İSTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

REAR MIDDLE BUMPER DESIGN OF A RAISED FLOOR BUS

M.Sc. THESIS

Alev BAĞSÜRER

Department of Mechanical Engineering

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JUNE 2018

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Thesis Advisor: Asst. Prof. Dr. Vedat TEMİZ

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

YÜKSEK TABANLI BİR OTOBÜSTE ARKA ORTA TAMPON TASARIMI

YÜKSEK LİSANS TEZİ

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Alev Bağsürer, a M.Sc. student of İTU Graduate School of Science Engineering and Technology student ID 503111201 successfully defended the thesis/dissertation entitled "REAR MIDDLE BUMPER DESIGN OF A RAISED FLOOR BUS", which he/she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my family and lovely cat,

FOREWORD

Firstly, I would like to express my sincere thanks and appreciation to Asst. Prof. Dr. Vedat Temiz who supported me during this study. Additionally, I am thankful to many people due to their great support and mentorship which helped me to bring this study to an issue.

I also thank my family and friends for their open-armed support in life.

June 2018 Alev Bağsürer Industrial Engineer

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ABBREVIATIONS

AISI	: The American Iron and Steel Institute
BMC	: Bulk moulding compound
CAD	: Computer aided design
CFR	: The Code of Federal Regulations
CFRP	: Carbon-fiber-reinforced plastic
CMVSS	: Canadian Motor Vehicle Safety Standard
DCPD	: Dicyclopentadiene
FEM	: Finite Elements Methods
FMVSS	: The United States Federal Motor Vehicle Safety Standard
GMT	: Glass-mat-reinforced thermoplastic
LDPE	: Low-density polyethylene
Max.	: Maximum
PC	: Polycarbonate
PP	: Polypropylene
PUR	: Polyurethane
RIM	: Reaction injection moulding
SMC	: Sheet molding compound
TPO	: Thermoplastic polyolefins
UNECE	: The United Nations Economic Commission for Europe
UP	: Unsaturated polyester
WHO	: World Health Organization
3D	: Three-dimensional

SYMBOLS

°C : Celcius
cm : centimeters
g/cm^3 : Gram per cubic centimetre
Gpa : Gigapascal
km/h : kilometers per hour
m^2 : Square meter
mm : milimeters
mm^2 : Square milimeter
Mpa : Megapascal
mph : miles per hour
J/m : Joules per meter

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REAR MIDDLE BUMPER DESIGN OF A RAISED FLOOR BUS

SUMMARY

In parallel with the development of technology in the automotive industry, from past to present, the usage of motor vehicles have increased rapidly. Together with the increased numbers of motor vehicles acting on highways, the huge number of highway collisions have started to be a critic problem for the nations.

The statistics of the World Health Organization show that worldwide more than 1.25 million people die and 20 to 50 people suffer from the highway accidents annually. At this point, integrating systems and structures that take a role on minimizing the impact of collisions on the passenger and pedestrians has become an important issue for the automobile makers. Bumper systems that are integrated to the front and rear ends of the motor vehicles are one of these impact reducers in case that an automobile hits any object or a pedestrian.

In this thesis study, it is aimed to review the present literature and applications of the automobile bumper systems and to introduce proper material, production method and design proposals for a rear middle bumper of a raised floor bus by taking the information of the present bumper applications into consideration.

This study starts with the review of the definition and functions of automobile bumper systems and the historical development of the present bumper structures. As the driver and passenger compartments in a raised floor bus is in a heigher level than the collision height, the primary functions of bus bumpers differs from the passenger cars. Therefore, the functions of bus bumpers are focused on in details in this study.

Afterwards, within the scope of this study, the types of bumper systems that are used in today's automobiles are explained and demonstrated with figures and information about the sub-components of these bumper systems are given in details. In order to explain the importance that automotive bumpers are not only parts that beautifies the automobile body, the current highway standards and regulations that concern the requirements demanded from the bumper systems of passenger cars are shortly described.

After the review of general information about the automotive bumper systems, current standards and regulations, in the oncoming sections of this study, the materials and most commonly used manufacturing technologies applied for the production of automotive bumpers are described in details by demonstrating also with figures. By explaining the advantages and disadvantages of each production method, a comparison of these applications are summarized in order to use as a reference during selection of the material and production method proposals of the rear middle bumper of a raised floor bus. In addition to the present applications, the challenges about the bumper materials that automotive manufacturers will face in the future are also shortly mentioned.

Prior to the design proposal of the rear middle bumper, as Finite Elements Methods (FEM) is used during the modeling phase of the rear middle bumper, a review about the Finite Elements Methods are given in the following sections of this study. The definition of FEM is explained and approaches used during a FEM study are described. Afterwards, the steps that are followed during a FEM analysis and the advantages of using this method are mentioned. In this study, the present computer aided design applications that use FEM during the design, modeling and structural analysis phases are also stated shortly. Among these applications, Siemens NX that is used during the design steps in this thesis study was explained in details.

Taking all these information explained above into consideration, in order to propose design solutions for the rear middle bumper of a raised floor bus within the scope of this thesis study, a systematic design approach starting with definition of the task and preparation of requirements list is implemented. After generating the requirements list, as the following step, by evaluating all the bumper material and production methods explained in the previous sections, two alternatives of bumper materials and production methods are proposed accordingly to the requirements expected from the rear middle bumper.

After selection of the bumper material and production method alternatives, firstly the surface modeling is figured out using the computer aided design software Siemens NX. Then, by adding volume on the surface model, the 3D models for both alternatives are generated. In order to minimize the part complexity and accordingly the unit cost, firstly the 3D models are figured out without any reinforcing ribs added on the part. In order to examine the strength of these models, the displacement and stress analysis are implemented in Siemens NX under certain load conditions. The analysis results are evaluated according to the allowed maximum limit values stated in the requirements list. Based on the weak results of the analyses applied for the ribless models, iterations by adding reinforcing ribs are implemented on the models and the analyses are repeated. At each stage of these step-by-step iterations, the figures of the 3D models showing the analysis results are demonstrated and the results are summarized in tables in order to give the reader a clear view.

As a consequence of this study, the proper rear middle bumper design solution that meets all the expectations stated in the requirements list is selected. As today’s competitive environment in the automotive industry will increase rapidly in the near future, to overcome the future challenges, recommendations for cost reduction and meeting public expectations, such as reduction of environment pollution, are also proposed for the rear middle bumper design in the scope of this study.

YÜKSEK TABANLI BİR OTOBÜSTE ARKA ORTA TAMPON TASARIMI

ÖZET

Otomotiv endüstrisindeki teknolojinin ilerlemesine paralel olarak, geçmişten günümüze motorlu taşıtların kullanımı hızlıca artmaktadır. Karayollarındaki motorlu taşıtların sayısının artmasıyla birlikte, karayollarında meydana gelen yüksek kaza sayıları ülkeler için kritik bir problem olmaya başlamıştır.

