ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

MSc THESIS

Gonca DEDE

DEVELOPMENT OF SEAT DESIGN AND SIMULATION OF SEATING SYSTEMS' TESTS ACCORDING TO EUROPEAN AND US REGULATIONS FOR SEATS

DEPARTMENT OF AUTOMOTIVE ENGINEERING

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We certify that the thesis titled above was reviewed and approved for the award of degree of the Master of Science by the board of jury on 22/03/2016.

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ABSTRACT

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DEPARTMENT OF AUTOMOTIVE ENGINEERING

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Today, due to the increment of energy consumption and greenhouse emissions, there is an extraordinary effort to overcome these problems in transportation sector. One of the most effective means to reduce fuel consumption and greenhouse gases is weight reduction of the vehicles. In transit vehicle sector, when the ratio of overall vehicle weight is analyzed, passenger seats have a significant energy saving potential. When studies are analyzed, it can be understood that two main ways are used to reduce the weight of the seat; using high strength steel and optimizing the design by using lightweight material instead of steel. The primary objective of this study is to obtain a weight reduction for passenger seats by using different materials for design and compare weight and strength of seat designs. This passenger seats were designed without compromising any comfort criteria and tested by using simulation program according to the FMVSS, APTA and ECE R80 regulations. Consequently, 31% weight reduction was obtained by using ultra high strength steel and 50% weight reduction was obtained by using aluminum alloy for design.

Key Words: Lightweight Seat, Ultra High Strength Steel, Aluminum, Finite Element Method

ÖZ

YÜKSEK LİSANS TEZİ

KOLTUK DİZAYNI GELİŞTİRİLMESİ, AVRUPA VE AMERİKA STANDARDLARINA GÖRE TESTLERİNİN SİMULE EDİLMESİ

Gonca DEDE

ÇUKUROVA ÜNİVERSİTESİ
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Günümüzde, artan enerji tüketimi ve sera gazı emisyonlarının sonucu olarak, ulaşım sektöründe bu olumsuzlukları giderme yönünde olağanüstü çaba vardır. Yakıt tüketimini ve sera gazı emisyonlarını azaltmanın en etkili yollarından biri araç ağırlığını azaltmaktır. Toplu taşıma araçlarının araç ağırlık oranına bakıldığında yolcu koltuklarının önemli ölçüde enerji tasarrufu potansiyeline sahip olduğu görülmektedir. Önceki çalışmalar incelendiğinde, yüksek mukavemetli çelik kullanarak tasarım optimizasyonu yapmanın ya da çelik yerine hafif malzeme kullanmanın, koltuk ağırlığını azaltmanın iki ana yolu olduğu anlaşılabilir. Bu çalışmanın ana amacı, farklı malzeme kullanarak yolcu koltuklarının ağırlığını azaltmak ve yapılan farklı malzeme dizaynlarını ağırlık, mukavemet yönünden karşılaştırmaktır. Yolcu koltukları herhangi bir konfor kriteri göz önünde bulundurulmadan dizayn edilmiş ve simülasyon programı kullanarak FMVSS, APTA ve ECE R80 regülasyonlarına göre test edilmiştir. Sonuç olarak, yüksek mukavemetli çelik kullanarak yapılan tasarımla %31 ve alüminyum alaşım kullanılarak yapılan tasarımla %50 ağırlık azalışı elde edilmiştir.

Anahtar Kelimeler: Hafifletilmiş Yolcu Koltuğu, Yüksek Mukavemetli Çelik, Alüminyum, Sonlu Elemanlar Analizi

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ABBREVIATIONS

CO_2	: Carbon dioxide
CH_4	: Methane
N_2O	: Nitrous oxide
pfcs	: Perfluorocarbons
OECD	: Organization for Economic Cooperation and Development Countries
IEO	: International Energy Outlook
FMVSS	: Federal Motor Vehicle Safety Standards
APTA	: American Public Transportation Association
ECE	: United Nations Economic Commission for Europe
PEG	: Porsche Engineering Group
ULSAB	: Ultra-Light Steel Auto Body
BIW	: Body in White
MMLV	: Multi-material lightweight vehicle
IBCAM	: Institute of British Carriage and Automobile Manufacturers
FEM	: Finite Element Method
U.S.	: United States
FRP	: Fiber Reinforced Polymer
GPa	: Giga Pascal
MPa	: Mega Pascal
kg	: kilogram
m^3	: cubic meter
AHSS	: Advanced high strength steels
UHSS	: Ultra high strength steels
CATIA	: Computer Aided Three-dimensional Interactive Application
CAD	: Computer Aided Design
CAM	: Computer Aided Manufacture
CAE	: Computer Aided Engineering
3D	: Three Dimensional
FEA	: Finite Element Analysis

SRP	: Seat Reference Point
kN	: Kilo newton
G	: Gravitational acceleration
Nm	: Newton-meter
mm	: millimeter
N	: Newton
Al	: Aluminum
sec	: seconds
msec	: miliseconds

1. INTRODUCTION

1.1. Greenhouse Gas Emission and Energy Consumption in Transportation

Transportation provides mobility for people and improves the standard of living in developed world. However, vehicles significantly impact the environment during their lifetime. Greenhouse gas emission and energy consumption are two of the most important impact of transportation.

Gases that keep the heat in the atmosphere are called greenhouse gases. These are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydro fluorocarbons, perfluorocarbons (pfcs), sulfur hexafluoride, and nitrogen trifluoride. Greenhouse gases make planet warmer by keeping the heat in the atmosphere. Previous studies show that the transportation sector accounts for approximately 15% of overall greenhouse gas emissions. The transportation sector's CO_2 emissions represent 23% (globally) and 30% (OECD countries- Organization for Economic Co-operation and Development Countries) of overall CO_2 emissions from fossil fuel combustion (International Transport Forum, 2010).

In addition to greenhouse gas emissions, energy consumption is another significant impact of transportation. According to the International Energy Outlook 2013 (IEO, 2013), world energy consumption will grow by 56 percent between 2010 and 2040 in the reference case IEO 2013. The transportation sector accounts for the largest share (63 percent) of the total growth in world consumption of petroleum and other liquid fuels from 2010 to 2040 (U.S. Department of Energy, 2013).

As a result of the energy consumptions' and greenhouse emissions 'data, there is a high emphasis on reducing greenhouse gas emissions and improving fuel efficiency in the transportation sector.

1.2. Methods of Reducing Fuel Consumption and Greenhouse Gas Emissions

There are different methods to reduce greenhouse gas emissions and fuel consumption. The first method of the reducing greenhouse gasses and fuel consumption can be specified changing the fuel type that is used for movement of the vehicle. Changing fuel type has different strengths and weaknesses. As an alternative fuel, biofuels can offer significant CO_2 emission reduction compared to petrol and diesel and electricity and hydrogen offer zero emission. However, use of alternative fuels has some risks, difficulties and technical challenges.

Increasing fuel efficiency can be specified as another method. In vehicle design, the engine system determines fuel efficiency and the fuel efficiency can be increased by improving vehicle and engine technology. In 2007, King Review (2007) showed that some technologies offer significant CO_2 and fuel efficiency savings for a typical petrol engine of 2000s. Some of these technologies are listed and their energy saving percentages is shown in the Table 1 (King, 2007).

Table 1.1. Engine and transmission efficiency savings (King, 2007)

Technology	**Efficiency saving**
Direct injection and lean burn	10 – 13 %
Variable valve actuation	5 – 7%
Downsizing engine capacity with turbo charging or supercharging	10 – 15%
Dual clutch transmission	4 – 5%
Stop–start	3 – 4%
Stop–start with regenerative braking	7%
Electric motor assist	7%
Reduced mechanical friction components	3 – 5%

One of the most effective means to reduce fuel consumption and greenhouse gases is weight reduction of the vehicles. It has been estimated that for every 10% of weight eliminated from a vehicle's total weight, fuel economy improves by 7%. This also means that for every kilogram of weight reduced in a vehicle, there is about 20 kg of carbon dioxide reduction over the vehicle's operating life (Ghassemieh, 2011).

In this study, weight reduction of vehicle is used as method of reducing fuel consumption and greenhouse gas emissions.

1.3. Aim of Study

When the ratio of overall vehicle weight is analyzed, passenger seats have a significant energy saving potential in transit vehicle. Approximately, %8 of unloaded vehicle weight is seat weight (Yuce, 2013). In addition to the energy saving potential of the seat, the seat has an important role in a crash event. Therefore, the importance of weight reduction is growing in transportation sector and the suppliers of seats should develop lightweight seat structures that retain optimum safety.

The primary objective of this study is to obtain a weight reduction for passenger seats by using different material for design and compare weight, strength of seat designs. This passenger seats are designed without compromising any comfort criteria and tested by using simulation program according to the FMVSS, APTA and ECE R80 regulations. The test results are used to compare strengths of seat designs and to examine the compliance of minimum safety requirements.

2. PRELIMINARY WORK

2.1. Vehicle Weight Reduction Literature Review

Several studies were conducted in literature to obtain weight reduction. by using aluminum alloys instead of steel.

In 1995, Stodolsky et al. performed a study which estimates total life-cycle energy savings over time as aluminum-intensive vehicles (AIVs). Their study showed that a 19-31% weight reduction (270-460 kg) is possible with the intensive use of aluminum in passenger cars and light trucks, resulting in a fuel economy improvement of 12.5-20% for AIVs over conventional steel vehicles. They defined in that at least three ways to decrease the empty weight of a vehicle in their study. These three ways are; reducing vehicles' size, optimizing its design to minimize weight, and replacing the materials used in its construction with lighter mass equivalents. According to the Stodolsky et al. the third alternative, use of lightweight materials could provide greater gains (Stodolsky et al., 1995).

One of the aluminum intensive vehicles in the automotive industry is produced by Ford Company. Ford Company produced a small demonstration fleet of Mercury Sables with aluminum bodies in 1994. Gaines and Cuenca studied with Mercury Sables with aluminum bodies and the primary object of their study was to observe the wear characteristics of the body under normal operating conditions. Although measurement of fuel economy was not included in the scope of their study, their experience during six years of operation demonstrated that the AIV was a very practical car with great performance and a fuel economy advantage over a comparable steel-body car (Gaines and Cuenca, 2002).

In addition to these, there are several studies which obtain weight reduction by using high strength steel. One of these studies is conducted by Porsche Engineering Group. Porsche Engineering Group (PEG) was contracted by a consortium of the world's sheet steel producers to design the ultra-light steel auto body (ULSAB). The goal of the ULSAB program was to develop a light-weight body structure design that is predominantly steel. This goal included; providing a significant mass reduction based on a future reference vehicle, meeting functional and structural performance targets, providing concepts that will be applicable for future car programs. In 1998, the consortium presented to the world automotive industry, a complete ULSAB body-in-white, which dramatically validated the design concepts. The benchmark design used by PEG for comparison had a BIW mass of 271 kg. In 1998, the resulting body design, which made extensive use of high strength steels, weighed 203 kg, a reduction of 25% (Porsche Engineering Services, 1998).

In later years, the optimal lightweight design studies conducted by using multi- material structures. William J. Joost who discussed the relationship between vehicle weight and U.S. transportation energy and reviewed the most promising lightweight materials, indicated that the optimal lightweight designs typically require the use of multi-material structures in his study (Joost,2012).

Wagner et al. explained the potential of multi-material lightweight vehicle (MMLV) design for light weighting of a five-passenger sedan while maintaining critical vehicle performance and occupant safety metrics. In their design study, aluminum, steel and lightweight materials were used. They achieved a 364 kg (23.4%) full vehicle mass reduction compared to the 2013 Fusion baseline. In turn, that weight savings enables use of a 1.0-liter three-cylinder engine, significantly improving fuel economy and reducing CO2 emissions. They indicated that the automotive industry continues to investigate innovative ways to incorporate lightweight materials that are both cost effective and affordable (Wagner et. al. 2012).

2.2. Lightweight Seat Structures Literature Review

In mass transit vehicle sector, when the overall ratio of vehicle weight is analyzed, it can be understood that passenger seats have a significant energy saving potential. To obtain considerable weight reduction, lightweight materials have been used in seat design studies.

One of these studies is conducted by Lear Corporation in 1997.They described their lightweight seat design in IBCAM Conference 97’. According to the speech of Daniel Bateson, their lightweight seat designs included aluminum extruded parts, magnesium die casting parts and 30% less weight was obtained compared with a steel pressing (Burman, 1997).

P.J. García Nieto et al. carried out the design of an automobile rear seat and the simulation by finite element method (FEM) on its performance using different standard tests. In that study, a considerable reduction of weight in the seat’s framework was obtained from the first geometrical model to the final framework model. That reduction of weight is due to the optimization of the thickness and material used in every part that makes up the seat’s framework. That weight reduction was 8,6 % in mass (Nieto et. al. 2007).

Tata Steel studied a front seat design with an ultra-lightweight body structure concept for future electric/hybrid vehicles with 35% weight reduction compared with the project baseline vehicle (and 23% compared with current production small cars). In the study, seat design, steel grades and thicknesses are optimized (Tata Steel Europe Limited, 2013).

In 2014, Jakob Steinwall and Patrik Viippola studied a lightweight seat design by using magnesium alloy instead of low alloy steel. Their results of the analyses shows that if compared to their reference seat, the final concept was 27 percent lighter, 1 percent cheaper in terms of unit cost, able to withstand the same impact load cases, and able to fulfill the same basic ergonomic requirements. Their study showed that it is possible to reduce the driver’s seat mass without compromising the safety, cost or ergonomic performance of their reference design (Steinwall and Viippola 2014).

C. Yuce conducted a design study for commercial vehicles. In that study, a lightweight passenger seat was designed by using high strength steel. High strength steel profiles thickness were determined according to the results of the finite element method analyzes. The lightweight seat was tested in accordance with ECE safety standards. As a result of the study 20% weight reduction was obtained compared with conventional seat structure. It is indicated in the study that the aluminum and composites materials can be used for further investigations (Yuce, 2013).

When these studies are analyzed, it can be understood that two main ways are used to reduce the weight of the seat; using high strength steel and optimizing the design, using lightweight material instead of steel.

3. MATERIAL

3.1. Lightweight Materials

Lightweight materials include magnesium, aluminum, advanced high-strength steels, titanium as well as polymer-matrix composites reinforced with glass and carbon fibers. A list of the lightweight materials and their potential for weight reduction are shown in Table 3.1. (U.S. Department of Energy, 2010).

Table 3.1. Potential Vehicle Materials Substitution (U.S. Department of Energy, 2010)

Lightweight Material	**Material Replaced**	**Mass Reduction**	**Relative Cost (per part)**
High Strength Steel	Mild Steel	10	1
Aluminum	Steel, Cast Iron	40-60	1.3-2
Magnesium	Steel or Cast Iron	60-75	1.5- 2.5
Magnesium	Aluminum	25-35	1-.1.5
Glass Fiber Reinforced Polymer (FRP) Composites	Steel	25-35	1-1.5
Graphite FRP Composites	Steel	50-60	2-10+
Aluminum Metal Matrix Composite	Steel or Cast Iron	50-65	1.5-3+
Titanium	Alloy Steel	40-55	1.5-10+
Stainless Steel	Carbon Steel	20-45	1.2-1.7

In automotive industry, high strength steel, aluminum alloys, magnesium alloy, composites are used to reduce weight. These materials must have the performance requirements (strong, durable, easily formed and joined into assemblies and components, sufficiently well-characterized) to use for vehicle design. Comparative properties of these materials are summarized in Table 3.2 (Cheah, 2010).

Table 3.2. Relevant properties of automotive materials (Cheah, 2010)

Material	**Density, g/cm3 (relative)**	**Yield Strength, MPa**	**Tensile Strength, MPa**	**Elastic Modulus, GPa**	**Equal stiffness thickness ratio**	**Equal strength thickness ratio**	**Relative Cost per part (25)**
Mild Steel	7.86 (1.00)	200	300	200	1.00	1.00	1.0
High Strength Steel	7.87 (1.00)	345	483	205	0.99	0.64	1.0-1.5
Iron (D4018)	7.10 (0.90)	276	414	166	-	-	-
Aluminum (AA6111)	2.71 (0.34)	275	295	70	1.42	0.85	1.3-2.0
Magnesium (AM50)	1.77 (0.23)	124	228	45	1.64	1.27	1.5-2.5
Composites -Carbon Fiber -Glass Fiber	1.57 (0.20)	Flexural: 200	810	190	1.01	-	2.0-10.0

3.2. Materials of Study

The properties of materials are given in Table 3.1. Material properties were taken from MatWeb for St- 37 Steel and Al-6061.Advanced high strength steel, Usibor 1500 material properties were taken from Arcelormittal product catalog.

Table 3.3. Material Properties

Materials	**Density (kg/m^3)**	**Elastic Modulus (GPa)**	**Poisson's Ratio**	**Tensile Strength, Yield (MPa)**	**Tensile Strength, Ultimate (MPa)**
St-37	7860	200	0,29	205	370
Al-6061 T6	2700	68,9	0,33	276	310
Usibor® 1500	7860	205	0,29	1100	1500

3.2.1. Advanced High Strength Steel (Ultra High Strength Steels)

Advanced high strength steels (AHSS) are more complex material than the mild steel. Conventional mild steels have relatively simple ferritic microstructure and it has low carbon content, minimal alloying elements. The mild steel is easily formed and it is used for its ductility. However, AHSS have usually multiphase microstructures for improved combination of strength and ductility. AHSS often has other advantageous mechanical properties, such as high strain-hardening capacity.

The AHSS family includes Dual Phase (DP), Complex-Phase (CP), Ferritic-Bainitic (FB), Martensitic (MS or MART), Transformation-Induced Plasticity (TRIP), Hot-Formed (HF), and Twinning-Induced Plasticity (TWIP). These 1st and 2nd Generation AHSS grades are uniquely qualified to meet the functional performance demands of certain parts. Recently there has been increased funding and research for the development of the "3rd Generation" of AHSS. These are steels with improved strength-ductility combinations compared to present grades, with potential for more efficient joining capabilities, at lower costs. These grades will reflect unique alloys and microstructures to achieve the desired properties. The broad range of properties is best illustrated by the famous Global Formability Diagram, captured in Figure 1. (Keeler and Kimchi, 2014).

