction in the simulation roll over test with the real roll over test)

The whole model is loaded with a gravitational load of 9.81 m/s^2

When the vehicle hits the ground, it has reference energy of

$E = mg\Delta h$

The outline of the damaged structure was decided consecutively, amongst each adjoining windows and/or door pillars. As a result, no part of the residual area projected outside the outline of the damaged body.

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