Dünya Sağlık Örgütü'nün istatistiklerine göre, dünya genelinde yılda ortalama olarak 1,25 milyonun üzerindeki insan trafik kazalarında yaşamını yitirmekte ve 20-50 milyon arasındaki insan ise bu kazalardan ölüm vakası olmadan kurtulmaktadır. Bu istatistikler dikkate alındığında, bir taşıtın herhangi bir nesne veya yayaya çarpması durumunda araç içindeki yolcuların ve yayaların yaralanmalarını azaltıcı sistem ve yapıların taşıtlara entegre edilmesi, otomobil üreticileri açısından oldukça önem kazanmaya başlamıştır. Motorlu bir taşıtın ön ve arka uçlarına entegre edilmiş olan tampon yapıları, kaza durumundaki çarpışma etkisini azaltan bu entegre sistemlerden biridir.

Bu tez çalışmasında, mevcut otomobil tampon sistemleri ve uygulamaları hakkında literatür araştırması yapılması ve mevcut uygulamalar ile ilgili bu bilgiler kullanılarak, yüksek tabanlı bir otobüsün arka orta tamponu için uygun malzeme, üretim yöntemi ve tasarımların önerilmesi amaçlanmaktadır.

Bu çalışmada öncelikle, otomotiv tampon sistemlerinin tanımı verilerek günümüzde kullanılan otomotiv tampon sistemlerinin işlevleri ve bu sistemlerin geçmişten günümüze olan tarihsel gelişimi hakkında okuyucuya bilgi verilmektedir. Yüksek tabanlı bir otobüste şoför ve yolcu mahallerinin yükseklikleri otobüsün çarpma seviyesinden daha yukarıda olduğundan, bir otobüs tamponunun öncelikli işlevleri bir binek aracınınkine göre farklılık göstermektedir. Bu sebeple söz konusu çalışmada, otobüs tampon sistemlerine ayrıca odaklanılmakta ve bu konuda okuyucuya detaylı bilgiler sunulmaktadır.

Ardından bu çalışma kapsamında, günümüzde kullanılmakta olan otomobillerdeki mevcut tampon sistemlerinin çeşitleri hakkında bilgi verilmekte ve bu bilgilerin okuyucu tarafından kolay anlaşılabilmesi amacıyla, bu bilgiler destekleyici şekiller ile görselleştirilmektedir. Buna ilave olarak, bir tampon sisteminin alt komponentleri hakkında da detaylı açıklama yapılmaktadır. Çalışmada ayrıca, binek araçlarında kullanılan tampon sistemleri ile ilgili farklı ülke ve bölgelerde geçerli olan karayolu standartları ve yönetmelikleri hakkında kısaca bilgi verilerek, otomotiv tamponlarının sadece görsel bir parça olmadığının önemi okuyucuya aktarılmaya çalışılmaktadır.

Otomobil tampon sistemleri hakkında detaylı verildikten ve tampon sistemlerinde aranan özellikler ile ilgili geçerli olan standart ve yönetmelikler hakkında kısaca bilgilendirme yapıldıktan sonra, çalışmanın ilerleyen bölümlerinde otomobil tamponlarının üretimi sırasında kullanılan malzemeler, bu malzemelerin önemli özellikleri ve en sık uygulanan üretim yöntemleri hakkında okuyucuya detaylı bilgiler

aktarılmaktadır. Çalışmada yer verilen tampon üretim yöntemlerinin çalışma şekilleri görseller ile okuyucuya aktarılmakta ve her biri için avantaj ve dezavantajlar açıklanmaktadır. Bu çalışmanın uygulama aşamasında arka orta tampon için malzeme ve üretim yöntemi önerilirken referans olarak kullanmak üzere, üretim yöntemleri ile ilgili bilgiler derlenerek bir tablo halinde karşılaştırılmaktadır. Mevcut uygulamalara ilave olarak, otomotiv üreticilerinin alternatif tampon malzemeleri ile ilgili gelecekte karşılabilecekleri zorluklar hakkında da okuyucuya kısaca fikir verilmektedir.

Tez çalışması kapsamında, arka orta tampon tasarımı sırasında Sonlu Elemanlar Yöntemi kullanıldığından, tasarım aşamasından önce Sonlu Elemanlar Yöntemi'nin tanımı ve kullandığı yaklaşımlar hakkında da bilgi verilmektedir. Sonlu Elemanlar Yöntemi kullanılarak yapılan bir çalışmada izlenen adımlar ve bu yöntemin kullanılmasının tasarımcıya sağladığı faydalar aktarılmaktadır. Buna ilave olarak, tasarım, modelleme ve yapısal analiz sırasında Sonlu Elemanlar Yöntemi'ni kullanmakta olan mevcut bilgisayar destekli tasarım yazılımları hakkında da kısaca bilgi verildikten sonra, bu tür yazılımlardan biri olup bu tez çalışmasında kullanılan Siemens NX programı hakkında detaylı bir bilgilendirme yapılmaktadır.

Yukarıda değinilen bilgiler dikkate alınarak, yüksek tabanlı bir otobüsün arka orta tampon tasarımı için uygun çözümler sunulması amacıyla, bu tez çalışmasının uygulama kısmında sistematik tasarım yaklaşımı kullanılmaktadır. Bu aşamada öncelikle, aranan tasarım için görev tariflenmekte ve ihtiyaçlar listesi oluşturulmaktadır. Bir sonraki adım olarak, ihtiyaçlar listesinde yer alan talepler dikkate alınarak önceki bölümlerde detaylı olarak ele alınan tampon malzeme ve üretim yöntemleri değerlendirilmekte ve arka orta tampon için talepleri karşılayacak iki uygun alternatif önerilmektedir.

Arka orta tampon için malzeme ve üretim yöntemi alternatifleri belirlendikten sonra, bilgisayar destekli tasarım yazılımı olan Siemens NX programı kullanılarak parçanın ana yapısının oluşturulması amacıyla parçaya ait yüzey modeli elde edilmektedir. Ardından bu yüzey modeline hacim eklenerek, her iki alternatif için üç boyutlu modelleme yapılmaktadır. İlk aşamada, parça karmaşıklığı ve buna bağlı olarak birim maliyeti minimize etmek amacıyla, her iki alternatif için üç boyutlu modeller öncelikle herhangi bir güçlendirici kaburga eklenmeden oluşturulmaktadır. Kaburga eklenmemiş olan modellere, belli kuvvet altında yükleme durumları için Siemens NX yazılımı kullanılarak yer değiştirme ve gerilme analizleri uygulanmaktadır. İhtiyaçlar listesinde yer değiştirme ve gerilme için belirlenmiş olan izin verilen maksimum değerler dikkate alınarak, analiz sonuçları değerlendirilmektedir. Bu kapsamda, kaburgasız modeller üzerinde yapılan analiz sonuçları yetersiz çıktığından, model üzerinde zayıf bölgelere güçlendirici kaburgalar eklenerek model üzerinde iyileştirme yapılmakta ve analizler tekrarlanmaktadır. Okuyucuya kolaylık sağlamak amacıyla, modeller üzerinde uygulanan adım adım iyileştirmeler sonrasında üç boyutlu modeller üzerinde yapılan analiz sonuçları görselleştirilmekte ve tablolar halinde özetlenmektedir.