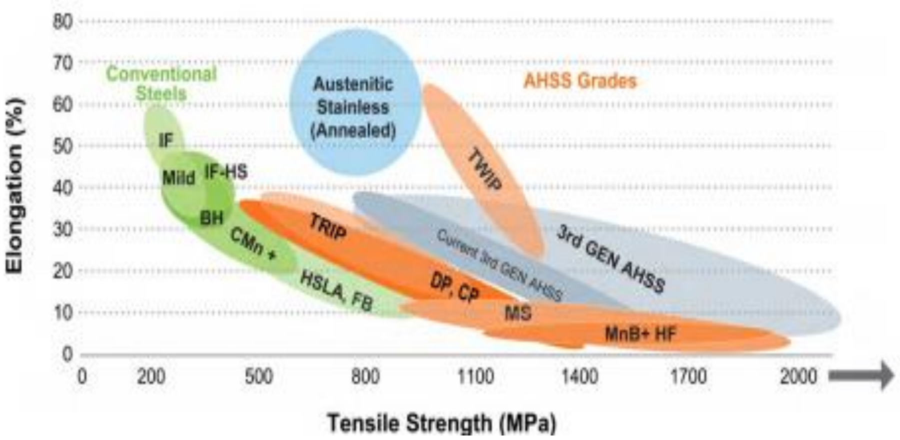

Figure 3.1. Global Formability Diagram, illustrating the range of properties available from today’s AHSS grades (World Auto Steel, 2014)

Steels with yield strength levels in excess of 550 MPa are generally referred to as AHSS. These steels are also sometimes called “ultrahigh-strength steels” for tensile strengths exceeding 780 MPa. AHSS with tensile strength of at least 1000 MPa are often called “GigaPascal steel” (1000 MPa = 1GPa). These materials have excellent strength combined with excellent ductility, and thus meet many vehicle functional requirements. Due to alloying content, however, they are expensive choices for many components, and joining can be a challenge. Third Generation AHSS seeks to offer comparable or improved capabilities at significantly lower cost (World Auto Steel, 2014).

In this study, ultra-high strength steel is used due to advanced mechanical properties (strength, formability, impact resistance etc.). This material allows substantial weight reduction.

3.2.2. Aluminum Alloys

Aluminum is a light metal and the use of aluminum offers considerable potential to reduce the weight of an automobile body. Aluminum is a soft metal, but high strength- weight ratios can be achieved in certain alloys.

An aluminum alloy is a chemical composition where other elements are added to pure aluminum in order to enhance its properties, primarily to increase its strength. These other elements include iron, silicon, copper, magnesium, manganese and zinc. These alloys divided several groups according to alloying elements. One of these groups is 6xxx series. The 6xxx series are versatile, heat treatable, highly formable, weldable and have moderately high strength coupled with excellent corrosion resistance. Alloys in this series contain silicon and magnesium in order to form magnesium silicide within the alloy. Extrusion products from the 6xxx series are the first choice for architectural and structural applications. Alloy 6061 is the most widely used alloy in this series and is often used in truck and marine frames. (Anonymous, 2016a)

4. METHOD

4.1. Computer Software

In this study, CAD and FEM software are used for the decision of the design, material. In this chapter basic information about these technologies are presented.

4.1.1. Computer Aided Design (CAD)

Computer aided design (CAD) can be defined as the use of computer systems to assist in the creation, modification, analysis or optimization of a design. CAD software consists of the computer programs to implement computer graphics on the system plus application programs to facilitate the engineering functions of the user company. CAD/ CAM products are used to increase productivity of the designer, improve the quality of design, improve communications through documentation, and create a database for manufacturing (Sarcar et al., 2008).

CATIA (Computer Aided Three-dimensional Interactive Application) is a multi-platform CAD/CAM/CAE commercial software suite developed by the French company Dassault Systemes and marketed worldwide by IBM. Written in the C++ programming language, CATIA is the cornerstone of the Dassault Systemes product lifecycle management software suite. The software was created in the late 1970s and early 1980s to develop Dassault's Mirage fighter jet, and then was adopted in the aerospace, automotive, shipbuilding, and other industries (Anonymous, 2016b).

4.1.2. Finite Element Method (FEM)

The FEM was first used to solve problems of stress analysis, and has since been applied to many other problems like thermal analysis, fluid flow analysis, piezoelectric analysis, and many others. Basically, the analyst seeks to determine the distribution of some field variable like the displacement in stress analysis, the temperature or heat flux in thermal analysis, the electrical charge in electrical analysis, and so on. The FEM is a numerical method seeking an approximated solution of the distribution of field variables in the problem domain that is difficult to obtain analytically. It is done by dividing the problem domain into several elements, as shown in Figures 4.1. Known physical laws are then applied to each small element, each of which usually has a very simple geometry. Figure 4.2 shows the finite element approximation for a one-dimensional case schematically. A continuous function of an unknown field variable is approximated using piecewise linear functions in each sub-domain, called an element formed by nodes (Liu and Quek, 2003).

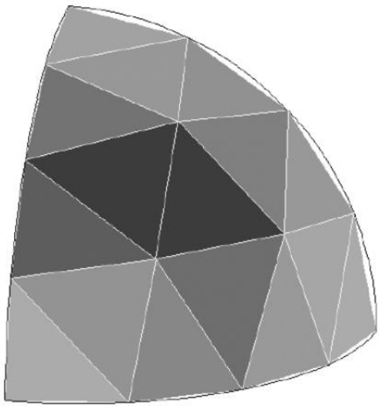

Figure 4.1. Hemispherical section discretized into several shell elements. (Liu and Quek, 2003)

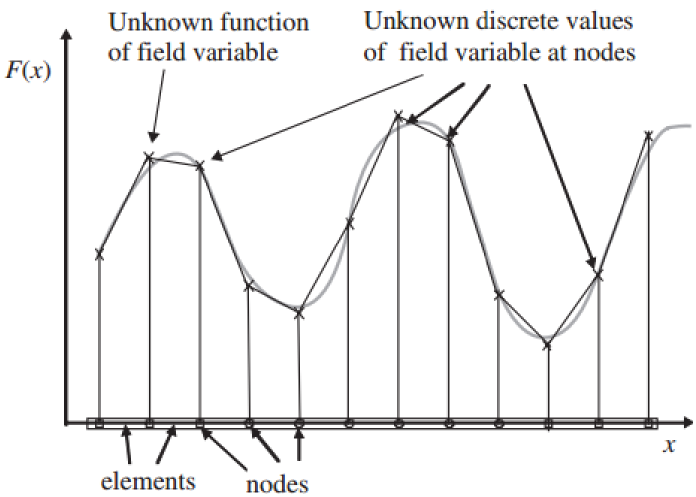

Figure 4.2. Finite element approximation for a one-dimensional case. A continuous function is approximated using piecewise linear functions in each sub-domain/element. (Liu and Quek, 2003)

The unknowns are then the discrete values of the field variable at the nodes. Next, proper principles are followed to establish equations for the elements, after which the elements are 'tied' to one another. This process leads to a set of linear algebraic simultaneous equations for the entire system that can be solved easily to yield the required field variable (Liu and Quek, 2003).

ANSYS is a general purpose software, used to simulate interactions of all disciplines of physics, structural, vibration, fluid dynamics, heat transfer and electromagnetic for engineers. ANSYS, which enables to simulate tests or working conditions, enables to test in virtual environment before manufacturing prototypes of products. Furthermore, determining and improving weak points, computing life and foreseeing probable problems are possible by 3D simulations in virtual environment. ANSYS works integrated with other used engineering software on desktop by adding CAD and FEA connection modules. ANSYS can import CAD data and also enables to build geometry with its "preprocessing" abilities. Similarly in the same preprocessor, finite element model (a.k.a. mesh) which is required for computation is generated. After defining loadings and carrying out analyses, results can be viewed as numerical and graphical (Anonymous, 2016c).

4.2. Seat Design Method

Seats are directly related to occupant safety. Therefore, seat design should provide safety for occupant. There are several design parameters for seats, such as, cost, weight, ergonomic constraints, strength, functionality, etc.

When the weight of the seat sub-systems’ distribution is reviewed, it can be seen that the mass of the frame is the largest contributor to seat total weight. The average seat which is made of St-37 is 45 kg and the seat frame is 29 kg (Yuce, 2013).

Seats’ frames consist of three base parts. These are seatback frame, seat frame and seat under frame which provides the connection between seat and vehicle floor. A bus seat and a seat frame are shown as examples of seat construction and design in Figure 4.3.

Figure 4.3. a) A complete bus seat (Anonymous,2016d) b) A bus seat frame (Anonymous,2016e)

A reference seat frame design was made to determine the weight reductions in this study. Following subchapters present seat dimension constraints, seat reference point specification method, topology optimization method which is used to optimize the design.

4.2.1. Seat Dimensions' Constraints

A CAD-model of seat frame was built based on reference dimensions of "Standard Bus Procurement Guidelines RFP" .This reference seat frame designed without compromising any comfort criteria. Reference dimensions are shown in Figure 4.4 (American Public Transportation Association, 2013).

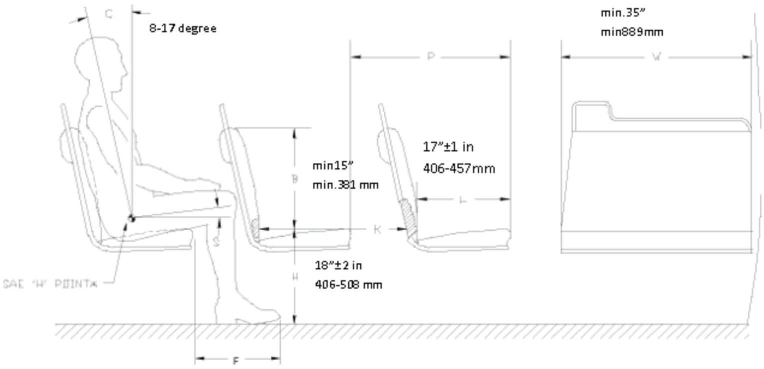

Figure 4.4. Seating Dimensions &Standard Configuration (APTA, 2013)

4.2.2. Seat Reference Point

The seat reference point was specified by using 95th percentile man manikin. The H-point of the manikin was specified as design reference point as it is described in SAE J1100 Motor Vehicle Dimension document. In Figure 4.5 the manikin, reference seat structure and H-point of the manikin are shown.

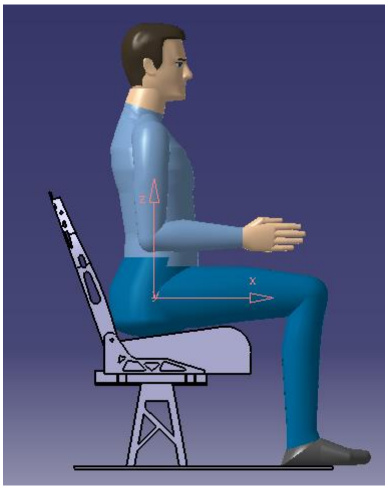
Figure 4.5. SRP of Seat Design with 95 Percentile Manikin

4.2.3. Seat Design by Using Topology Optimization Program

In order to optimize the design by using topology optimization program, forces and constraints must be determined. The dimension constraints were considered to specify the design area of topology optimization program. This design area is shown in Figure 4.6. The load cases that are explained in seat regulation and seat tests section were used to specify the forces for optimization. Before the optimization process, all load case analyses were done in FEA program and peak forces were specified for the design area. The specified design area was optimized to withstand the specified forces with minimum mass. The results of the topology optimization process are shown in Figure 4.7.

Figure 4.6. Seat Design Area

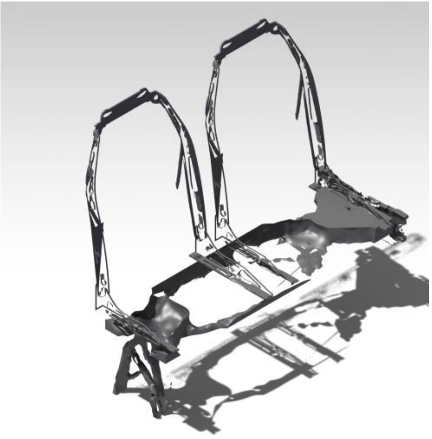

Figure 4.7. Topology Optimization Results of Seat Design Study

In automotive sector there are several regulations which specify the minimum requirements of seats. According to these regulations, the seats must be designed to meet various loading conditions like forward, reward dynamic loads and other static loads. In this chapter, the seat test which was used to verify the design is presented.

There are different standards for seats in Europe and United States. In United States, American Public Transportation Association (APTA) Standards (Standard Bus Procurement Guidelines) is used as a reference by seat designers. The Economic Commission for Europe (ECE) is the organization responsible for enacting legislation relative to seats for large-size passenger transit vehicles in Europe and for approving such seats. In Table 4.1, 4.2, 4.3 show an overview of seat standards. The load cases that are shown in tables were used in this study.

Table 4.1. Overview of APTA Standards (United States) (Bergeron and Audet, 2004)

Load Case	**Experimental Conditions**	**Area of Application**	**Max. Deformation (mm)**
Deceleration	10 G Duration: 10 msec	Entire Seat	<355 (upper part of seat)
Vertical Force	2,23 kN	Cushion	6,5
Horizontal Force	2,23 kN	Seatback(force equally distributed over the seatback)	6,5

Table 4.2. Overview of FMVSS 207(FMVSS 207, 2008)

Load Case	**Experimental Conditions**	**Area of Application**
Rearward Force	F=20*9,81*Ws Duration: Apply-5secs Hold-5secs Release-5secs	Center of Gravity
Moment Force	M=373 Nm F=373/D(distance between SRP and upper cross member) Duration: Apply-5secs Hold-5secs Release-5secs	Uppermost Cross Member

Table 4.3. Overview of ECE Regulation 80 (Bergeron and Audet, 2004).

Load Case	**Experimental Conditions**	**Area of Application**	**Maximum Deformation (mm)**
Deceleration	10G Duration: 10msec	Entire Seat	
Horizontal Force	1.0kN Duration: 200msec	Seatback (force equally distributed over the width of the seatback up to a predetermined height of between 70 cm and 80 cm from the floor)	400
Horizontal Force	2.0kN Duration: 200msec	Seatback (force equally distributed over the width of the seatback up to a predetermined height of between 45 cm and 55 cm from the floor)	
Vertical Force	5.0 kN	Anchorage	

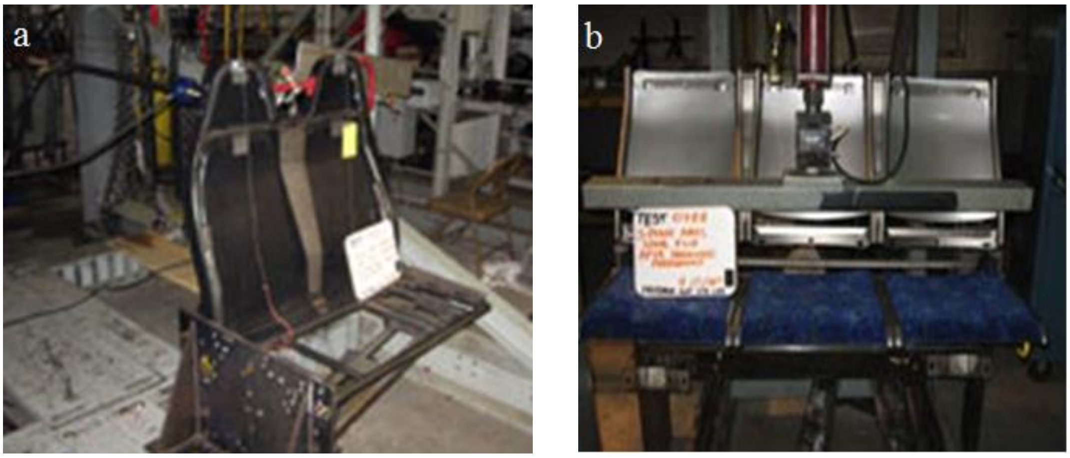

Figure 4.8. Actual APTA Seat Tests Photos a) APTA Horizontal Seatback Load Application b) APTA Vertical Force Application (Anonymous, 2016f)

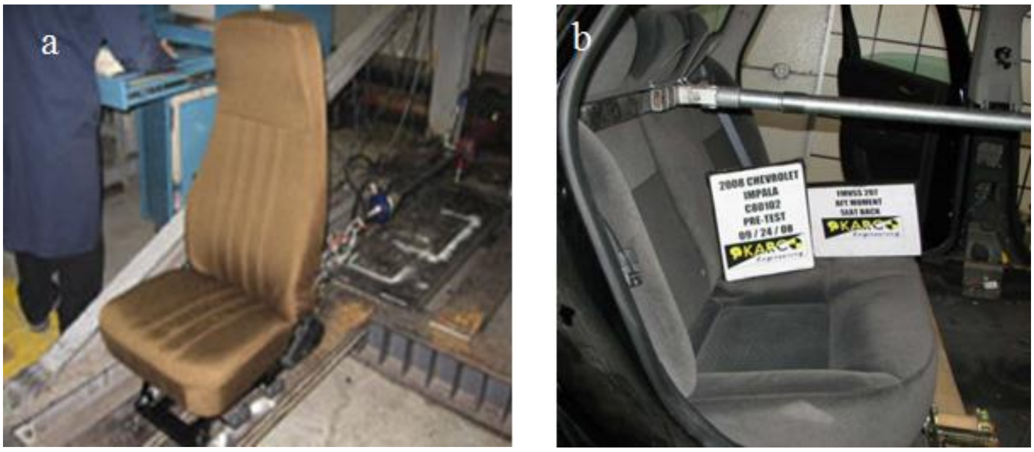

Figure 4.9. Actual FMVSS 207 Seat Tests Photos a) FMVSS Rearward Force Application (Anonymous, 2016f) b) FMVSS Rearward Moment Load Application (Kratzke, 2008)

Figure 4.10. Actual ECE R80 Seat Tests Photos (Anonymous, 2016g)

Normally ECE R80 static tests have minimum deformation requirement. The seats have minimum 100 mm deformation for horizontal loading condition 1 kN at a level between 700 mm and 800 mm and 50 mm deformation for horizontal condition 2 kN at a level between 450 mm and 500 mm. In this study, this minimum deformation requirement was ignored due to the APTA horizontal deformation requirements.