Tasarlanan modeller üzerinde uygulanan adım adım iyileştirmelerin ardından yapılan yer değiştirme ve gerilim analizleri sonrasında nihai olarak, ihtiyaçlar listesinde belirtilen tüm istekleri karşılayan uygun arka orta tampon tasarımı, malzeme ve üretim yöntemi seçilmektedir.

Bugün otomotiv endüstrisinde hakim olan rekabetçi ortam yakın gelecekte hızlıca artacağından, özellikle azalan maliyetler ve çevreye karşı duyarlılığın artması otomotiv üreticileri için tasarım ve üretim süreçlerinde önemli kriterler haline gelmeye başlayacaktır. Gelecekte yüzleşilebilecek bu zorlayıcı görevlere karşı ayakta durulabilmesi amacıyla, tez çalışması kapsamında seçilen arka orta tampon malzemesi ve tasarımı için gelecekte maliyet ve çevre kirliliğini azaltabilecek öneriler de sunulmaktadır.

1. INTRODUCTION

A highway collision is an accident occuring when a motor vehicle crashes with another vehicle, pedestrian, animal or any article around. According to the statistics of WHO (World Health Organization), every year more than 1.25 million people around the world die and between 20 to 50 million more people suffer non-fatal injuries as a result of highway collisions [1].

Highway traffic injuries bring about considerable economic loses to victims, their families and to nations as a whole. Road traffic accidents cost most countries about 3% of their gross domestic product [1].

The factors that increase the risk of a highway collision can be stated as the following:

- Speed
- Unsafe road infrastructure
- Distracted driving
- Unsafe vehicles
- Alcohol and substance addiction
- Driver skills

In order to reduce the impact of a highway collision, some structures and systems are integrated on the motor vehicles. One of these collision impact reducers applied on motor vehicles are bumpers, which are structures integrated across the front and rear of motor vehicles in order to reduce the damage of a crash by absorbing the impact in a minor collision.

In most regions in the world, the regulations for bumpers are defined in details by the motor vehicle safety standards. However, it is defined by the laws almost everywhere in the world that the front and rear of motor vehicles acting in highways, except for special vehicles, should be protected in such a manner that low speed collisions only damage the vehicle slightly, or not at all [2]. Therefore, it is very important for the automative manufacturers to meet these regulations and standards during the design, prototype, approval and production processes of bumpers. Within these processes, the most important one that affects the functionality and performance of a bumper structure is undoubtedly the design phase.

1.1 Purpose of Thesis

The purpose of this thesis is to investigate the existing applications of motor vehicle bumper structures and to design the rear middle bumper of a raised floor bus in consideration of the existing standards and norms, conditions of production, transport, painting, assembly processes and to decide on both the material type and production method of the rear middle bumper according to safety, performance, function, esthetic and cost criterias.

An example of a rear middle bumper integrated to a raised floor bus can be seen in Figure 1.1. A raised floor bus, which will be addressed in this thesis study, has a bus deck design that passengers require to climb up one or more steps at the front or rear entrance to access the interior floor that is placed at a higher position.

Figure 1.1 : Example of a rear middle bumper integrated to a raised floor bus.

In comparison with passenger cars, rear bumpers of buses have a longer structure. Therefore, the risk of torsion and structural imperfection of bus bumpers during production, transport, painting and assembly processes is high. In order to minimize this risk, the conditions of production, transport, painting and assembly processes will be among the main criterias that will be considered during designing the rear middle bumper in this thesis.

In order to minimize the unit cost, alternative solutions will be proposed and among the proposed alternatives it is aimed to decide on a single bumper design, material type and production method that will meet all the requirements and functions expected from the rear middle bumper.

During the design phase, it is aimed to use Finite Elements Methods (FEM) to investigate the stiffness performance under various loading conditions for each design alternative. In order to investigate dynamic problems such as the displacement and stress analysis of bumpers, Finite Elements Methods (FEM) are increasingly used as this simulation-based numerical approach reduces the costs of experiments and prototypes [4].

2. AUTOMOTIVE BUMPER SYSTEMS

2.1 Definition and Functions of Automotive Bumper Systems

The automotive bumpers are structures attached to the front and rear ends of an automobile in order to absorb energy in a low speed impact.

Bumper structures consist of three main parts called fascia, energy absorber and bumper beam. The fascia is a non-structural component having the task of reducing air resistance, while the energy absorber depletes part of the kinetic energy during collision and the bumper beam absorbs the low impact energy by bending resistance [4]. A demonstration of these main parts can be seen in Figure 2.1.

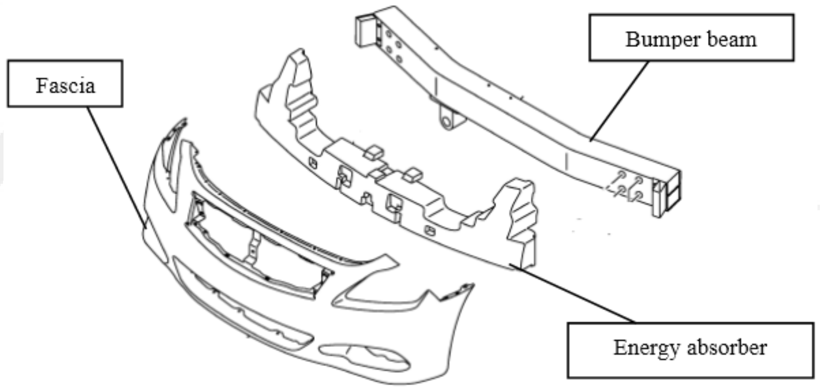


Figure 2.1 : Three main parts of an automotive bumper system [5].

In general terms, a bumper structure has four main functions [4]:

- It minimizes the injury of the pedestrians and passengers in case that the automobile hits pedestrians.
- It can protect the fender, radiator, engine hood, and lamps when low-speed collision happens between the automobile and other automobiles or any articles and transfers the impact energy to other components of the automobile in case of high-speed collisions.

- It may perform the car body aerodynamic requirements.
- It adds aesthetics and beautifies the automobile body.

Among these four functions, the first two are undoubtedly the most significant ones especially for passenger cars. As the sitting height from road ground in a passenger car is almost the same as the ground clearance of the car, in case of collision, the risk of injury or death of the driver and passengers is high. Therefore, the prior function expected from a bumper system applied on passenger cars is minimization of the injuries by absorbing the low impact energy.

On the other hand, for a raised floor bus that will be analyzed in this thesis, the floor of the driver compartment is approximately 900 mm and the floor of the passenger compartment is approximately 1300 mm above the road ground [6]. Therefore, when compared with passenger cars, in case of a collision, the risk of injury or death of the passengers and the driver in a bus is lower.