5. RESEARCH AND DISCUSSION

5.1. Analysis Results of Load Cases for Reference Seat Design

A reference seat design was made according to the topology optimization results; it is shown in Figure 5.1. The wall thicknesses and weights of the design parts are shown in Table 5.1. Reference seat material was selected as St-37. To verify the design the load cases and tests were simulated by using FEM software. A finite element model was formed in FEM software. This final element model consists a seat structure. Most of seat structures are made of sheet and tube. Seat structure modeled as surface elements to obtain better mesh element quality. Weld connections were simulated as bonded contact. Bolt connections were modeled by using line elements. The surface of sidewall and floor were defined as fixed support.

The reference seat was analyzed according to the APTA, ECE and FMVSS. The reference seat passed all tests. Table 5.2 shows the results of the tests.

Figure 5.1. Reference Seat Design

Table 5.1. Wall Thickness and Weights for Reference Design

Part Name	**Reference Wall Thickness (mm)**	**Reference Seat Weight (kg)**
Seat-Floor Attachment	4	2,133
Seat Frame	2	4,398
Seat Upper Frame	6	0,918
Sidewall Attachment	5	0,83
Seatback	10	5,447
Total Weight		21,927

Table 5.2. Reference Seat Analysis Results

Standards	**Load Case**	**Requirement Max. Deformation (mm)**	**Max. Deformation (mm)**	**Max. Stress (MPa)**
APTA Load Cases	Deceleration	<355 (upper part of seat)	15	161
	Vertical Force	6,5	0,64	82
	Horizontal Force	6,5	6,3	327
ECE R80 Load Case	Deceleration	-	15	161
	Horizontal Force (1kN)	400	3,8	154
	Horizontal Force(2kN)	-	19	297
	Vertical Force	-	0,69	85,4
FMVSS	Rearward Force	-	0,16	339
	Rearward Moment	-	0,2	338,9

In these subchapters the results of each test were shown and explained in details.

5.1.1. APTA & ECE Regulation 80 Deceleration Load Case Analysis

The seat design was analyzed according to the APTA and ECE R80, 10G deceleration was applied to the seat during 10 milliseconds. The maximum total deformation of the entire seat is 15 mm. This value is below the requirement of the APTA standard. The maximum stress of the seat design is 160 MPa, this values is below the tensile strength of St-37. Consequently, the seat design withstands the deceleration force according to ECE Regulation 80.

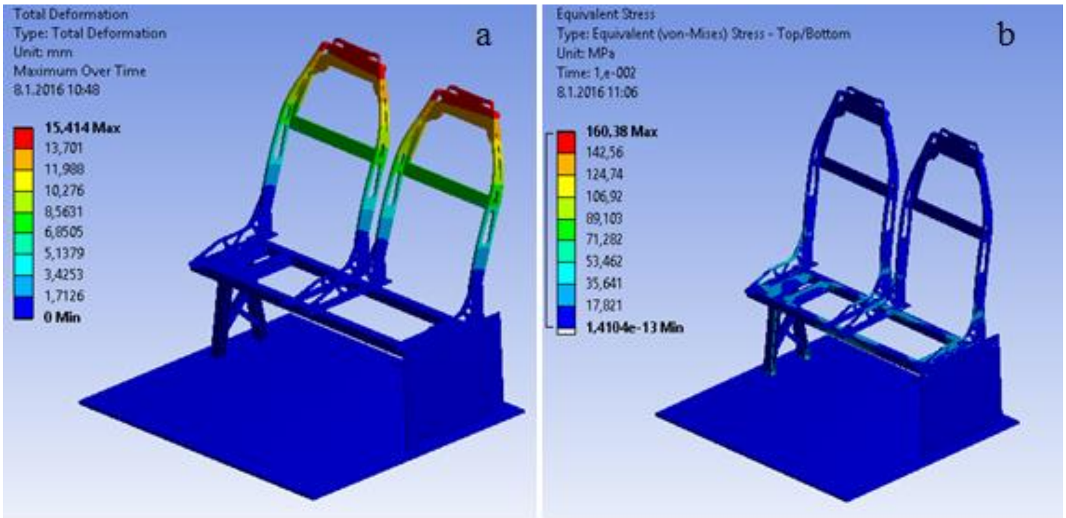

Figure 5.2. APTA & ECE R80 Deceleration Load Case Analysis Results a) Total Deformation b) Maximum Equivalent Stress

5.1.2. APTA Horizontal Force to Seatback Load Case Analysis

The seat design was analyzed according to the APTA, 2,23 kN load was applied to the upper cross member of seatback through the loading bar. The maximum total deformation of the entire seat is 6,3 mm. This value is below the requirement of the APTA standard.

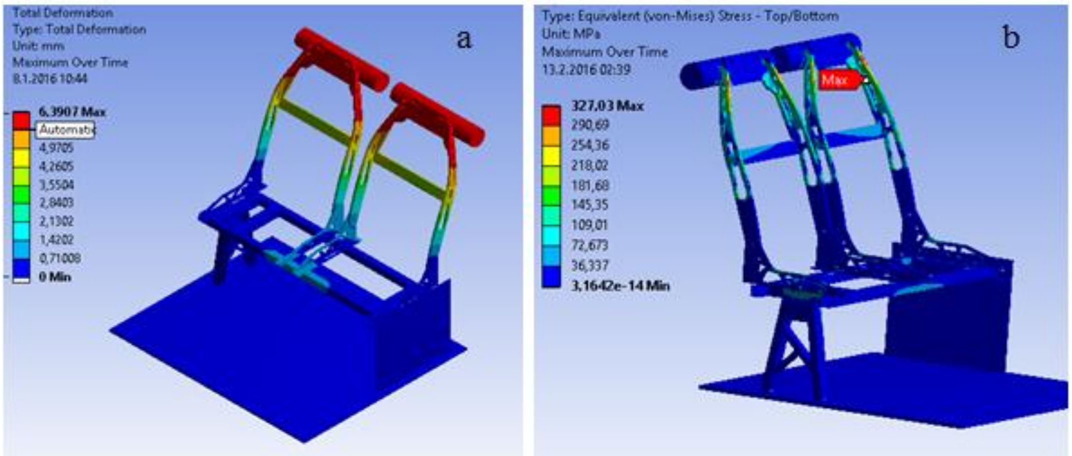

Figure 5.3. APTA Horizontal Force to Seatback Load Case Analysis Results a) Total Deformation b) Maximum Equivalent Stress

5.1.3. APTA Vertical Force to Seat Cushion Part Load Case Analysis

The seat design was analyzed according to the APTA, 2,23 kN load was applied to the upper cross member of seatback through the loading bar. The maximum total deformation of the entire seat is the 1 mm. This value is below the requirement of the APTA standard.

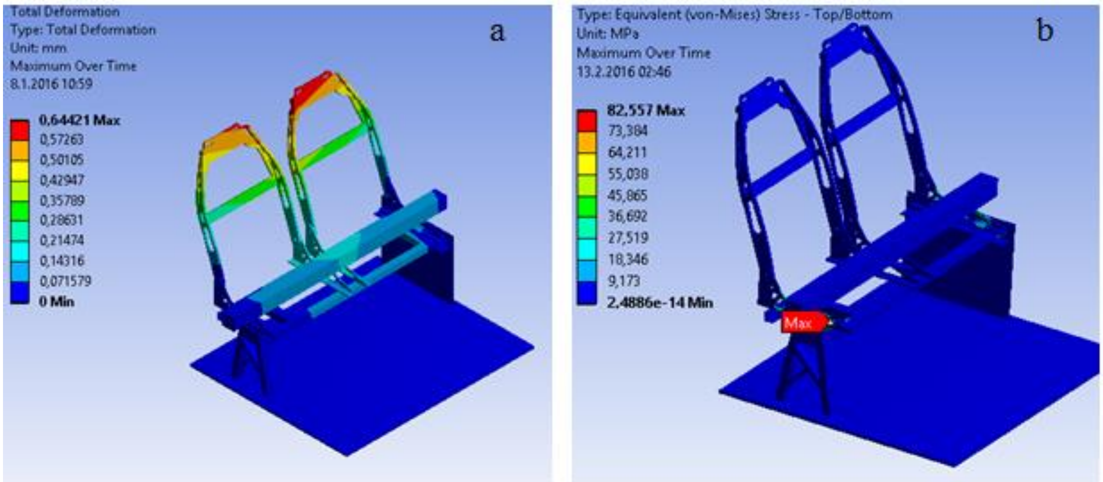

Figure 5.4. APTA Vertical Force to Seat Cushion Part Load Case Analysis Results a) Total Deformation b) Maximum Equivalent Stress

5.1.4. ECE Regulation 80 Horizontal Force to Seatback Load Case Analysis 1

The seat design was analyzed according to the ECE R80, 1 kN load was applied to the seatback through the loading bar during 200 ms. Seatback force was applied at a height 740,94 mm from the floor. The maximum deformation of design is below the maximum deformation limit of ECE R 80.

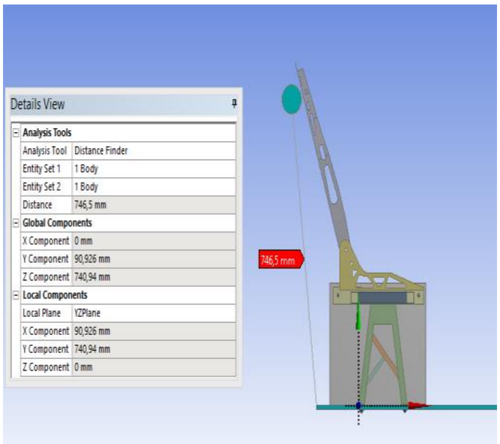

Figure 5.5. Loading bar height from the floor

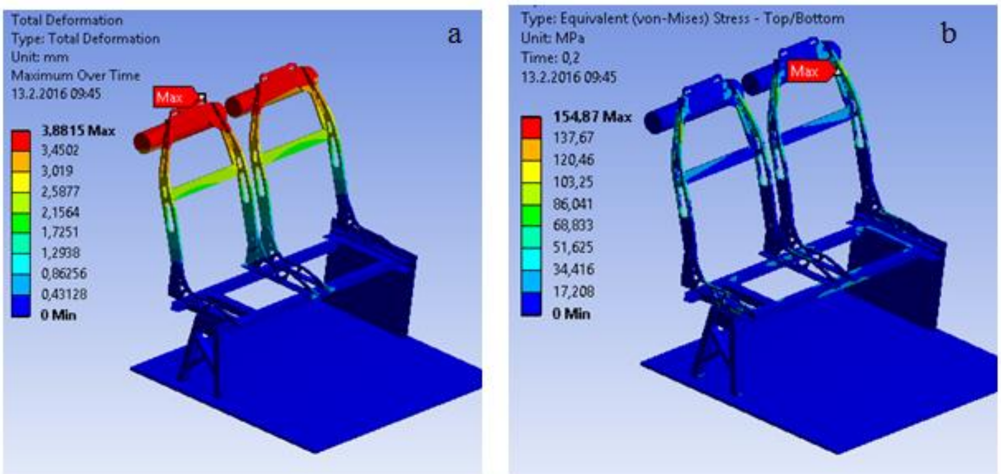

Figure 5.6. ECE Regulation 80 Horizontal Force to Seatback Load Case Analysis 1 Results a) Total Deformation b) Maximum Equivalent Stress

5.1.5. ECE Regulation 80 Horizontal Force to Seatback Load Case Analysis 2

The seat design was analyzed according to the ECE Regulation 80,2 kN load was applied to seatback through the rigid bar at a height 451,33 mm from the floor. The maximum stress value is below the tensile strength of material. This seat design can withstand this load value.

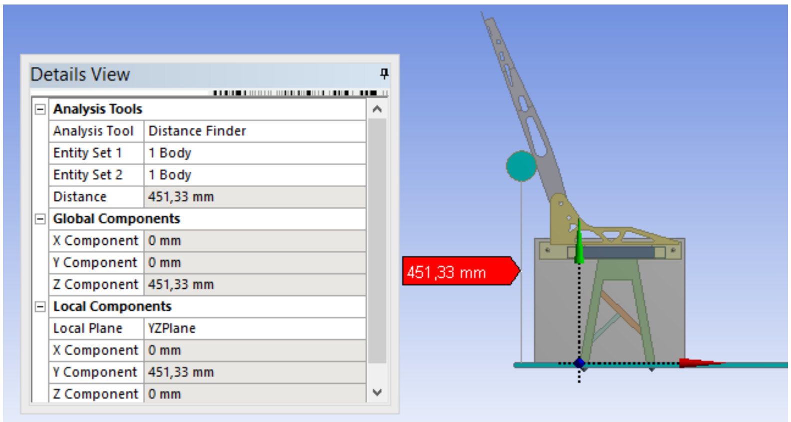

Figure 5.7. Loading bar height from the floor

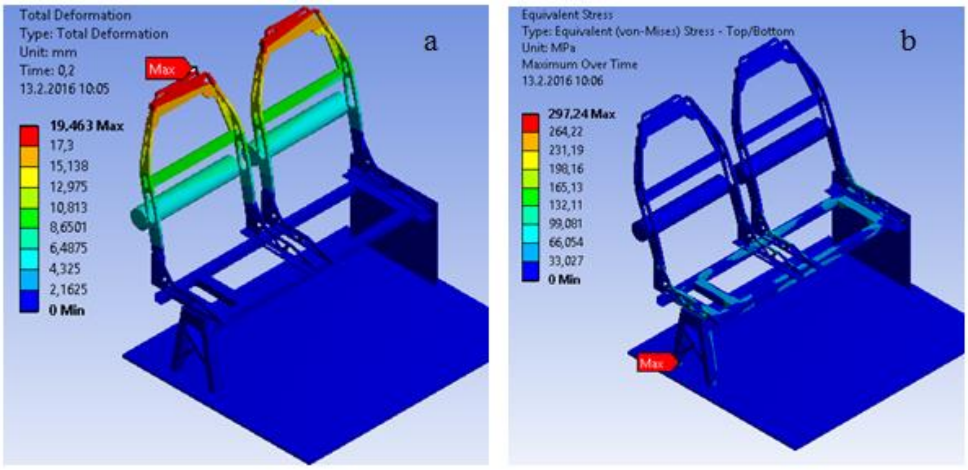

Figure 5.8. ECE Regulation 80 Horizontal Force to Seatback Load Case Analysis 2 Results a) Total Deformation b) Maximum Equivalent Stress

5.1.6. ECE Regulation 80 Vertical Force to Anchorage

A vertical force which is equal to 5 kN was applied to the anchorage points of design. The maximum stress of the seat design is about 345 MPa. This value is below the ultimate tensile strength of St-37, therefore the seat design withstands the vertical load case of ECE R80.

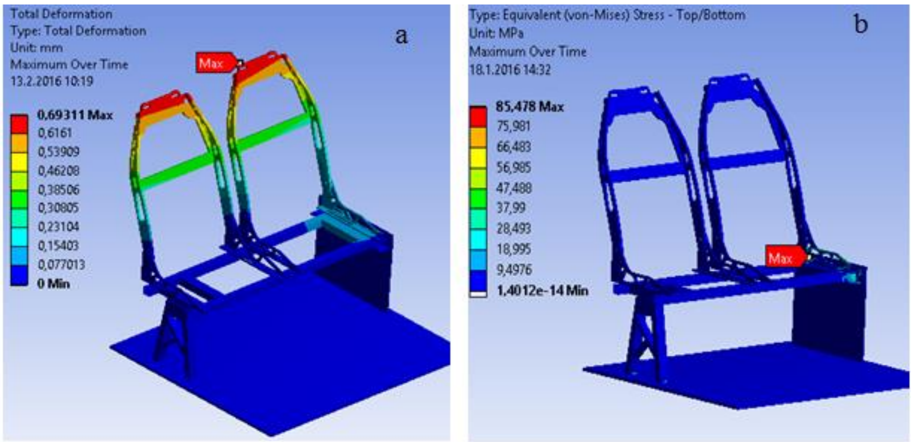

Figure 5.9. ECE Regulation 80 Vertical Force to Anchorage Analysis Results a) Total Deformation b) Maximum Equivalent Stress

5.1.7. Rearward Force Application Test Simulation

The force was applied through the center of gravity on a rigid member. The force, which was determined according to the FMVSS 207, was equal to the 20 times the mass of the seat in kilograms multiplied by 9.8. The force was applied in 5 seconds, hold for 5 seconds and released in 5 seconds.

Load: 20*23*9,81 Newton =4513 N

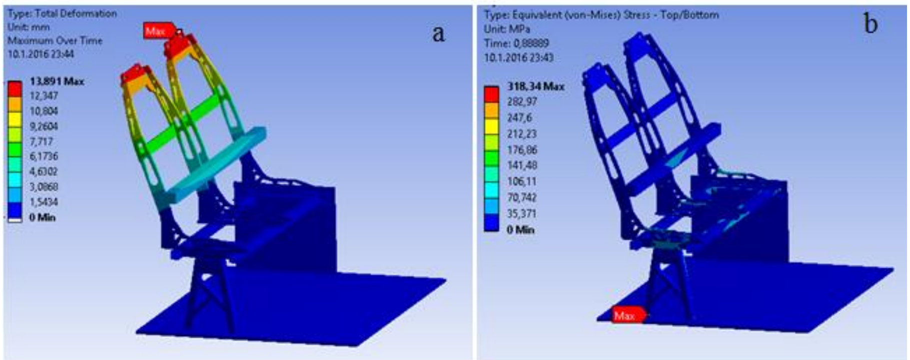

Figure 5.10. Rearward Force Application Test Analysis Results a) Total Deformation b) Maximum Equivalent Stress

5.1.8. Moment applied in a Rearward Longitudinal Direction Test Simulation

The force was applied to the upper cross-member of the seat backs. All loads were applied in 5 seconds, hold for 5 seconds and released in 5 seconds.

Moment= 373 N-m/occupant

Force=373 N-m/occupant / (D x No. Of Occupants)

D= Vertical distance between SRP plane and upper cross member

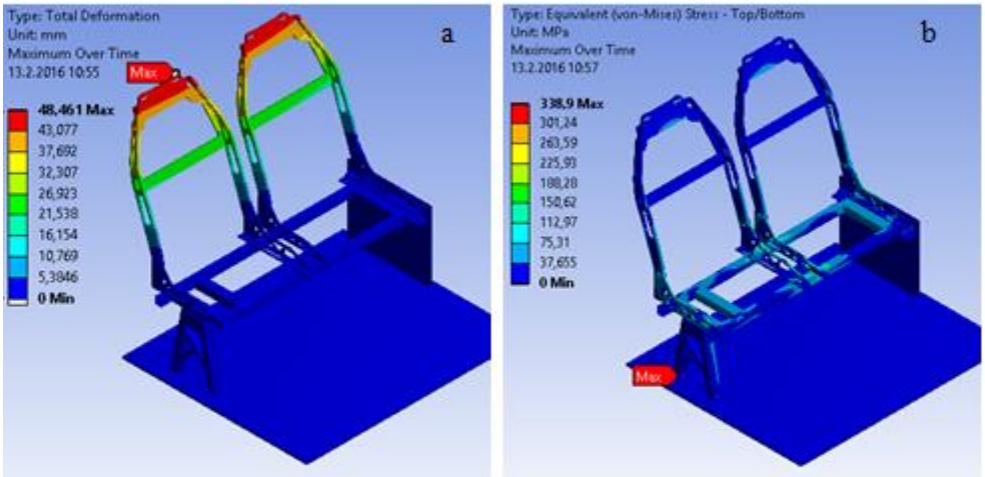

Figure 5.11. Rearward Force Application Test Analysis Results a) Total Deformation b) Maximum Equivalent Stress

The reference seat design was fulfilled the requirements of APTA, ECE R80 and FMVSS 207.

5.2. Seat Design for Ultra High Strength Steel

In this chapter, ultra-high strength steel was used to reduce the seat weight. The design was tested according to specified load cases. Four steps were applied to obtain a successful design.

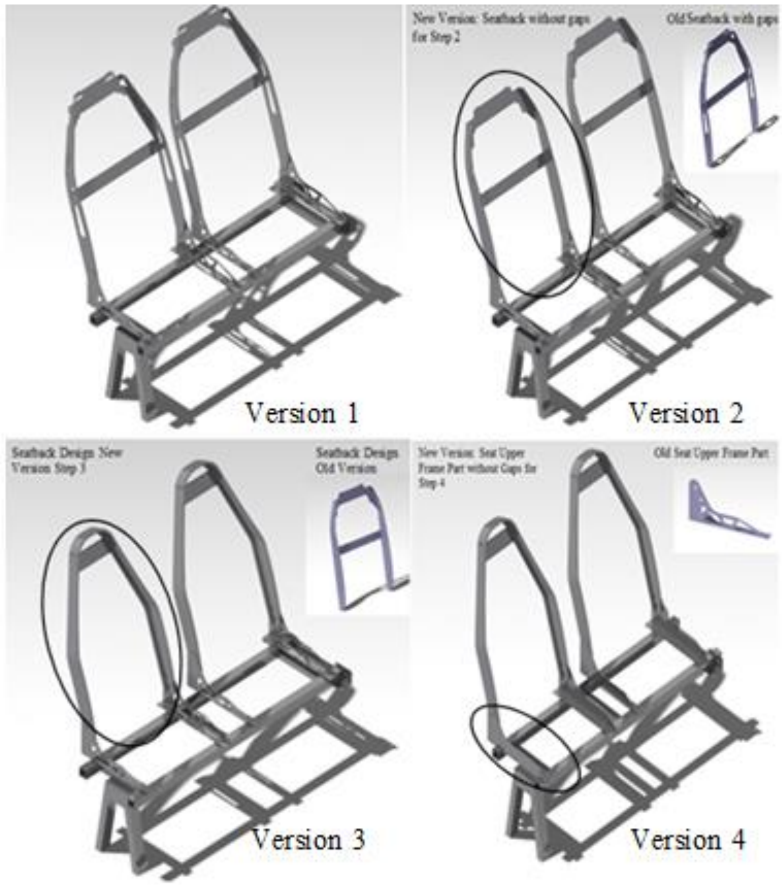

Figure 5.12. Seat Design Versions for UHSS

5.2.1. Seat Design Development Step 1

The wall thicknesses of the reference design were reduced as a first step. The specified tests were simulated for this design by using FEM software. The tests results are shown in Table 5.2. This design was failed for APTA horizontal force load case.

Figure 5.13. Seat Design for Step 1

Table 5.3. Wall Thickness and Weights for Reference Design and UHSS Design Step 1

Part Name	**Reference Wall Thickness (mm)**	**UHSS Wall Thickness (mm)**	**Reference Seat Weight (kg)**	**UHSS Seat Weight(kg)**
Seat-Floor Attachment	4	1,5	2,133	0,713
Seat Frame	2	1,5	4,398	2,771
Seat Upper Frame	6	2	0,918	0,288
Sidewall Attachment	5	2	0,874	0,35
Seatback	10	6	5,414	3,518
Total Weight			21,927	12,024

Table 5.4. Load Case Analysis Results for Step 1

Standards	Load Case	Requirement Max. Deformation (mm)	Max. Deformation (mm)	Max. Stress (MPa)
APTA Load Cases	Deceleration	<355 (upper part of seat)	14,42	458,8
	Vertical Force	6,5	5,8	482
	Horizontal Force	6,5	22,5	1565
ECE R80 Load Case	Deceleration	-	14,42	458,8
	Horizontal Force (1kN)	400	12,39	669
	Horizontal Force(2kN)	-	3,96	1171,3
	Vertical Force	-	0,32	389
FMVSS	Rearward Force Application Test Simulation	-	13,8	934
	Rearward Moment Application Test Simulation	-	50,53	1253

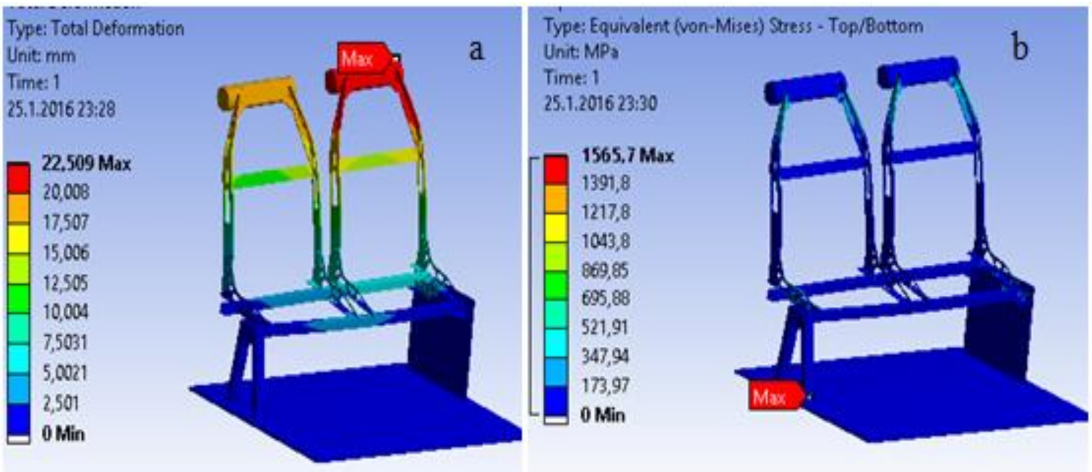

Figure 5.14. APTA Horizontal Force Test Analysis Results for Step 1 a) Total Deformation b) Maximum Equivalent Stress

5.2.2. Seat Design Development Step 2

The seatback deformation is above the regulation, therefore the gaps on seatbacks was removed.

Figure 5.15. Seat Design for Step 2

Table 5.5. Wall Thickness and Weights for Reference Design and UHSS Design Step 2

Part Name	**Reference Wall Thickness (mm)**	**UHSS Wall Thickness (mm)**	**Reference Seat Weight (kg)**	**UHSS Seat Weight (kg)**
Seat-Floor Attachment	4	1,5	2,133	0,713
Seat Frame	2	1,5	4,398	2,771
Seat Upper Frame	6	2	0,918	0,288
Sidewall Attachment	5	2	0,83	0,35
Seatback	10	6	5,447	3,692
Total Weight			21,927	12,517

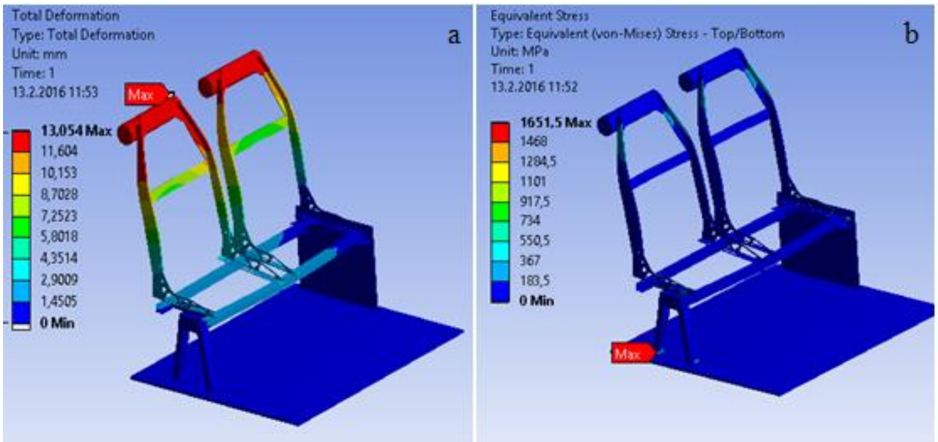

Figure 5.16. APTA Horizontal Force Test Analysis Results for Step 2 a) Total Deformation b) Maximum Equivalent Stress

5.2.3. Seat Design Development Step 3

The seatback deformation is above the regulation; therefore the seatback design was changed.

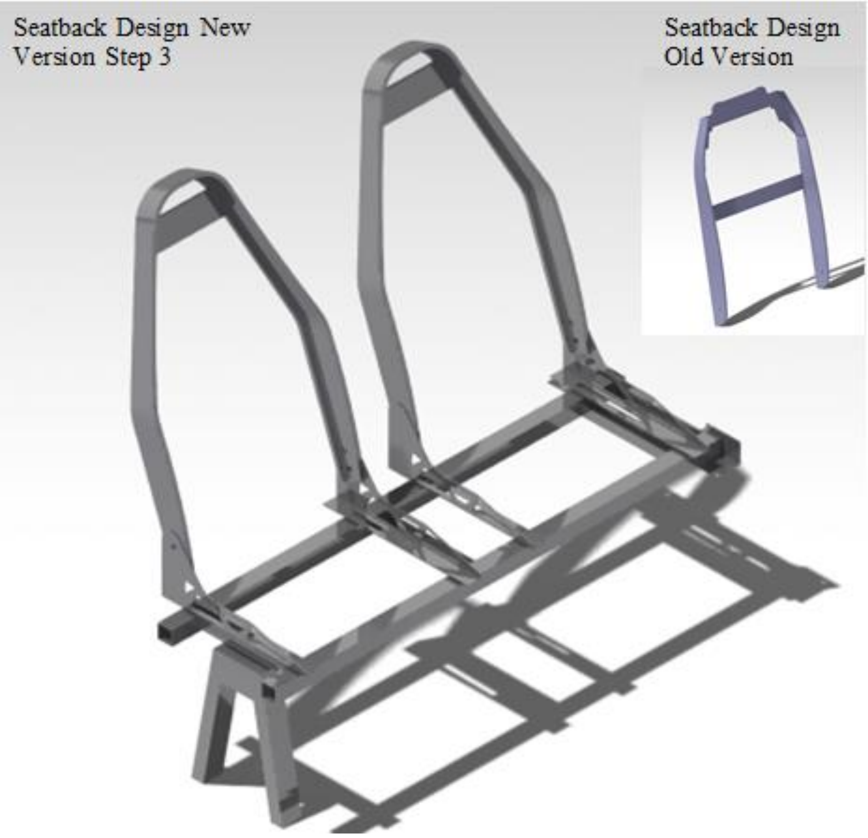

Figure 5.17. Seat Design for Step 3

Table 5.6. Wall Thickness and Weights for Reference Design and UHSS Design Step 3

Part Name	**Reference Wall Thickness (mm)**	**UHSS Wall Thickness (mm)**	**Reference Seat Weight (kg)**	**UHSS Seat Weight (kg)**
Seat-Floor Attachment	4	1,5	2,133	0,577
Seat Frame	2	1,5	4,398	2,917
Seat Upper Frame	6	2	0,918	0,223
Sidewall Attachment	5	3	0,83	0,45
Seatback	10	8	5,447	4,83
Total Weight			21,927	14,496

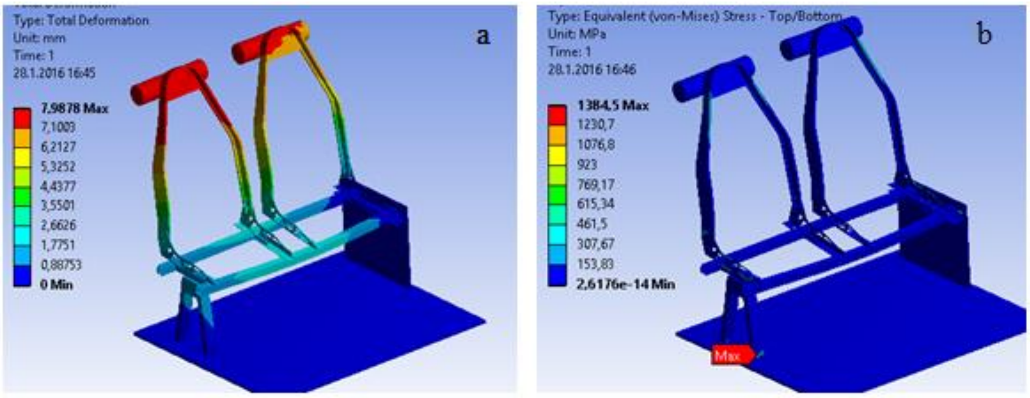

Figure 5.18. APTA Horizontal Force Test Analysis Results for Step 3 a) Total Deformation b) Maximum Equivalent Stress

5.2.4. Seat Design Development Step 4

The total deformation was above the regulation; therefore the gaps on upper part of seat frame were removed. In this step, the total deformation of seat design is below the requirement. This design is passed the regulation. The other load case analyses were done.

Figure 5.19. Seat Design for Step 4

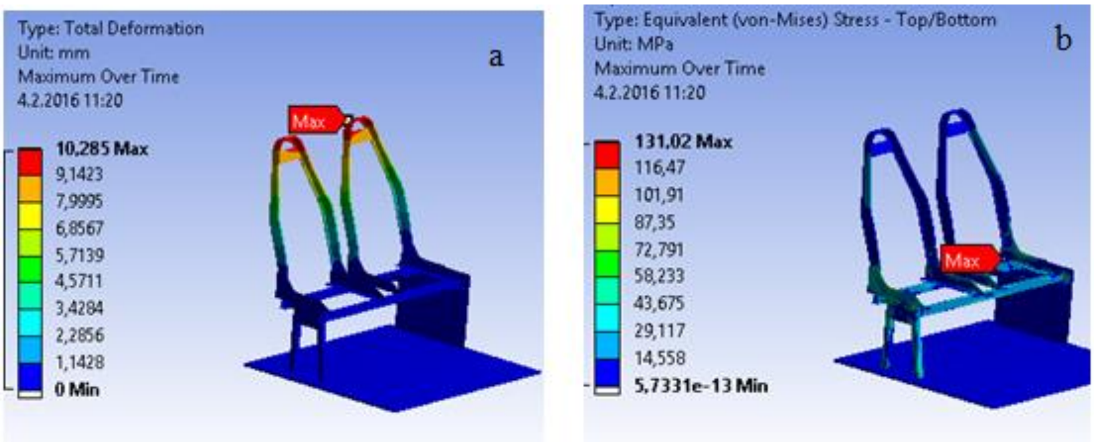

Figure 5.20. APTA & ECE Regulation 80 Deceleration Analysis Results a) Total Deformation b) Maximum Equivalent Stress

Table 5.7. Wall Thickness and Weights for Reference Design and UHSS Design Step 4

Part Name	**Reference Wall Thickness (mm)**	**UHSS Wall Thickness (mm)**	**Reference Seat Weight (kg)**	**UHSS Seat Weight (kg)**
Seat-Floor Attachment	4	1,5	2,133	0,577
Seat Frame	2	1,5	4,398	2,917
Seat Upper Frame	6	2	0,918	0,432
Sidewall Attachment	5	3	0,83	0,45
Seatback	10	8	5,447	4,83
Total Weight			21,927	15,051

Table 5.8. UHSS Seat Analysis Results

Standards	**Load Case**	**Requirement Max. Deformation (mm)**	**Max. Deformation (mm)**	**Max. Stress (MPa)**
APTA Load Cases	Deceleration	<355 (upper part of seat)	10,28	131,02
	Vertical Force	6,5	0,42	50,72
	Horizontal Force	6,5	6,13	311,62
ECE R80 Load Case	Deceleration	-	3,7	230,3
	Horizontal Force (1kN)	400	2,64	148,8
	Horizontal Force(2kN)	-	1,66	283,41
	Vertical Force	-	0,9	150
FMVSS	Rearward Force Application Test Simulation	-	18,2	311,21
	Rearward Moment Application Test Simulation	-	42,2	587,1

5.2.4.1. APTA & ECE Regulation 80 Deceleration Load Case Analysis

The seat design was analyzed according to the APTA; 10G deceleration was applied to the seat during 10 milliseconds. The maximum total deformation of the entire seat is 10,28 mm. This value is below the requirement of the APTA standard. This load case is defined in the same way at the ECE Regulation 80.The maximum stress of the seat design is 131,02 MPa, this values is below the tensile strength of UHSS. Consequently, the seat design withstands the deceleration force according to ECE Regulation 80.