Beside being in a higher position than the road ground, the front collision guard, which is a safety system designed for protecting the driver and the person sitting on the guide seat in case of a frontal impact, is also an important factor that increases the safety of the driver compartment in a raised floor bus. In raised floor buses having front collision guards, the driver compartment including the steering, pedals and driver seat, is mounted on a solid frame structure that slides horizontally in order to increase the driver's space and prevent the driver and the person sitting on the guard seat from being squeezed in case of a serious frontal collision.

Due to the above mentioned factors that reduces the risk of injury or death of the passengers and the driver in a bus, the priorities that bus manufacturers consider during the design phase of the bumper systems applied on their products differ from carmakers.

As also shortly stated in section "1.1 Purpose of Thesis", the main functions expected from a bus bumper system can be summarized as the following:

- Minimizing the injury of the pedestrians in case that the bus hits pedestrians.
- Preventing the damage of the equipments such as electrical devices, cable harness, sensors, spare tire fixations and the chassis located back of the bumper covers in case of collisions.

- Carrying the components such as lamps, sensors, design and brand logo parts properly that are fixed on the bumpers.
- Keeping its form against the strain occuring during production, transport, carriage and assembly processes.
- Resisting against the oven temparature during painting processes and the temperature conditions of the countries where the buses are supplied to.
- Beautifying the bus body.

2.2 History of Automotive Bumpers

In 1897, Czechoslovakian automaker Nesselsdorfer Wagenbau-Fabriksgesellschaft was the first who fit an automobile with bumpers. After several years, a British engineer named Frederick Simms began working on fully functional and collision-absorbing bumpers in 1901. After 4 years of his studies, he received a patent for them in 1905. In the following years, several appearances of bumpers were introduced until the Ford Model A seen in Figure 2.2 became a widespread application in 1927. [7]

Figure 2.2 : The Czechoslovakian Nesselsdorfer Wagenbau-Fabriksgesellschaft (on the left) and the Ford Model A (on the right) [7].

Various styles of chrome bumpers with the layout of basic metal bars positioned some distance away from the vehicle were seen on different models manufactured between the early 1930s and the early 1960s. During the 1960s and early 1970s, chrome bumpers became slimmer and trimmer. [7]

Until 1973, no standards for bumpers were defined. In 1973, The United States Federal Motor Vehicle Safety Standard (FMVSS) No. 215 mandated that the 1973 model year bumpers have to be strong enough that headlights, tail lights, fuel system components and other safety items do not get damaged after a 5 mph frontal impact and 2.5 mph rear impacts [7,8]. Due to this regulation, steel bumpers were made larger and more durable.

In 1979, the regulations were revised and they stated that not just lights, all body panels must be protected in case of 5 mph impacts. For 1980-1982 model years, a new requirement stating that all bumpers have to be placed between 16 and 20 inches above the ground was added to the regulations. For the 1983 model years, the regulations were again revised and stated that 2.5 mph on front and rear straightforward barrier tests and 3 mph on corner impact tests bumpers can be damaged as long as body panels and lights were unaffected [7,8].

During the following years, automakers began experimenting with plastic covers instead of massive metal bumper structures. In parallel with these experiments, the oil crisis in 1979 dictated more economical fuel consumption through lighter weight and improved aerodynamics. Based on this, in 1980, Mercedes S-class seen in Figure 2.3 was the first having wraparound plastic bumper covers that saved weight. These covers have become the norm of today.

Figure 2.3 : 1980 Mercedes S-class.

2.3 Types of Automotive Bumper Systems

The main criteria that automakers have to take into consideration during bumper system selection is that the bumper must be able to absorb the energy enough as stated in the company specifications and consequently it does not get damaged at a limited speed of impacts. Additionally, the weight, producibility, transportability, transferability, assemblability and cost of bumper systems are the other important criterias for automobile manufacturers.

In 2003, The American Iron and Steel Institute (AISI) offered four proposals for bumper systems [9]:

1) Metal facebar
2) Plastic fascia + reinforcing beam
3) Plastic fascia + reinforcing beam + mechanic absorber
4) Plastic fascia + reinforcing beam + energy absorber material (foam or honeycomb)

The demonstrations of these four proposals for the bumper systems can be seen in Figure 2.4.

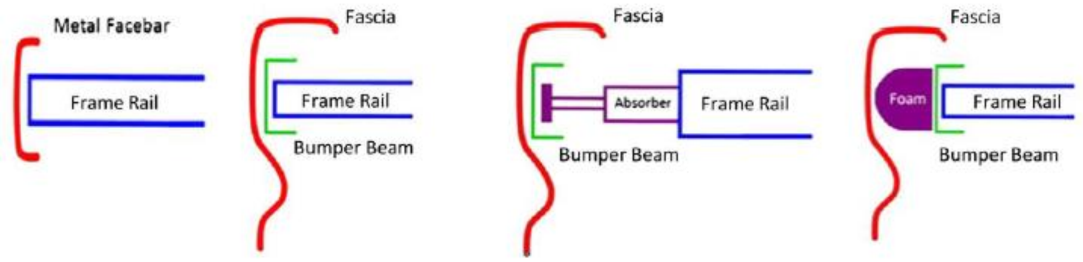


Figure 2.4 : Types of bumper systems [9].

In addition to these four bumper systems, Choi et al. (2004) proposed a concept that includes two types of energy absorbers [10]. The first absorber Choi et al. offered is a low reinforcement absorber which is designed for protection against pedestrian impact. The second absorber, called the irreversible absorber, embodies the beam and the crushable energy absorber that is generally positioned at the back of the beam and connected to the main face bar [10]. A demonstration of a bumper system that includes two types of energy absorbers can be seen in Figure 2.5.

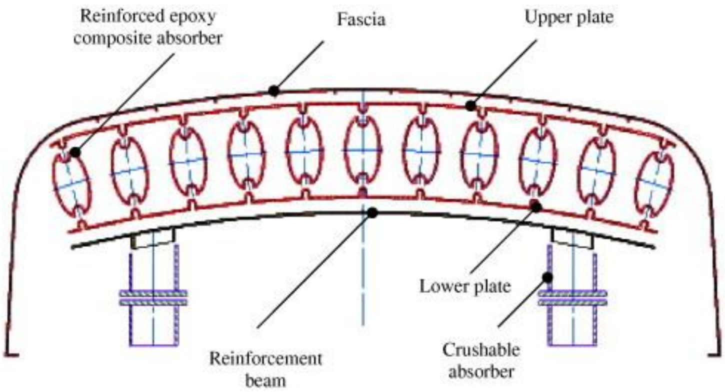


Figure 2.5 : A demonstration of a bumper system consisting two types of energy absorbers [11].

2.4 Automotive Bumper System Components

2.4.1 Metal facebar

Metal facebars are generally made of steel material and produced by applying deep drawing, cutting and/or bending methods using press or moulds. Steel or plastic parts can be adjusted on metal facebars. Except of steel, aluminium is also be used as material. After the shaping processes, anticorrosive applications such as chrome-nickel plating or galvanized coating and painting are implemented on metal facebar bumpers [12].

2.4.2 Plastic fascia

The plastic fascia of a bumper system is usually used for aesthetics and to decrease the aerodynmaic drag force [5]. As the plastic fascia does not have the task to tolerate the impact energy, it is considered to be a non-structural component. The design and material of a plastic fascia have an important role on reducing the air pressure, enabling air circulation inside the motor area and lightening the vehicle. By lightening the vehicle, the plastic fascia of a bumper system also reduces the fuel consumption.

Bumper fascias are hardly 3 mm thick. Today, the mostly used materials are polypropylenes due to mechanical proporties and advantage on cost.

Due to the ability of high flexibility, polyurethane fascias have the advantage of avoiding deformation under 5 km/h impact speed, as in this condition the polyurethane fascia will roll back into its initial shape [13].

2.4.3 Bumper beam

Bumper beam is the part by which the bumper is mounted to the vehicle body. They are attached to the front and rear ends of automobiles by favour of brackets that have the task of taking the loads mainly in the axial direction [14]. Bumper beams have to be designed to minimize the damage of the vehicle and the risk of injury of the passengers by absorbing the energy arised from a collision.

The weight of a bumper beam is very important as it has a direct effect on fuel consumption. However, in order to minimize production costs, the bumper beams must have a simple manufacturing process.

Mainly, steel, aluminium, magnesium and, more likely today, polymeric-based composites are used as materials for bumper beams. The use of a polymer composite material can be very advantageous as this material is easy to manufacture and has a lower weight [9].

2.4.4 Energy absorber

The energy absorber component of a bumper system has an important role on absorbing the kinetic energy occured during collision. Usually two types of energy absorbers are applied in bumper systems: mechanical absorber or absorber material.

The mechanical absorber can be considered as an telescope-type shock absorber placed between the bumper beam and the vehicle frame. In case of a front-end impact, the mechanical absorber shortens and if this impact is between the strength limit of the absorber, the telescope-type absorber returns back to its actual length. The biggest disadvantage of mechanical absorbers are that they are heavy and have a limited absorption ability .

Absorber materials are usually made of foam or honeycomb structured polypropylene, polyurethane and low density polyethylene materials which are advantageous as being lightweight and high strength [12]. A honeycomb bumper is a combination of a core and a shell. The core and the shell can be made of the same materials such as metal, plastic or paper based materials. The core of a honeycomb bumper has a structure consisting of many cells, having either a hexagonal or any other geometric shape, that have the task to absorb the impact force. The shell is the cover of the core and accounts for maintaining the style and desing of the motor vehicle.

2.5 Safety Standards of Automotive Bumper Systems

The United Nations Economic Commission for Europe (UNECE) Regulation No. 42 stipulates principles regarding the approval of passenger cars in scope of the front and rear protective devices based on low speed impact test procedure. According to this regulation, in case that a passenger car under loaded and unloaded conditions is impacted by a moving barrier on the front or rear longitudinally at 4 kilometers per hour and on the front and rear corner at 2.5 kilometers per hour at the height 45.5 cm above the ground, the safety systems of the car have to continue to operate in a normal way [15].

Another requirement that this regulation provides is that, the surfaces of the front and rear protective devices on the vehicle which usually get in contact with other objects shall be covered by, or made of rubber or any equivalent material, the hardness of which shall not exceed 60 Shore A [16].

The United States CFR (The Code of Federal Regulations) 49 Part 581 standard requires the same conditions as the UNECE Regulation No. 42 for the lower impact speeds, with longitudinal impacts conducted at only 4 kilometers per hour. More strictly than these standars, the Canadian Motor Vehicle Safety Standard (CMVSS) 215 for bumpers is based on a series of 8 kilometers per hour front and rear longitudinal and 4 kilometers per hour corner impacts after which the safety systems of the vehicle have to function normally [17].

In the scope of these bumper standards, there are two types of impact tests that are applied on the front and rear bumpers of passenger cars. The first test is the longitudinal impact test which applies two impacts on the front and two impacts on the rear bumper. On each bumper, one impact is tested in unladen weight condition and the other is tested with laden weight condition [17]. According to the UNECE Regulation No. 42 and the United States CFR 49 Part 581 standards, the speed of the impactor should be 4 km/h while for the CMVSS 215 standard it should be 8 km/h.

The second test is the corner impact test. Similar to the longitudinal test, this test also applies two impacts on the front bumper and two impacts on the rear bumper. The first impact is tested on one corner of both the front and the rear bumpers in unladen weight condition while the second impact is tested with laden condition [17]. According to the UNECE Regulation No. 42 and the United States CFR 49 Part 581 standards, the speed of the impactor should be 2.5 km/h while for the CMVSS 215 standard it should be 4 km/h.

The impactor used during these tests should either have a structure like a pendulum or be secured to a moving barrier. In order to satisfy a proper test condition, the moving barrier should not be deformed by the impact or the plane of the pendulum should remain parallel with its rotation axis.

2.6 Materials and Production Methods of Automotive Bumpers

2.6.1 Materials of automotive bumpers

In addition to the main functions stated in section "2.1 Definition and Functions of Automotive Bumper Systems", a bumper is also expected to contribute to lightweighting of vehicles in order to improve fuel consumption and reduce environmental pollution, besides being recyclable.

Due to the their high cost and resisting problem against corrosion, the high-strength steel and aluminium bumper beams used 50 years ago became within time unfavorable and car makers got in search of new materials. Focus has thus shifted to the use of plastics and polymer composites which have many advantageuous properties such as mentioned in the following [18]:

- High corrosion resistance,
- Light weight,
- Functional design and manufacturing,
- Higher ability of shock energy absorption,
- Satisfying aesthetics,
- Lower cost,
- Reduced maintenance.

Based on their low density, light weight, high strength and stiffness, polypropylene (PP), polyurethane (PUR) and polycarbonate (PC) are the main materials used in recent times for bumper fascias. However, PP, PUR, low-density polyethylene (LDPE) and foams though thermoplastic polyolefins (TPOs) are the commonly used material for energy absorbers of bumper systems [13,18]. In order to improve the strength and stiffness, these materials are usually reinforced with other materials.

In the matter of bumper beams and reinforcement bars, sheet molding compound (SMC) and glass-mat-reinforced thermoplastic (GMT) have been the alternatives to steel and aluminium. Due to its better mechanical properties and approximately 60% less weight, current investigations focus on replacing these with carbon-fiber-reinforced plastic (CFRP) [13,18].

The aim of using fiber reinforced plastics is to combine the stiffness and strength of the fibrous material which has high corrosion resistance, low density and mould ability [19]. The widespread reinforced plastics produced recently are glass reinforced epoxy or polyester resins. Phenolics, silicones, polystyrene and polyvinyl chloride are materials used with glass fibers.

As having good compatibility with glass fibers, high strength, low viscosity and low flow rates that allow good wetting of fibres, epoxy resins are the most commonly used resins [19].