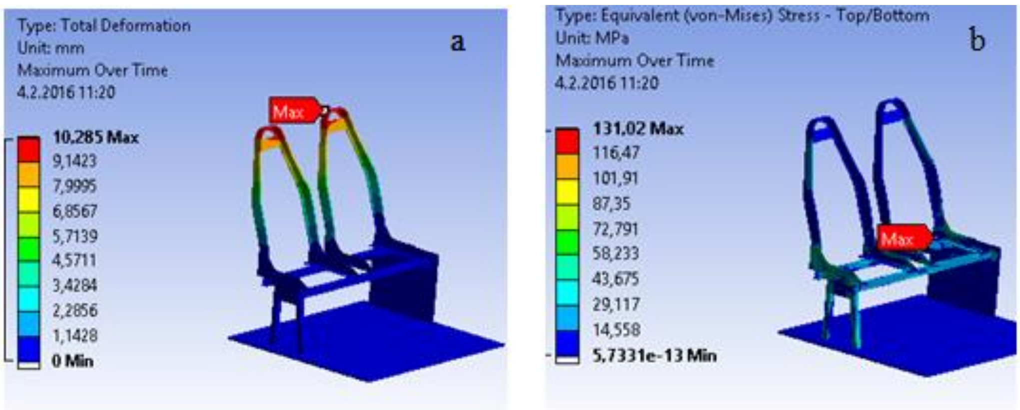

Figure 5.21. APTA & ECE Regulation 80 Deceleration Analysis Results a) Total Deformation b) Maximum Equivalent Stress

5.2.4.2. APTA Horizontal Force to Seatback Load Case Analysis

The seat design was analyzed according to the APTA, 2,23 kN load was applied to the upper cross member of seatback through the loading bar. The maximum total deformation of the entire seat is 6,13 mm. This value is below the requirement of the APTA standard.

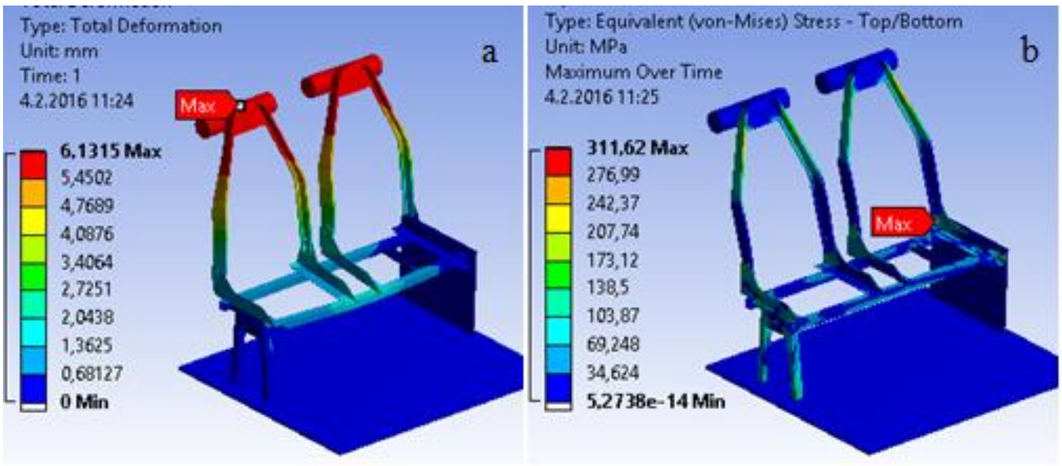

Figure 5.22. APTA Horizontal Force Application Analysis Results a) Total Deformation b) Maximum Equivalent Stress

5.2.4.3. APTA Vertical Force to Seat Cushion Part Load Case Analysis

The seat design was analyzed according to the APTA, 2,23 kN load was applied to the upper cross member of seatback through the loading bar. The maximum total deformation of the entire seat is below 1 mm. This value is below the requirement of the APTA standard.

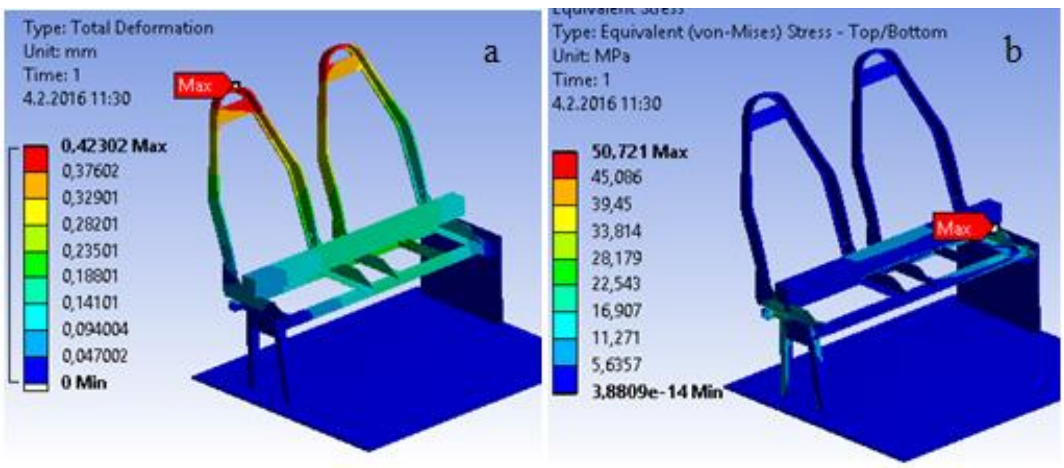

Figure 5.23. APTA Vertical Force Application Analysis Results a) Total Deformation b) Maximum Equivalent Stress

5.2.4.4. ECE Regulation 80 Horizontal Force to Seatback Load Case 1 Analysis

The seat design was analyzed according to the ECE Regulation 80, 1 kN load was applied to the seatback through the loading bar during 200 ms. Seatback force was applied at a height 748 mm from the floor. The maximum deformation of design is below the maximum deformation limit of ECE R 80.

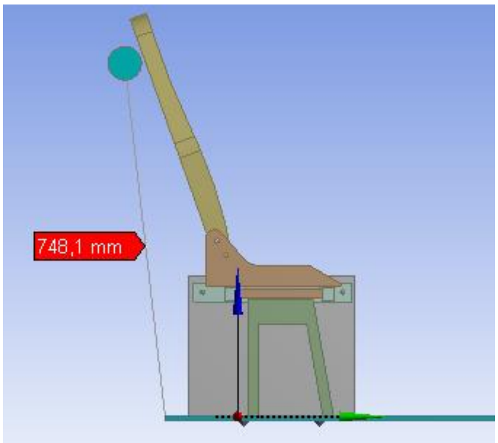

Figure 5.24. ECE R80 Horizontal Force Application, Height of Loading Bars

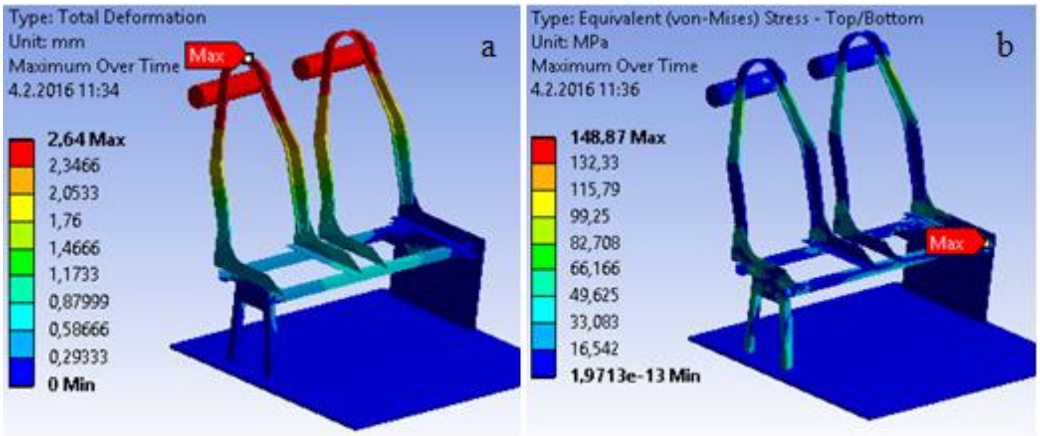

Figure 5.25. ECE R80 Horizontal Force Application Load Case 1 Analysis Results a) Total Deformation b) Maximum Equivalent Stress

5.2.4.5. ECE Regulation 80 Horizontal Force To Seatback Load Case 2 Analysis

The seat design was analyzed according to the ECE Regulation 80, 2 kN load was applied to seatback through the rigid bar at a height 463 mm from the floor. The maximum stress value is below the tensile strength of material. This seat design can withstand this load value.

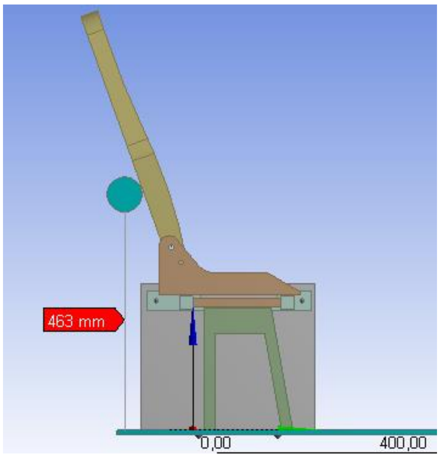

Figure 5.26. ECE R80 Horizontal Force Application, Height of Loading Bars

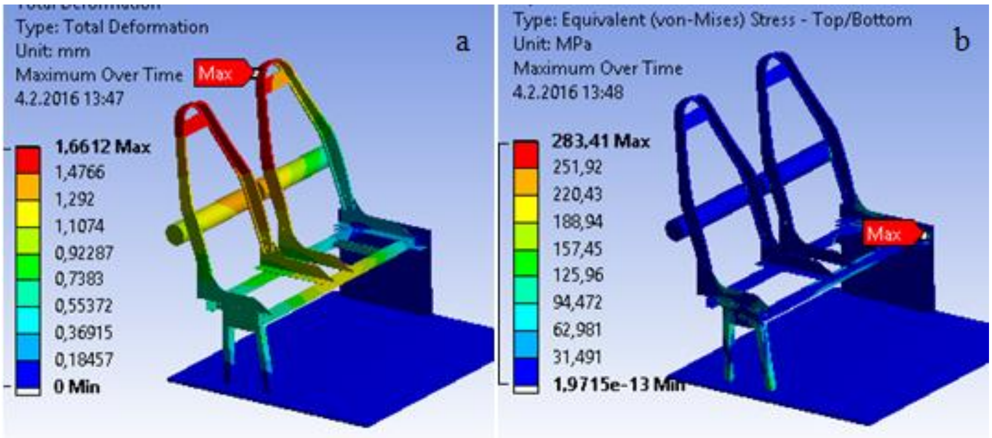

Figure 5.27. ECE R80 Horizontal Force Application Load Case 2 Analysis Results a) Total Deformation b) Maximum Equivalent Stress

5.2.4.6. ECE Regulation 80 Vertical Force to Anchorage

A vertical force which is equal to 5 kN was applied to the anchorage points of design. The maximum stress of the seat design is about 345 MPa. This value is below the ultimate tensile strength of UHSS, therefore the seat design withstands the vertical load case of ECE R80.

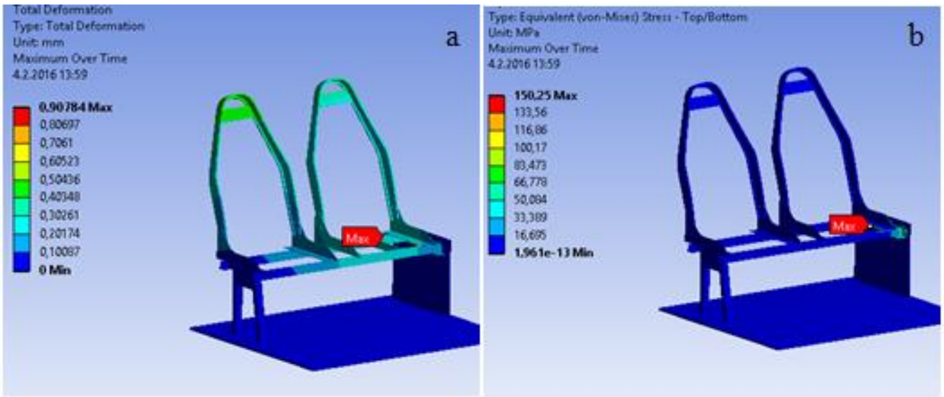

Figure 5.28. ECE R80 Vertical Force Application Load Case Analysis Results a) Total Deformation b) Maximum Equivalent Stress

5.2.4.7. Rearward Force Application Test Simulation

The force was applied through the center of gravity on a rigid member. The force, which was determined according to the FMVSS 207, was equal to the 20 times the mass of the seat in kilograms multiplied by 9.8. The force was applied in 5 seconds, hold for 5 seconds and released in 5 seconds.

Load: 20*23*9,81 Newton =3044 N

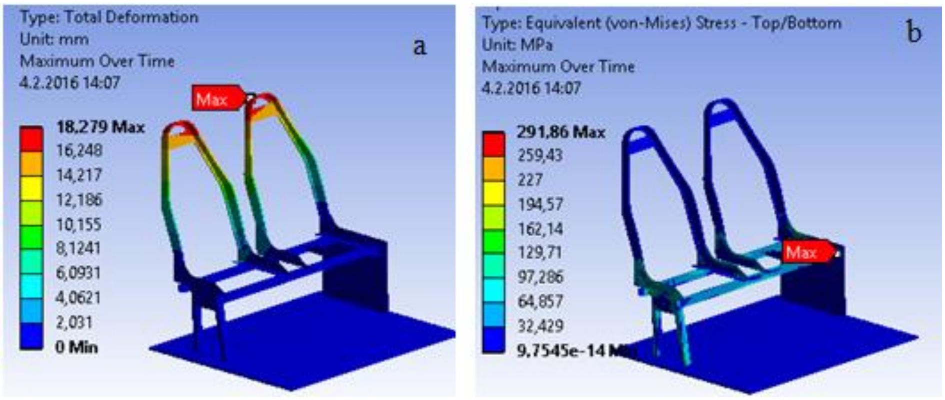

Figure 5.29. FMVSS 207 Rearward Force Application Load Case Analysis Results a) Total Deformation b) Maximum Equivalent Stress

5.2.4.8. Moment applied in a Rearward Longitudinal Direction Test Simulation

The force was applied to the upper cross-member of the seat backs. All loads were applied in 5 seconds, hold for 5 seconds and released in 5 seconds.

Moment= 373 N-m/occupant

Force=373 N-m/occupant / (D x No. Of Occupants)

D= Vertical distance between SRP plane and upper cross member

F=373/0,363= 950 N

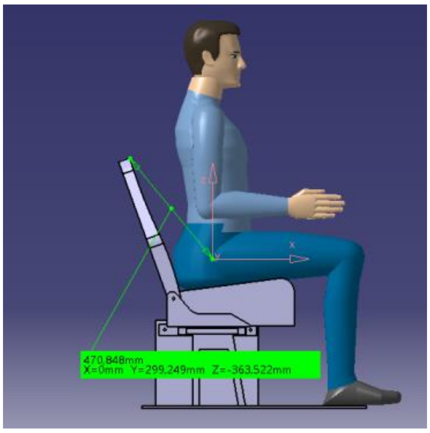

Figure 5.30. Vertical distance between SRP plane and upper cross member

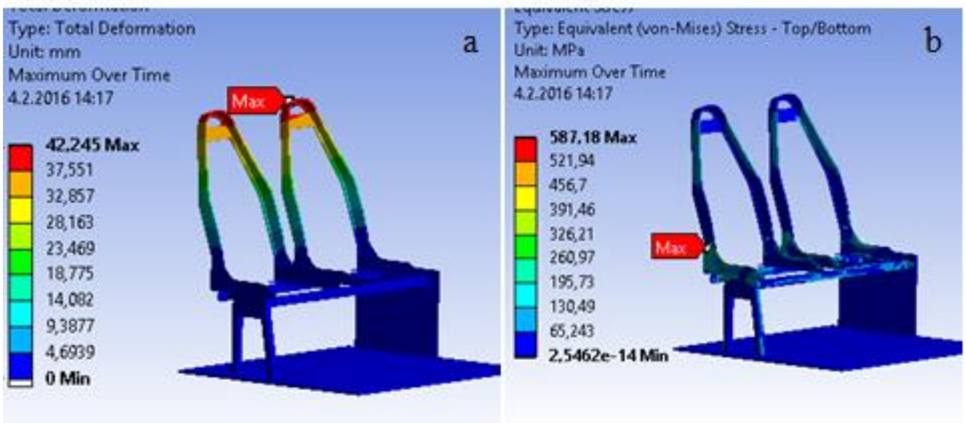

Figure 5.31. FMVSS 207 Rearward Moment Force Application Load Case Analysis Results a) Total Deformation b) Maximum Equivalent Stress

5.3. Seat Design for Al-6061 T6

The first method in this study to reduce the seat weight is using a material that has low density. According to the maximum stress of reference seat design Al 6061 material was chosen.

Figure 5.32. Seat Design Versions for Aluminum Alloy

5.3.1. Seat Design Development Step 1

Aluminum 6061 T6 was used instead of St-37 with same design. When the seat was analyzed, for the APTA horizontal force load case and FMVSS the maximum stress of the frame is above the ultimate tensile strength of material.