Table 2.1 lists the mechanical properties of materials used in bumpers.

In addition to these materials, thermosets prepared through reaction injection molding have being investigated to be used for bumper fascias due to their crashworthiness at lower temperatures and recyclability [18].

Table 2.1 : Mechanical and other important properties of bumper materials [18,19].

Material	Density (g/cm^3)	Ultimate Tensile Strength (MPa)	Elastic Modulus (GPa)	Impact Strength (J/m)
Steel	7.8	648	206	
Aluminium	2.7	234	69	
PP	0.9-0.95	33	1.4	27-100
LDPE	0.91-0.93	8-12	0.2-0.4	No break
PUR	1.12-1.24	3.4-24.6	0.4-31.6	58.7-800.7
PC	1.20-1.31	60	2.5	800
ABS-high impact	1.02-1.04	24-45	1.38-2.42	163-436
TPO	0.88-0.98	4-17	0.008-0.113	No break
SMC (UP-GF25)	1.7-2	65-80	8.5-12.5	6,000-9,000
SMC (UP-GF50)	1.85-2	124-204	12.2-19.1	12,000-20,000
GMT (30 wt.% PP)	1.1-1.6	40-70	5.2-8.0	
CFRP (PC reinforced with 30% carbon fiber)	1.31	170	16	100-130
CFRP (PA 6 or 66 reinforced with 30% carbon fiber)	1.26	230	19	80-100
DCPD (Dicyclopentadiene)	1.02-1.20	43-76	1.76-2.57	53.4-507

2.6.2 Production methods of automotive bumpers

In the scope of this thesis, the recent widespread production methods of automotive bumpers will be investigated and described.

2.6.2.1 Hand lay-up

In the hand lay-up method, in other words hand laminating method, a liquid resin is mixed by hand in a bucket and applied by using a brush or mohair roller on the mould

[20,21]. Then, the fiber glass is placed on the top of the resin manually. By the help of a roller, the fiber is embrued with the resin. Until the proper thickness is created, another resin and reinforcement layer is applied stepwise.

Large or thick forms are mainly made in several stages by permitting the resin to gel after each stage before the following step is applied. Likewise, support ribs, core materials and metal inserts can be placed during the build-up of the laminate and encapsulated by following layers [21]. The stages of the hand lay-up method can be seen in Figure 2.6.

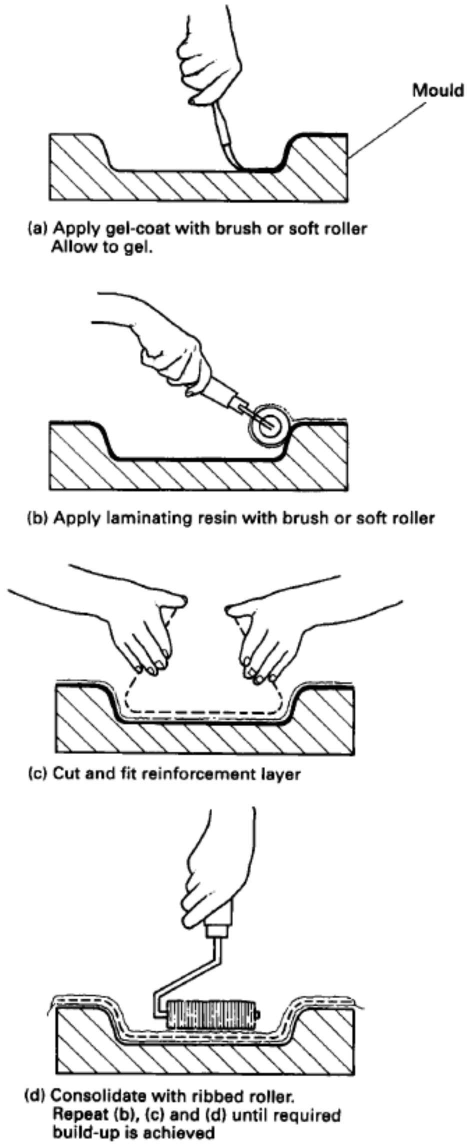


Figure 2.6 : Stages of hand lay-up process [21].

A homogeneous fiber drench is obtained by the pressing action with a roller and the part is then waited for curing at room temperature for about one week. After the part is solidified, it is taken out from the mould. Any thin-walled and simple shape which allows access for the operator can be produced by the hand lay-up method [21].

Advantages of hand lay-up

- The mould design is very simple as it only requires room temperature for curing with low pressure and plastics can be used as mould material. Therefore, the cost for producing a prototype part is very low [21].
- Instead of high investment cost for mould and equipments, the hand lay-up process is based on intensive workmanship which enables low capital cost.
- Any type of fiber material can be selected with any other fibre orientation.
- Comparing with other production processes of composites, there is no size limit for the parts produced by hand lay-up and the flexibility is higher.

Disadvantages of hand lay-up

- As the process is workship dependent, the weight and thickness control is poor [21]. In addition, there is a risk that the quality of the parts produced can vary from each other.
- The process is mainly proper for prototypes and parts having large structures.
- The number of units produced by this method is very low when comparing with the other composite production processes.
- Because of its open mould nature, only one moulded face can be built up. Therefore, the secondary surface requires trimming [20,21].
- Due to open mould structure, the hand lay-up causes environmental pollution.

2.6.2.2 Injection moulding

Injection moulding is a process that enables large numbers of production of the precision plastic components. This process is used mainly for thermoplastics, but thermosets, composites and elastomers can also be processed.

In case that a composite part will be produced with the traditional injection moulding process, firstly a paste must be mixed containing all ingredients including the reinforcement inside the machine hopper. Then, the granulated material is melted or plasticized in a heated barrel by a back-and-forth moving screw and then injected into a closed mould by applying a high pressure [13].

A demonstration of the traditional injection moulding technique is shown in Figure 2.7.

The sequence of plasticization, injection, cooling and ejection operations are monitored on a very certain time cycle [13].

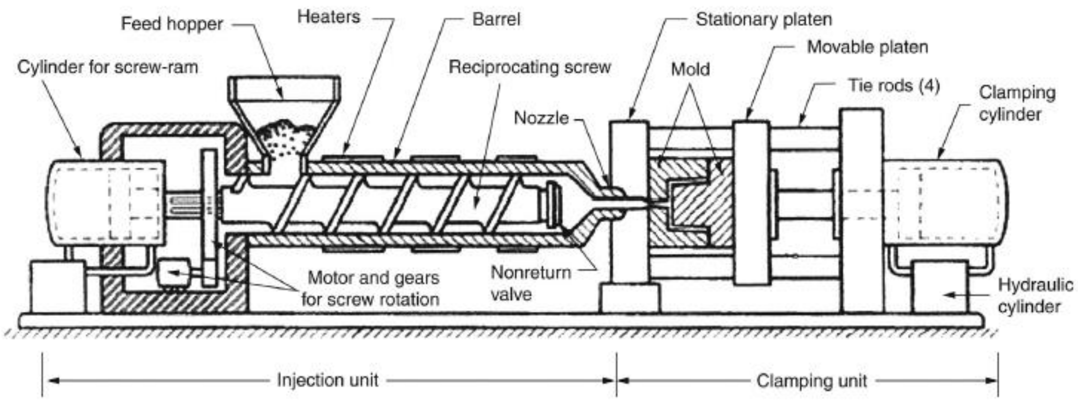


Figure 2.7 : Traditional injection moulding technique [22].

Advantages of injection moulding

- As the process is based on equipment and mould performance instead of workship, the production rate is very higher (in average 200 to 10,000 parts yearly) than the hand lay-up process.
- Due to high production volume, the unit cost of parts is very low.
- Direct labour cost is low especially when compared with hand lay-up.
- It is a design freedom process that enables wide variations in shape and complex forms produced with close tolerances [21].
- As a smooth surface is produced, the trimming and painting cost is minimal.
- Number of parts and assembly operations can be reduced due that component consolidation is enabled with injection moulding [22].

Disadvantages of injection moulding

- As the moulds of injection moulding processes must have errorless dimensions and have to be made of wear resistance materials, the tooling cost is very high.
- Beside tooling, the equipment cost of injection moulding technique is also high.

- The lead time can take several weeks based on long manufacturing processes of complex dies.
- The nature of injection moulding process does not allow to produce closed shapes or shapes with extreme undercuts [22].

2.6.2.3 Reaction injection moulding

The commonly used type of reaction injection moulding (RIM) process for producing automotive bumpers is the thermoset DCPD (Dicyclopentadiene) RIM.

In the DCPD reaction injection moulding process, two components of DCPD resins are filled into a mixing tank by the help of cylinders and pistons and then injected into the mould at a high speed where polymerizaiton and descendent concretion occur [23].

The methodology of reaction injection moulding can be seen in Figure 2.8.

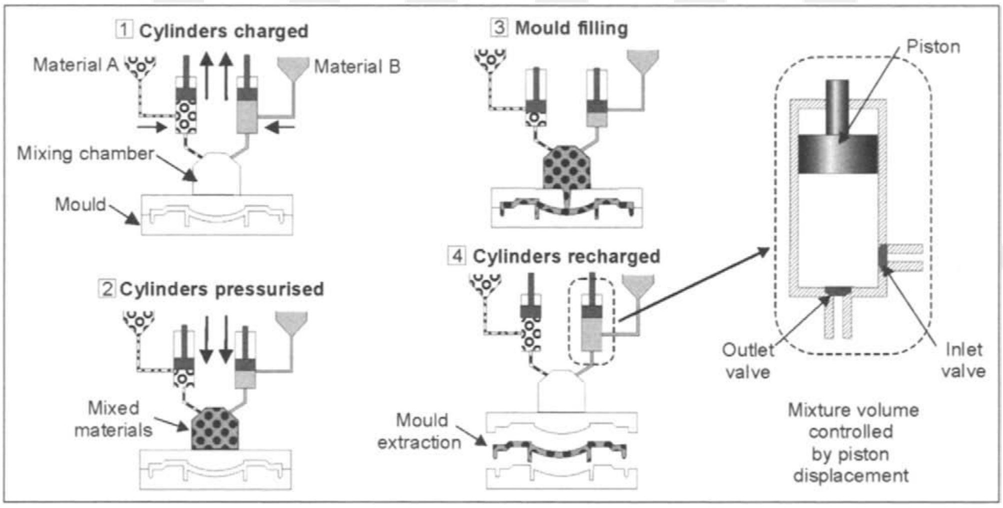


Figure 2.8 : Reaction injection moulding [23].

The DCPD resin is created by using a catalyst (to open the dicyclo ring in the thermoplastic DCPD resin) mixed in either side of a two component mix [24]. Today, manufacturers prefer to use DCPD instead of unstaurated polyester resins. The main reason of this change is having the possibility of reducing the content of styrene resins (approximately from 42% to 35%) and lowering the cost when using DCPD. The low styrene content decreases the shrinkage during curing of lamination and a better surface quality can be built up.

The common parts made with the DCPD RIM are automotive bumpers, containers, air spoilers and fenders.

Advantages of reaction injection moulding

- Foamed materials having a solid skin can be built up.
- As the tools are commonly made up from aluminium, the tooling cost is lower than injection moulding.
- Direct labour cost is low especially when compared with hand lay-up.
- As only approximately 1% of scrap lost occurs during reaction injection moulding, the material utiliziation is good [23].
- As the bi-component mixture injected into the mould has a much lower viscosity than molten thermoplastic polymers, by using DCPD RIM it is possible to produce large (up to 13 m^2), thin-walled, lightweight, impact and high heat deflection resistant parts [24].
- This process is economic for medium production volumes [23].
- As a smooth surface is produced, the trimming and finishing requirement is low.
- It is possible to produce parts with complex shapes having ribs and holes.

Disadvantages of reaction injection moulding

- The scraps of reaction injection moulding can not be recycled.
- Such in injection moulding, the lead time can take several weeks based on long manufacturing processes of complex dies.
- The equipment cost is high.

2.6.2.4 Compression moulding

In compression moulding process, rigid and properly matched set of moulds are mounted in a hydraulic press which has the capacity to exert a pressure of at least 2 bars. In order to fasten the curing phase, heat is also applied on the mould surface. To maximize the output, the mould needs to be at 140 °C which brings up the necessity to use metal moulds [21].

The methodology of compression moulding can be seen in Figure 2.9.

Recently, preimpregnated reinforcements are prefferd to be used for compression moulding. These prepreg reinforcements are either in the form of continuous fibre prepregs or sheet and bulk moulding compounds, which are known as SMC and BMC, and contain shredded fibre reinforcement [21].

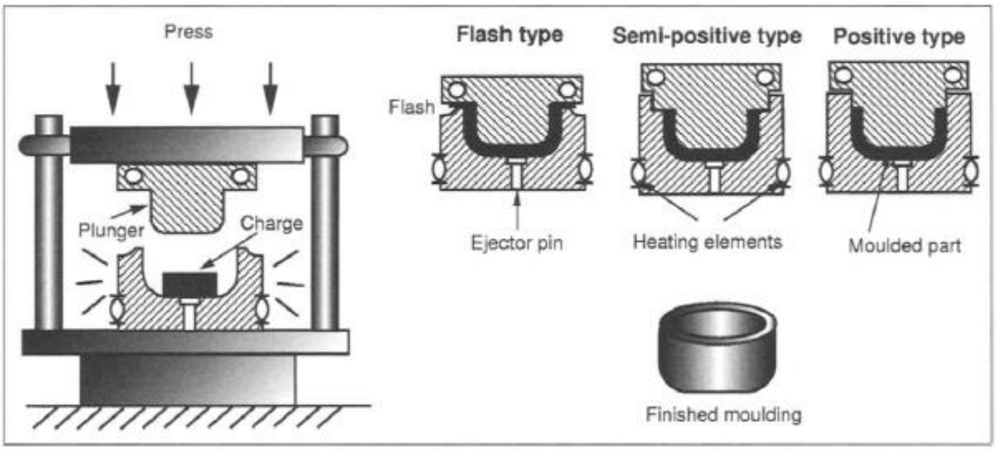


Figure 2.9 : Compression moulding [23].