Figure 5.33. Seat Design

Table 5.9. Al- 6061 T6 Seat Analysis Results with Same Design

Standards	Load Case	Requirement Max. Deformation (mm)	Max. Deformation (mm)	Max. Stress (MPa)
APTA Load Cases	Deceleration	<355 (upper part of seat)	7,1	49,7
	Vertical Force	6,5	0,37	84,2
	Horizontal Force	6,5	17,2	312
ECE R80 Load Case	Deceleration	-	7,1	49,7
	Horizontal Force (1kN)	400		
	Horizontal Force(2kN)	-	28	257
	Vertical Force	-	0,52	112
FMVSS	Rearward Force Application Test Simulation	-	5,6	82,6
	Rearward Moment Application Test Simulation	-	64	337

Table 5.10. Wall Thickness and Weights for Reference Design and Al 6061 Design Step 1

Part Name	**Reference Wall Thickness (mm)**	**AL 6061 Wall Thickness (mm)**	**Reference Seat Weight (kg)**	**AL 6061 Seat Weight (kg)**
Seat-Floor Attachment	4	4	2,133	0,53
Seat Frame	2	2	4,398	1,09
Seat Upper Frame	6	6	0,918	0,23
Sidewall Attachment	5	5	0,874	0,22
Seatback	10	10	5,414	1,34
Total Weight			21,927	5,41

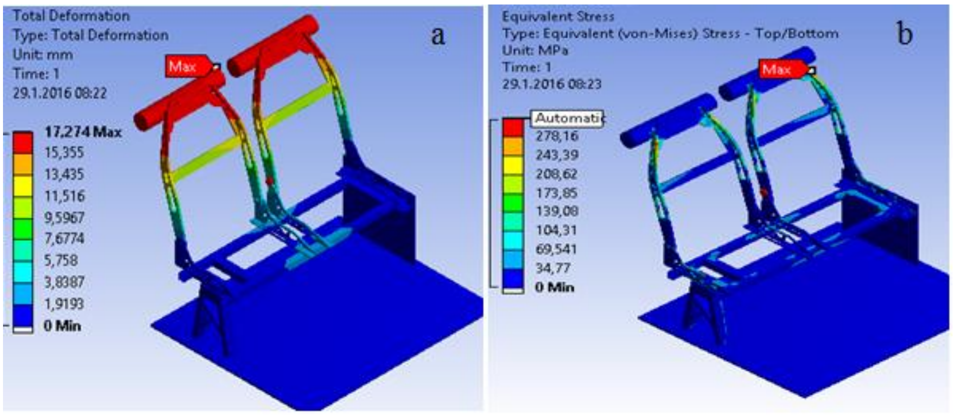

Figure 5.34. APTA Horizontal Force Test Analysis Results Step 1 a) Total Deformation b) Maximum Equivalent Stress

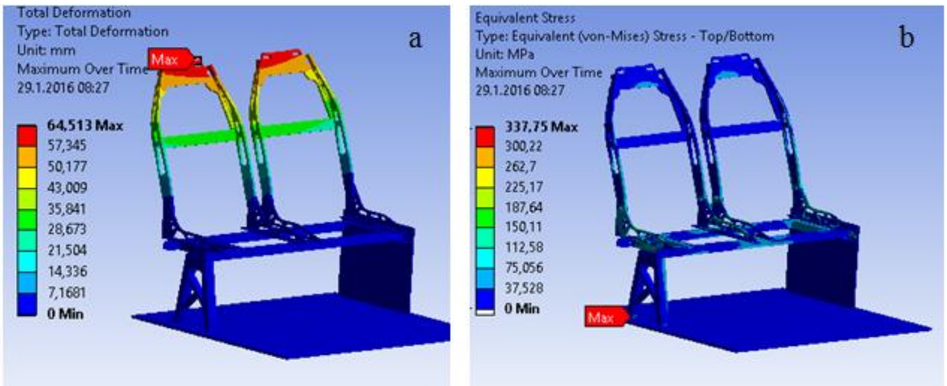

Figure 5.35. FMVSS Moment Force Application Test Analysis Results Step 1 a) Total Deformation b) Maximum Equivalent Stress

5.3.2. Seat Design Development Step 2

Seat and floor attachment part dimensions were changed. The design passed the FMVSS Rearward Moment Test. However, the design didn't pass the APTA Horizontal Force application test. The maximum deflection is above the requirement.

Figure 5.36. Seat Design

Table 5.11. Wall Thickness and Weights for Reference Design and Al 6061 Design Step 2

Part Name	Reference Wall Thickness (mm)	Al-6061 Wall Thickness (mm)	Reference Seat Weight (kg)	Al-6061 Seat Weight (kg)
Seat-Floor Attachment	4	4	2,133	0,90
Seat Frame	2	2	4,398	1,09
Seat Upper Frame	6	6	0,918	0,23
Sidewall Attachment	5	5	0,874	0,22
Seatback	10	10	5,414	1,34
Total Weight			21,927	5,78

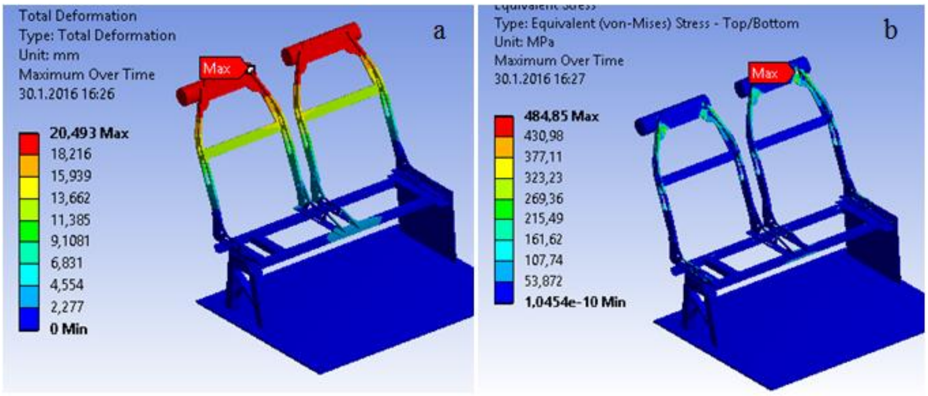

Figure 5.37. APTA Horizontal Force Test Analysis Results Step 2 a) Total Deformation b) Maximum Equivalent Stress

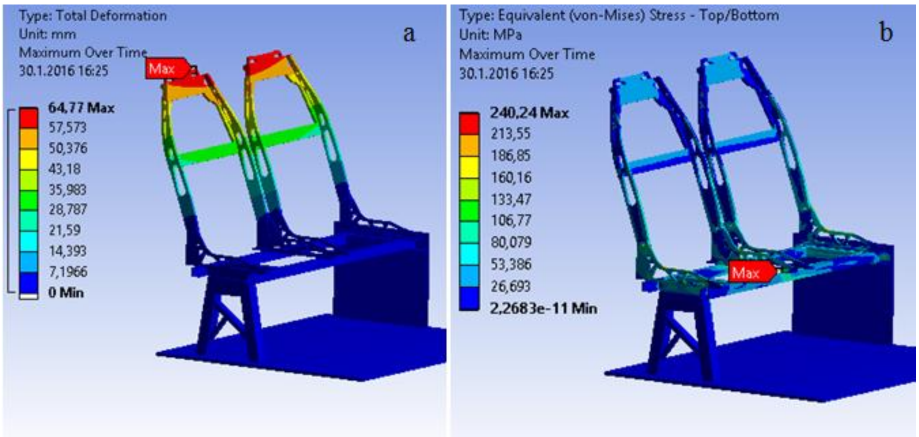

Figure 5.38. FMVSS Moment Force Application Test Analysis Results Step 2 a) Total Deformation b) Maximum Equivalent Stress

5.3.3. Seat Design Development Step 3

The seatback deformation is above the regulation; therefore the gaps on seatbacks were removed.

Figure 5.39. Seat Design

Table 5.12. Wall Thickness and Weights for Reference Design and Al 6061 Design Step 3

Part Name	Reference Wall Thickness (mm)	Al-6061 Wall Thickness (mm)	Reference Seat Weight (kg)	Al-6061 Seat Weight(kg)
Seat-Floor Attachment	4	4	2,133	0,90
Seat Frame	2	2	4,398	1,09
Seat Upper Frame	6	6	0,918	0,23
Sidewall Attachment	5	5	0,874	0,22
Seatback	10	10	5,414	2,32
Total Weight			21,927	7,74

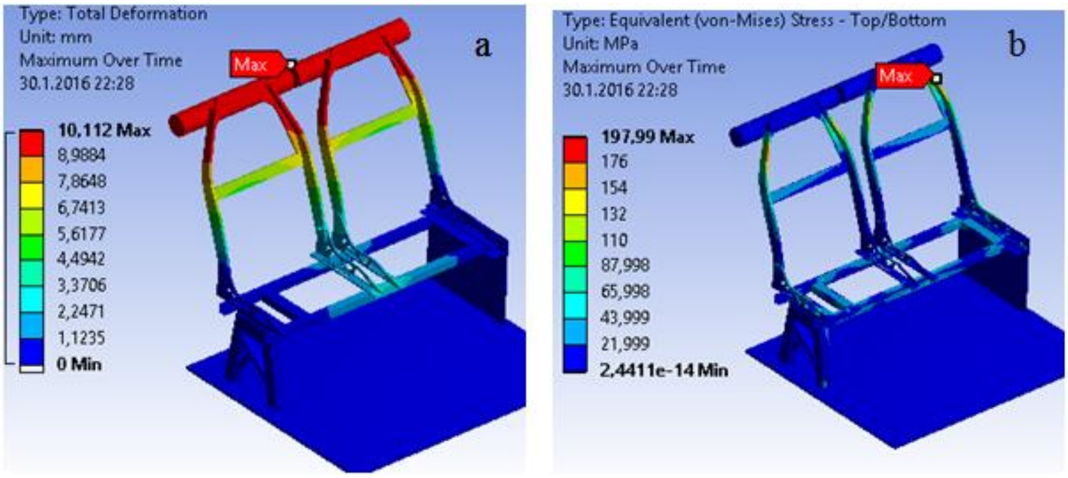

Figure 5.40. APTA Horizontal Force Test Analysis Results Step 3 a) Total Deformation b) Maximum Equivalent Stress

5.3.4. Seat Design Development Step 4

The total deformation is above the regulation; therefore the gaps on upper seat frame parts were removed.

Figure 5.41. Seat Design

Table 5.13. Wall Thickness and Weights for Reference Design and Al 6061 Design Step 4

Part Name	**Reference Wall Thickness(mm)**	**Al-6061 Wall Thickness(mm)**	**Reference Seat Weight (kg)**	**Al-6061 Seat Weight(kg)**
Seat-Floor Attachment	4	4	2,133	0,90
Seat Frame	2	2	4,398	1,09
Seat Upper Frame	6	6	0,918	0,46
Sidewall Attachment	5	5	0,874	0,22
Seatback	10	10	5,414	2,32
Total Weight			21,927	8,67

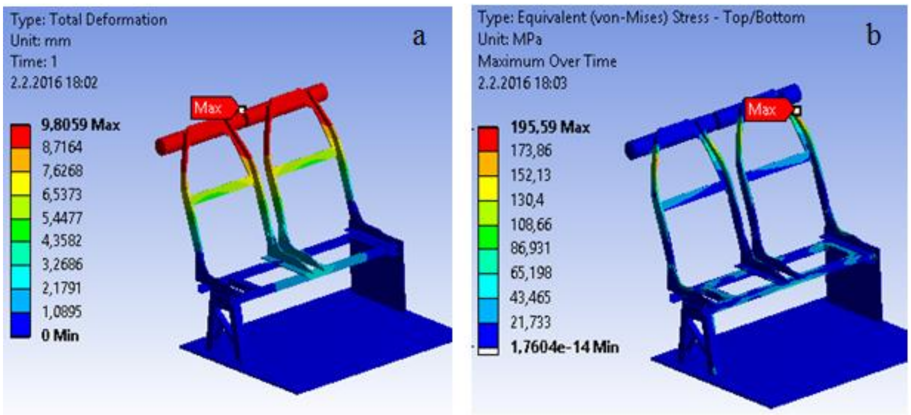

Figure 5.42. APTA Horizontal Force Test Analysis Results Step 4 a) Total Deformation b) Maximum Equivalent Stress

5.3.5. Seat Design Development Step 5

The total deformation is above the regulation; therefore the seat frame wall thickness was increased.

Figure 5.43. Seat Design

Table 5.14. Wall Thickness and Weights for Reference Design and Al 6061 Design Step 5

Part Name	Reference Wall Thickness(mm)	Al-6061 Wall Thickness (mm)	Reference Seat Weight(kg)	Al-6061 Seat Weight(kg)
Seat-Floor Attachment	4	4	2,133	0,90
Seat Frame	2	4	4,398	3,14
Seat Upper Frame	6	6	0,918	0,46
Sidewall Attachment	5	5	0,874	0,22
Seatback	10	10	5,414	2,32
Total Weight			21,927	10,72

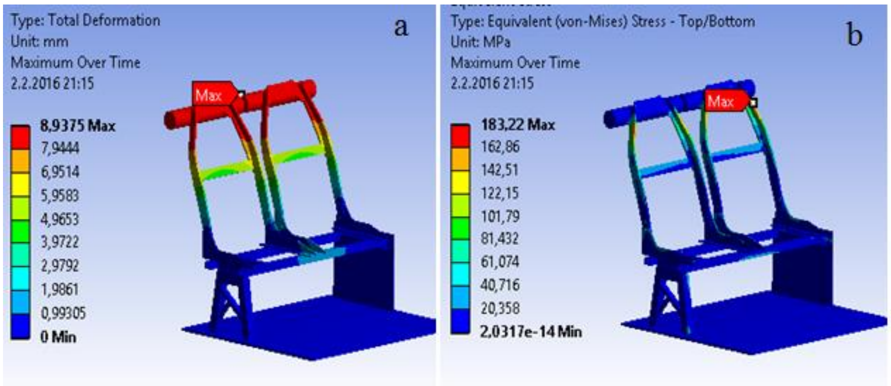

Figure 5.44. APTA Horizontal Force Test Analysis Results Step 5 a) Total Deformation b) Maximum Equivalent Stress

5.3.6. Seat Design Development Step 6

Seat and floor attachment part location was changed to reduce the total deformation. It was relocated to the near the sidewall.

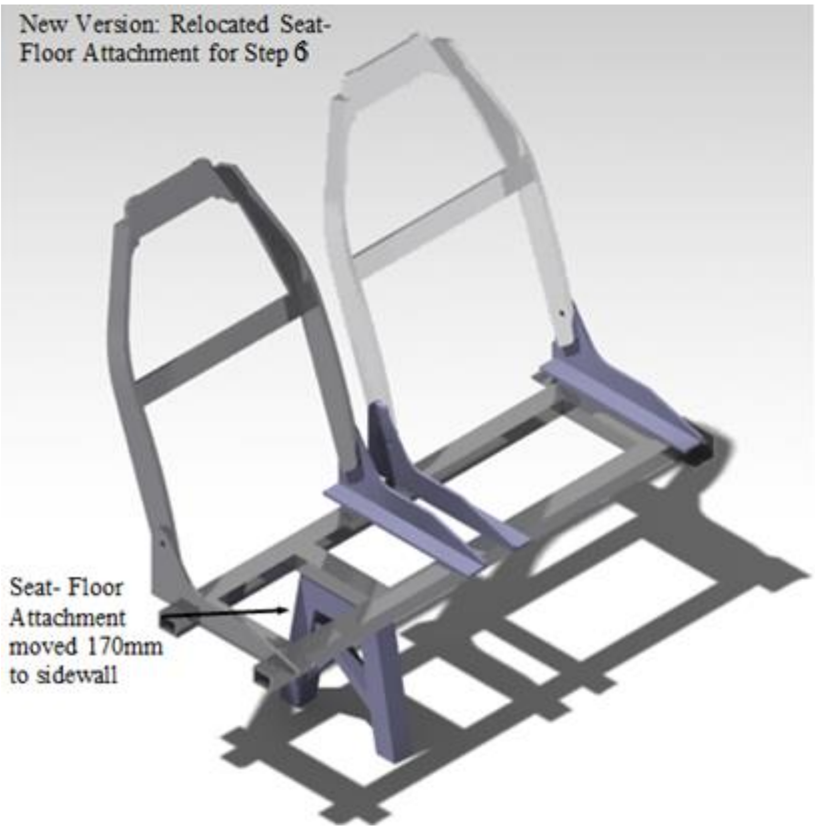

Figure 5.45. Seat Design

Table 5.15. Wall Thickness and Weights for Reference Design and Al 6061 Design Step 6

Part Name	**Reference Wall Thickness(mm)**	**Al-6061 Wall Thickness (mm)**	**Reference Seat Weight (kg)**	**Al-6061 Seat Weight (kg)**
Seat-Floor Attachment	4	4	2,133	0,90
Seat Frame	2	4	4,398	3,14
Seat Upper Frame	6	6	0,918	0,46
Sidewall Attachment	5	5	0,874	0,22
Seatback	10	10	5,414	2,32
Total Weight			21,927	10,72

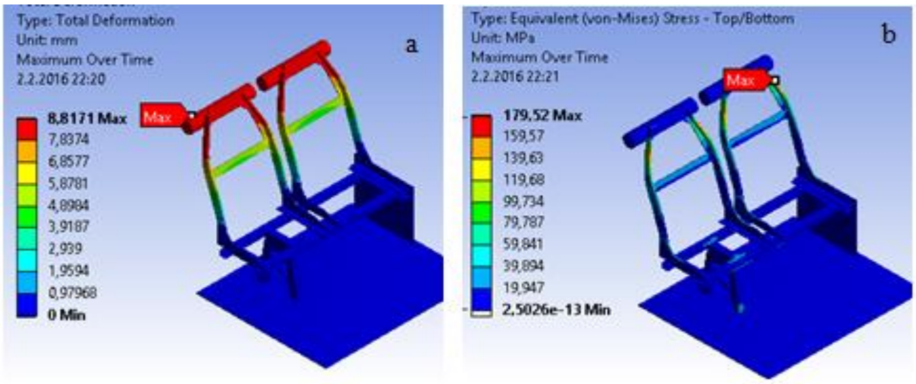

Figure 5.46. APTA Horizontal Force Test Analysis Results Step 6 a) Total Deformation b) Maximum Equivalent Stress

5.3.7. Seat Design Development Step 7

The parts on the seat frame profile were relocated to the front.

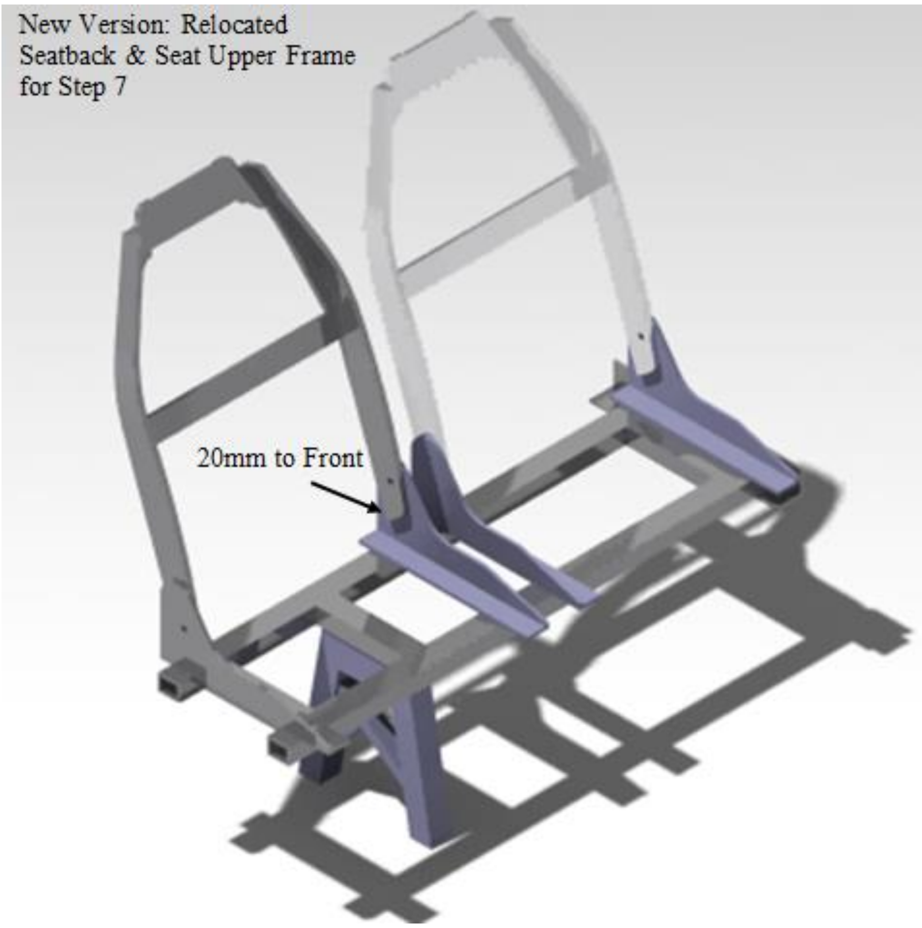

Figure 5.47. Seat Design

Table 5.16. Wall Thickness and Weights for Reference Design and Al 6061 Design Step 7

Part Name	Reference Wall Thickness(mm)	Al-6061 Wall Thickness(mm)	Reference Seat Weight(kg)	Al-6061 Seat Weight(kg)
Seat-Floor Attachment	4	4	2,133	0,90
Seat Frame	2	4	4,398	3,14
Seat Upper Frame	6	6	0,918	0,46
Sidewall Attachment	5	5	0,874	0,22
Seatback	10	10	5,414	2,32
Total Weight			21,927	10,72

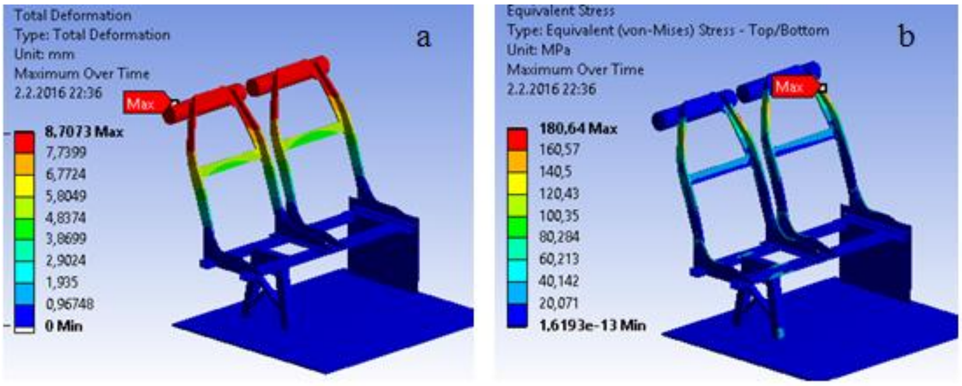

Figure 5.48. APTA Horizontal Force Test Analysis Results Step 7 a) Total Deformation b) Maximum Equivalent Stress

5.3.8. Seat Design Development Step 8

The side profile width of the seatback was increased.

Figure 5.49. Seat Design

Table 5.17. Wall Thickness and Weights for Reference Design and Al 6061 Design Step 8

Part Name	**Reference Wall Thickness(mm)**	**Al-6061 Wall Thickness(mm)**	**Reference Seat Weight(kg)**	**Al-6061 Seat Weight(kg)**
Seat-Floor Attachment	4	4	2,133	0,90
Seat Frame	2	4	4,398	3,14
Seat Upper Frame	6	6	0,918	0,46
Sidewall Attachment	5	5	0,874	0,22
Seatback	10	10	5,414	2,57
Total Weight			21,927	11,23

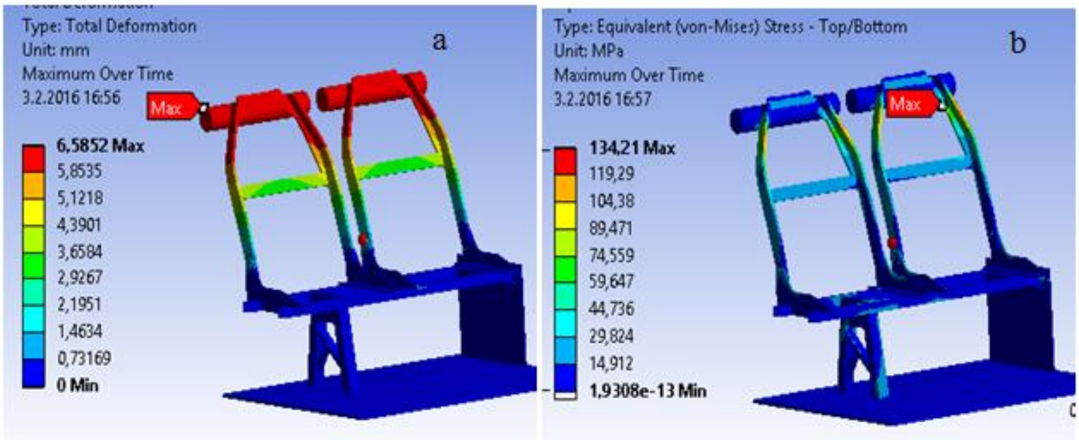

Figure 5.50. APTA Horizontal Force Test Analysis Results Step 8 a) Total Deformation b) Maximum Equivalent Stress

5.3.9. Seat Design Development Step 9

The height of upper cross member of seat was reduced.

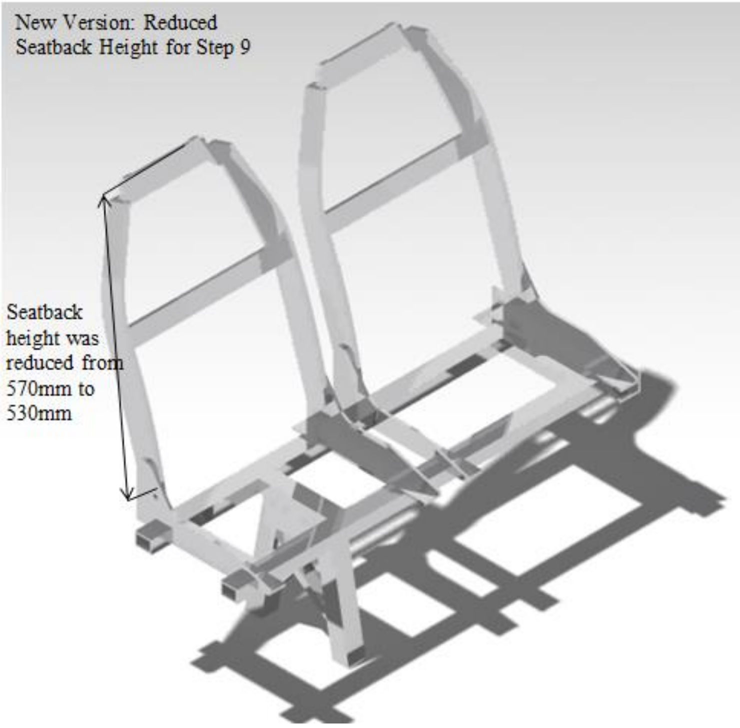

Figure 5.51. Seat Design

Table 5.18. APTA Horizontal Force Test Analysis Results Step 9

Part Name	**Reference Wall Thickness(mm)**	**Al-6061 Wall Thickness(mm)**	**Reference Seat Weight (kg)**	**AL 6061 Seat Weight(kg)**
Seat-Floor Attachment	4	4	2,133	0,90
Seat Frame	2	4	4,398	3,14
Seat Upper Frame	6	6	0,918	0,46
Sidewall Attachment	5	5	0,874	0,22
Seatback	10	10	5,414	2,42
Total Weight			21,927	10,93

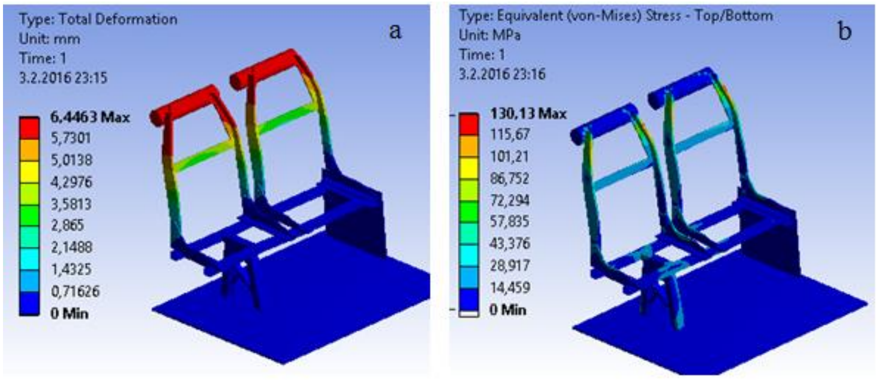

Figure 5.52. APTA Horizontal Force Test Analysis Results Step 9 a) Total Deformation b) Maximum Equivalent Stress

5.3.10. Test Result for Al 6061 Seat Design

After the final step of development, the seat design was passed the tests. Test results are shown in table and figures in below.

Table 5.19. Wall Thickness and Weights for Reference Design and Al 6061 Design Step 9

Part Name	**Reference Wall Thickness(mm)**	**Al- 6061 Wall Thickness(mm)**	**Reference Seat Weight(kg)**	**Al-6061 Seat Weight (kg)**
Seat-Floor Attachment	4	4	2,133	0,90
Seat Frame	2	4	4,398	3,14
Seat Upper Frame	6	6	0,918	0,46
Sidewall Attachment	5	5	0,874	0,22
Seatback	10	10	5,414	2,42
Total Weight			21,927	10,93

Table 5.20. Wall Thickness and Weights for Reference Design and Al 6061 Design Step 9

Standards	Load Case	Requirement Max. Deformation (mm)	Max. Deformation (mm)	Max. Stress (MPa)
APTA Load Cases	Deceleration	<355 (upper part of seat)	3,99	16,73
	Vertical Force	6,5	0,29	17,8
	Horizontal Force	6,5	6,44	130,13
ECE R80 Load Case	Deceleration	-	3,99	16,73
	Horizontal Force (1kN)	400	6,39	119
	Horizontal Force(2kN)	-	17,4	78,45
	Vertical Force	-	0,19	2,44
FMVSS	Rearward Force Application Test Simulation	-	2,72	74,4
	Rearward Moment Application Test Simulation	-	36,28	175,61

5.3.10.1. APTA & ECE Regulation 80 Deceleration Load Case Analysis

The seat design was analyzed according to the APTA; 10G deceleration was applied to the seat during 10 milliseconds. The maximum total deformation of the entire seat is 3,99 mm. This value is below the requirement of the APTA standard. This load case is defined in the same way at the ECE Regulation 80.The maximum stress of the seat design is 16,73 MPa, this values is below the tensile strength of Al 6061. Consequently, the seat design withstands the deceleration force according to ECE Regulation 80.

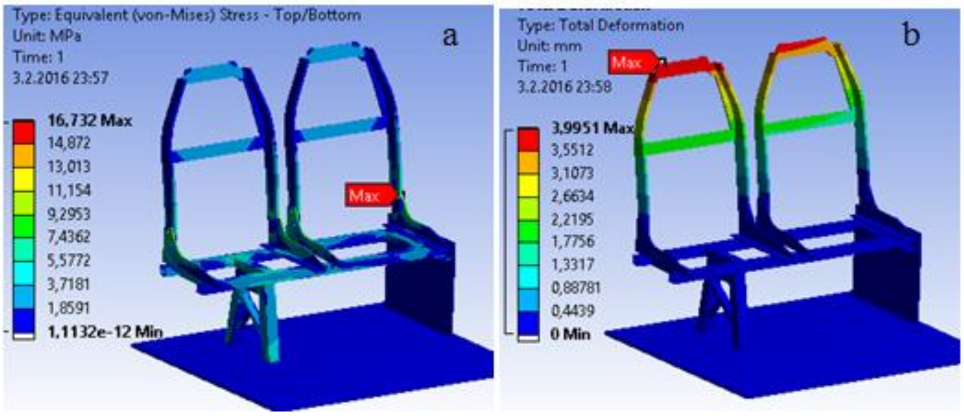

Figure 5.53. APTA& ECE R80 Deceleration Load Case Analysis Results a) Total Deformation b) Maximum Equivalent Stress

5.3.10.2. APTA Horizontal Force to Seatback Load Case Analysis

The seat design was analyzed according to the APTA, 2,23 kN load was applied to the upper cross member of seatback through the loading bar. The maximum total deformation of the entire seat is 6,44 mm. This value is below the requirement of the APTA standard.

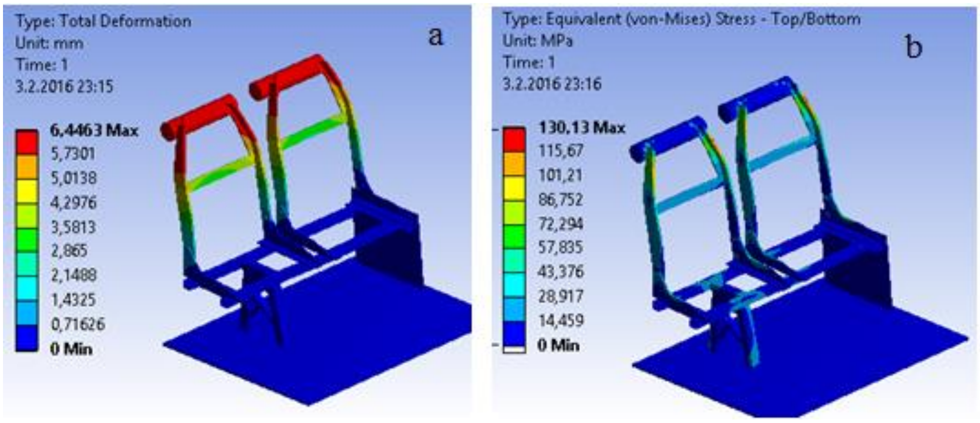

Figure 5.54. APTA Horizontal Force to Seatback Load Case Analysis a) Total Deformation b) Maximum Equivalent Stress

5.3.10.3. APTA Vertical Force to Seat Cushion Part Load Case Analysis

The seat design was analyzed according to the APTA, 2,23 kN load was applied to the upper cross member of seatback through the loading bar.

The maximum total deformation of the entire seat is below 1 mm. This value is below the requirement of the APTA standard.

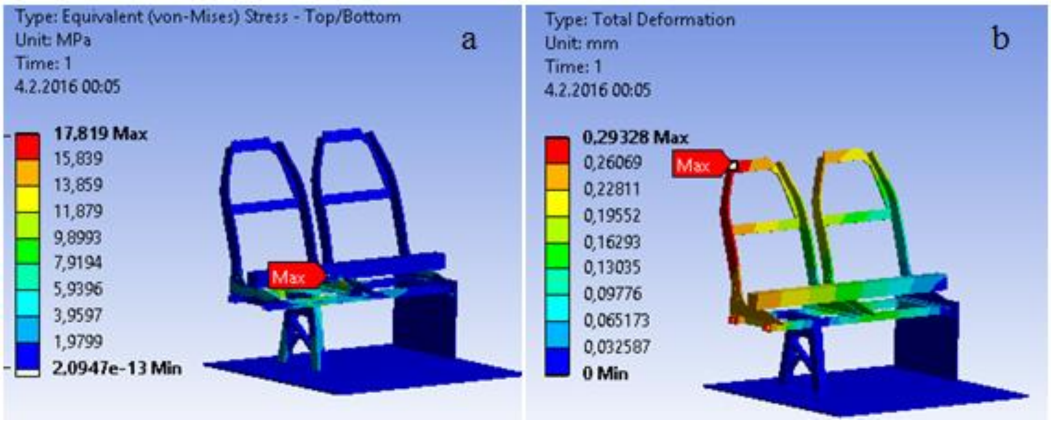

Figure 5.55. APTA Vertical Force to Seat Cushion Part Load Case Analysis a) Total Deformation b) Maximum Equivalent Stress

5.3.10.4. ECE Regulation 80 Horizontal Force to Seatback Load Case 1 Analysis

The seat design was analyzed according to the ECE Regulation 80, 1 kN load was applied to the seatback through the loading bar during 200 ms. Seatback force was applied at a height 775 mm from the floor. The maximum deformation of design is below the maximum deformation limit of ECE R 80.

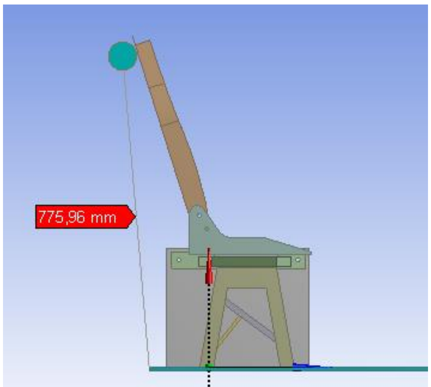

Figure 5.56. ECE R80 Horizontal Force Application, Height of Loading Bars

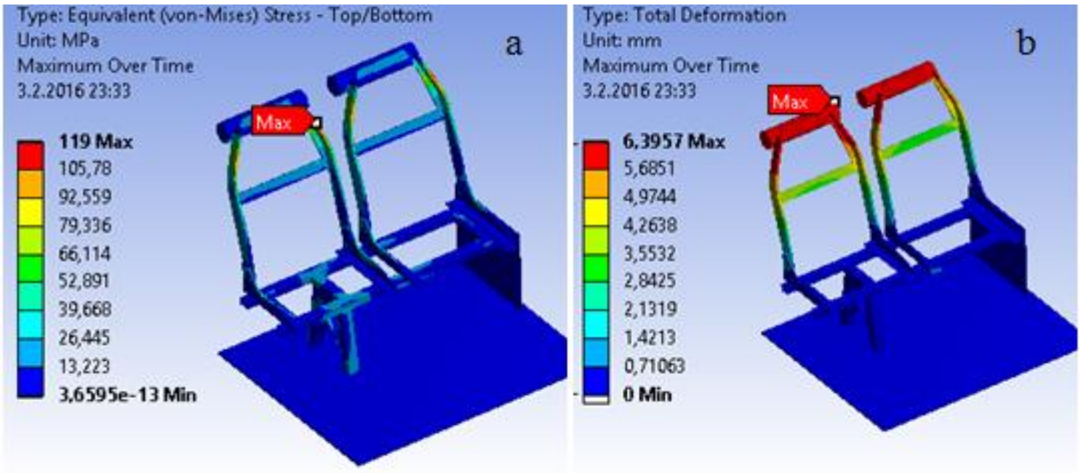

Figure 5.57. ECE Regulation 80 Horizontal Force To Seatback Load Case Analysis 1 a) Total Deformation b) Maximum Equivalent Stress

5.3.10.5. ECE Regulation 80 Horizontal Force to Seatback Load Case 2 Analysis

The seat design was analyzed according to the ECE Regulation 80, 2 kN load was applied to seatback through the rigid bar at a height 463 mm from the floor. The maximum stress value is below the tensile strength of material. This seat design can withstand this load value.

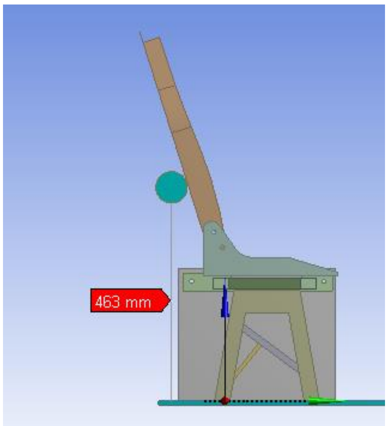

Figure 5.58. ECE R80 Horizontal Force Application, Height of Loading Bars

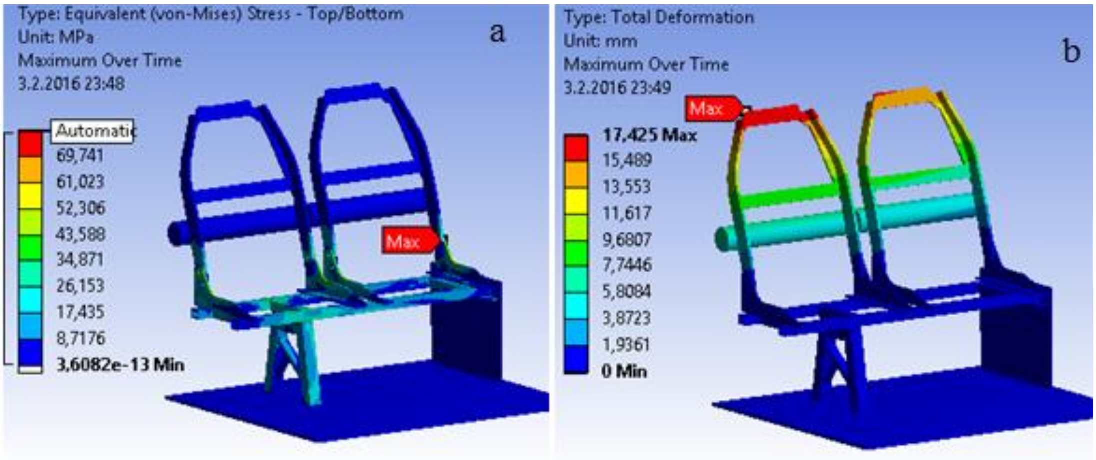

Figure 5.59. ECE Regulation 80 Horizontal Force To Seatback Load Case Analysis 2 a) Total Deformation b) Maximum Equivalent Stress

5.3.10.6. ECE Regulation 80 Vertical Force to Anchorage

A vertical force which is equal to 5 kN was applied to the anchorage points of design. The maximum stress of the seat design is about 2,44 MPa. This value is below the ultimate tensile strength of Al 6061, therefore the seat design withstands the vertical load case of ECE R80.

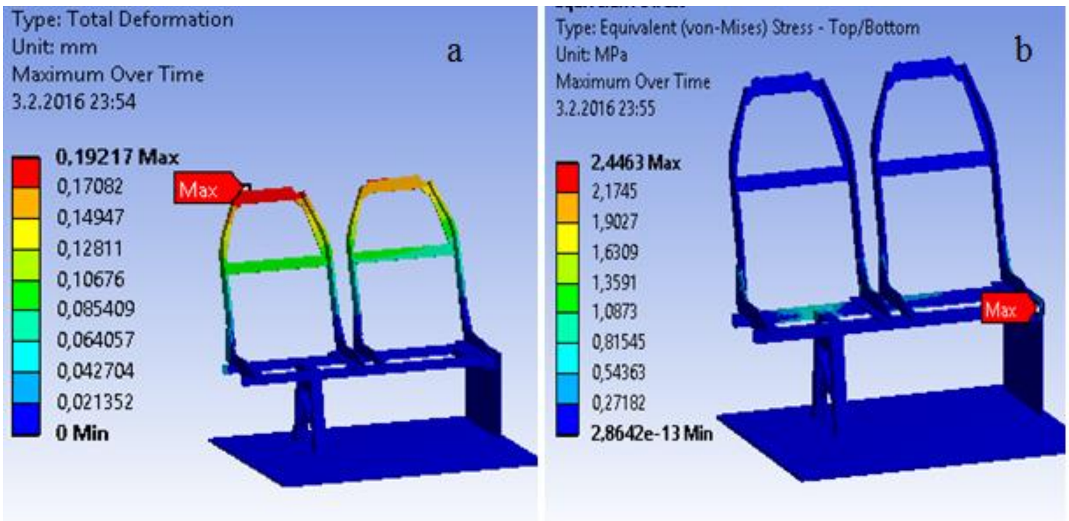

Figure 5.60. ECE Regulation 80 Vertical Force to Anchorage Load Case a) Total Deformation b) Maximum Equivalent Stress

5.3.10.7. Rearward Force Application Test Simulation

The force was applied through the center of gravity on a rigid member. The force, which was determined according to the FMVSS 207, was equal to the 20 times the mass of the seat in kilograms multiplied by 9.8. The force was applied in 5 seconds, hold for 5 seconds and released in 5 seconds.

Load: 20*10,93*9,81 Newton =2145 N

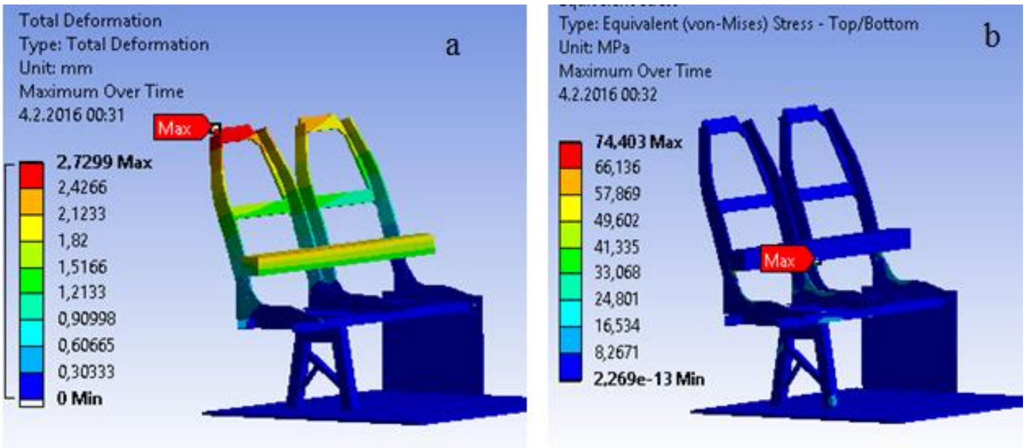

Figure 5.61. Rearward Force Application Test Simulation a) Total Deformation b) Maximum Equivalent Stress

5.3.10.8. Moment applied in a Rearward Longitudinal Direction Test Simulation

The force was applied to the upper cross-member of the seat backs. All loads were applied in 5 seconds, hold for 5 seconds and released in 5 seconds.

Moment= 373 N-m/occupant

Force=373 N-m/occupant / (D x No. Of Occupants)

D= Vertical distance between SRP plane and upper cross member

F=373/0,329= 1133 N

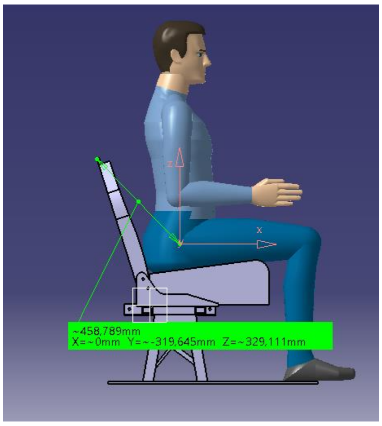

Figure 5.62.Vertical distance between SRP plane and upper cross member

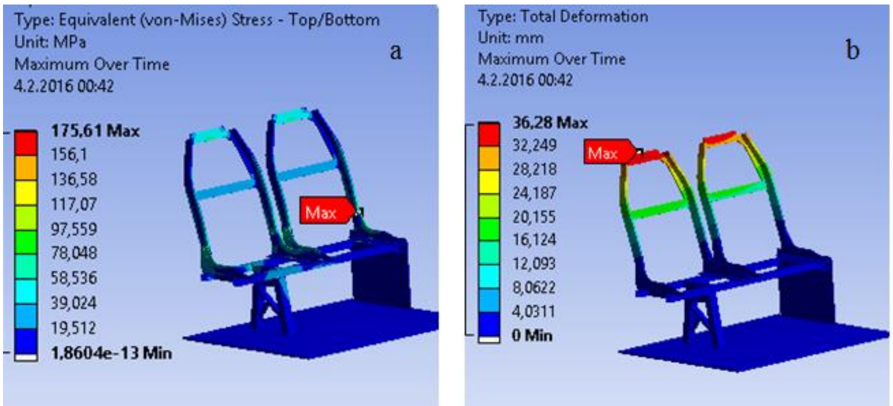

Figure 5.63. Rearward Moment Application Test Simulation a) Total Deformation b) Maximum Equivalent Stress

5.4. Comparison of Seat Design

The main objective of this study is reducing the seat weight. Therefore, two different materials were used to reduce the weight. High strength steel and an aluminum alloy were selected. The seat structures were tested safety standards that are set for bus seats. The seat designs are shown in Figure 5.62.

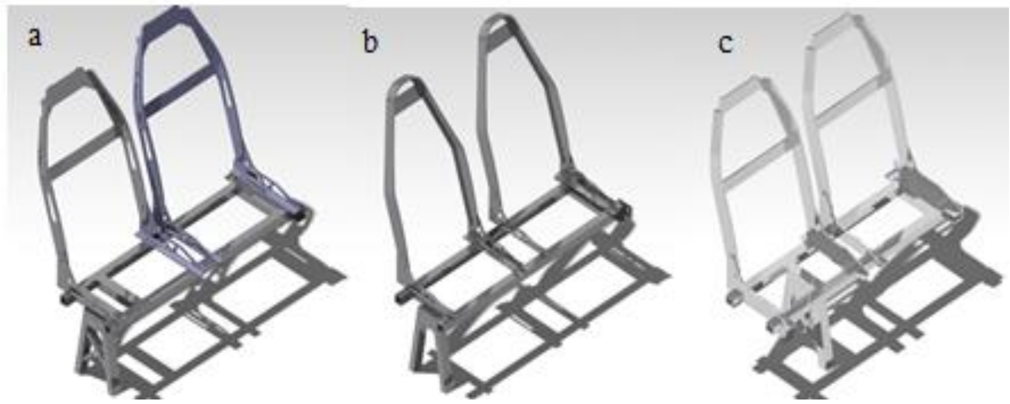

Figure 5.64. Seat Designs a) Reference Seat Design b) UHSS Seat Design c) Aluminum Alloy Seat Design

The UHSS seat design wall thicknesses and seatback design width are lower than the reference design. The aluminum alloy design has highest wall thickness for seat frame part. Seat and floor attachment part of aluminum alloy design is closer to the sidewall.

Table 5.21. Comparison of Seat Designs

Part Name	**Reference Wall Thickness (mm)**	**UHSS Wall Thickness (mm)**	**Al-6061 Wall Thickness (mm)**	**Reference Seat Weight (kg)**	**UHSS Seat Weight (kg)**	**Al-6061 Seat Weight(kg)**
Seat-Floor Attachment	4	1,5	4	2,133	0,577	0,90
Seat Frame	2	1,5	4	4,398	2,917	3,14
Seat Upper Frame	6	2	6	0,918	0,432	0,46
Sidewall Attachment	5	3	5	0,83	0,45	0,22
Seatback	10	8	10	5,447	4,83	2,42
Total Weight				21,927	15,051	10,93

The seats are account for approximately 8% of mass of the busses (Yuce, 2013). According to this information, the seat weight reduction of a bus was calculated. When the designs are compared to the weight, the aluminum alloy design has lowest weight. In Table 5.22 shows the weight comparison of the seat designs.

Table 5.22. Weight Comparison

	St-37	UHSS	Al 6061
Total Weight (kg)	21,92	15,05	10,93
Weight Reduction (kg)	0	6,87	10,99
Weight Reduction (%)	0	31,34	50,14
Bus Weight Reduction* (%)	0	1,54	2,83

* This calculation is done for a bus with 40 seats

As seen in the Table 5.22, both materials provide weight reduction, but the aluminum alloy decrease the reference seat's total mass 21,92 to 10,99 kg (49 % in mass). The reference seat's total mass decreased from 21,92 to 15,51 kg (31,35 % in mass) for ultra-high strength steel.

Despite the fact that the aluminum alloy provides more weight reduction, using the ultra-high strength is safer and feasible. When we calculate the factor safety these designs, it can be seen that the ultra-high strength steel has a high factor safety. Therefore, using the aluminum instead of ultra-high strength steel to provide higher weight reduction, decrease the safety relatively.

$$factor\ of\ safety = \frac{material\ yield\ stress}{maximum\ design\ stress}$$

for UHSS

$$factor\ of\ safety = \frac{1100}{588} = 1{,}87$$

for Al 60611

$$factor\ of\ safety = \frac{276}{175} = 1{,}57$$

Reducing vehicle weight can help decrease energy and petroleum consumption by increasing efficiency. In addition, it decreases the greenhouse gas emissions. Ghassmieh estimated that for every 10% of weight eliminated from a vehicle's total weight, fuel economy improves by 7% and for every kilogram of weight reduced in a vehicle; there is about 20 kg of carbon dioxide reduction (Ghassemieh, 2011). According to the Ghassmieh's estimations fuel economy and CO2 reductions were calculated approximately for this study, calculation results are shown in Table 5.23 and 5.24.

Table 5.23. Fuel Economy and CO2 Reduction Calculation for UHSS Seat Design

Estimation		**Calculation for UHSS**	
Vehicle Weight Reduction	**Fuel Economy**	**Vehicle Weight Reduction**	**Fuel Economy**
10%	7%	2%	1,4%
Weight Reduction	**CO_2 Reduction**	**Weight Reduction ***	**CO_2 Reduction ***
1 kg	20 kg	240 kg	4800 kg

* This calculation is done for a bus with 40 seats

Table 5.24. Fuel Economy and CO2 Reduction Calculation for Al 6061 Seat Design

Estimation		**Calculation for Al 6061**	
Vehicle Weight Reduction	**Fuel Economy**	**Vehicle Weight Reduction**	**Fuel Economy**
10%	7%	3%	2,1%
Weight Reduction	**CO_2 Reduction**	**Weight Reduction ***	**CO_2 Reduction ***
1 kg	20 kg	440 kg	8800 kg

* This calculation is done for a bus with 40 seats

Material cost is an important factor for design. Therefore, material costs for aluminum and advanced high strength steel is calculated. The material costs are taken from CES Edu Pack for aluminum alloy and St-37 steel. Advanced steel material cost is taken from a study which was conducted by Ruth. (March, 2016) According to the calculation results, material cost of UHSS seat design is highest. Material costs are shown in Table 5.25. However, this material provides a significant weight reduction and it has highest tensile strength, therefore it offers a higher safety for passenger.

Table 5.25. Material Costs

	Reference Design with St-37	**Seat Design with UHSS**	**Seat Design with Aluminum Alloy**
Total Weight (kg)	21,92	15,05	10,93
Material Cost (TL/kg)	0,6221-1,4	4,80	1,866-3,036
Max. Material Cost (TL)*	31	72,24	33,18

* Production costs of all seat design are assumed as equal.

6. CONCLUSION

The aim of this study was designing a lightweight seat design for a transit vehicle. Ultra-high strength steel and aluminum alloys material was used to reduce the weight of the seat design.

Conclusions based on the comparison of designs with reference seat design

- 31% weight reduction was obtained by using ultra high strength steel as seat material.
- If ultra-high strength steel design used for a bus with 40 seat, 1,4% fuel economy could be obtained and 4800 kg CO_2 emission could be prevented during lifetime in comparison with the reference design.
- The ultra-high strength steel design has lower wall thicknesses.
- The material cost of ultra-high strength steel is approximately equal to two times the cost of the conventional steel and this design has the highest material cost.
- 50% weight reduction was obtained by using aluminum alloy as seat material.
- If aluminum alloy design used for a bus with 40 seat, 2,1% fuel economy could be obtained and 8800 kg CO_2 emission could be prevented during lifetime in comparison with the reference design.
- Aluminum material cost is nearly same with the cost of St-37 steel.

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