Sheet moulding compound (SMC)

Sheet moulding compound is a compression moulding compound involving fiber reinforced thermoset materials and is mainly used for producing large parts where high mechanical strength is needed. The glass reinforcement of SMC is between 10% to 60% and the glass length is betwen 12.5 mm to 25 mm [25].

As seen in Figure 2.10, during the production of sheet moulding compounds, the material is mantled with a polyethylene or nylon plastic film from both top and bottom in order to prevent adhesion. The paste is exuded uniformly onto the bottom film and redded glass fibers are randomly laid up on the paste [25]. After the top film is applied, the sandwich structure is rolled and left to cure for 48 hours.

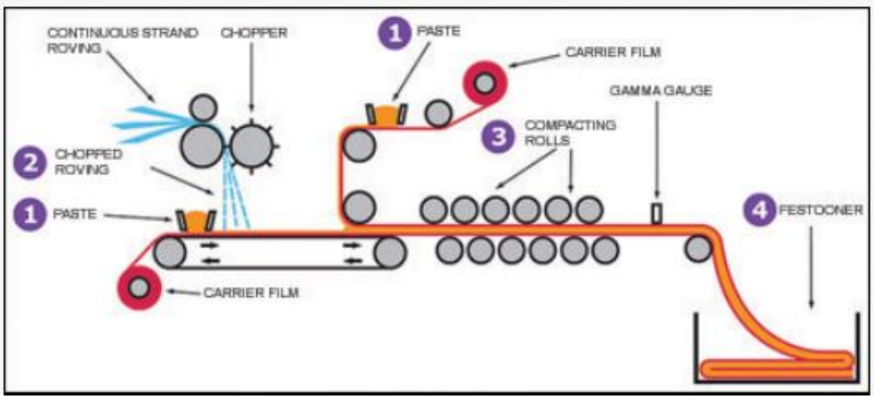


Figure 2.10 : SMC manufacuring process [24].

SMC is widely used for producing automotive bumpers, drinking water tanks, electrical and bathroom products due to its properties such as having smooth surface, high strength, good insulating performance, resistance to corrosion and efficiency of high production.

Bulk moulding compound (BMC)

Bulk molding compound is a thermoset plastic resin that consists of various inert fillers, fiber reinforcements, catalysts, stabilizers and pigments that form a viscous injection moulding compound highly filled and reinforced with short fibers. The glass reinforcement of BMC is between 10% to 30% and the glass length is betwen 0.8 mm to 12.5 mm [25].

Due to wide design and production flexibility, smooth surface, ease of coloring, ability of recycling, high strength, resistance to corrosion and heat, BMC is widely used in several industries such as automotive, aircraft, home appliances and toy production.

Advantages of compression moulding

- A very high production rate which upon part size and thickness varies in average from 20 to 140 parts per hour can be figured out [23].
- High density parts can be produced when composites such as SMC, BMC or thermosetting materials are used.
- The compression moulding process produces high strength and complex parts having a wide variety of sizes, even structures with holes.
- During compression moulding, both the resin and the fibre are able to flow under the implementation of heat and pressure that enable to build up complex forms of single parts.
- Direct labour cost is low especially when compared with hand lay-up.
- The equipment and tooling cost is lower than injection moulding processes.
- The tools of compression moulding have relatively a long life.
- The products of compression moulding have a very high accuracy and stability.
- Due to two excellent finished surfaces, the trimming and finishing costs are minimal.
- Metal inserts can be put inside the gap of the mould. Thus, it is possible to build up parts strengthened with inserts.

Disadvantages of compression moulding

- As in injection moulding process, the lead time can take several weeks based on long manufacturing processes of complex dies.
- As each cavity is feeded manually, the cycle time is restricted because of material handling [23].
- The variability in mechanical properties can be a problem.
- As the process requires high pressure, the tools are generally made of steel. Therefore, the tooling cost is higher when compared with hand lay-up and reaction injection moulding.
- Due to huge sizes of metal moulds, big presses are required.

2.6.2.5 Resin transfer moulding

In resin transfer moulding (RTM) process, after a dry reinforcement pack or a fiber mat is loaded into the heated mould, the mould closes under low pressure and then a low-viscosity resin and catalyst is loaded into a mixing head and forced into the mould by an air-driven dispensing machine through one or more injection points where curing takes place [21,23]. The forcing time into the mould can vary between 1 to 10 minutes subject to the size and fibre content. A schematic of resin transfer moulding can be seen in Figure 2.11.

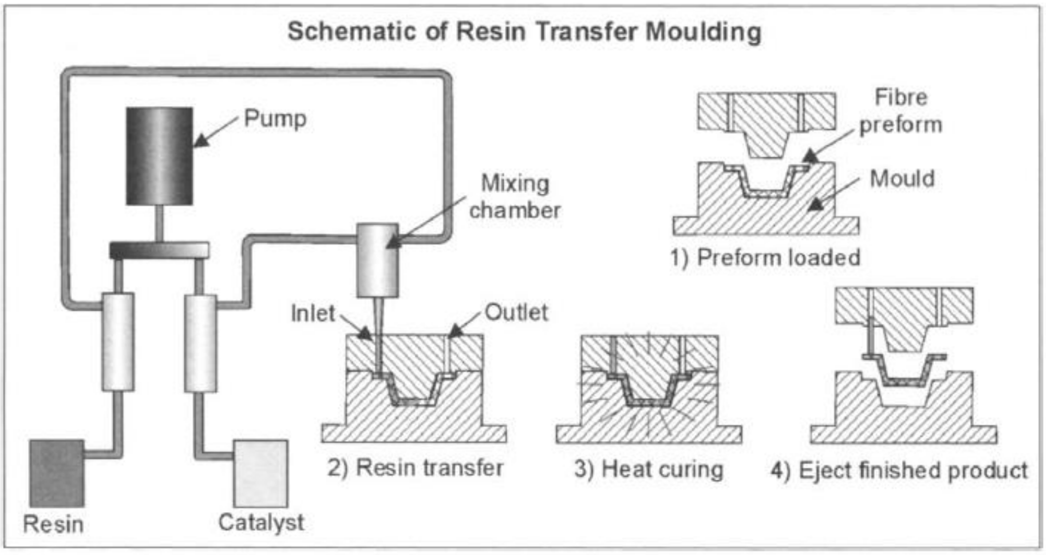


Figure 2.11 : Resin transfer moulding process [23].

Resin injection is limited to only several thermosetting plastics and elastomers, either with or without fillers. Pre-pressed fiber packs, containing glass or carbon, can also be used to fit the moulds. The resin material can be polyester, polyurethane or epoxy with low density viscosity [21].

The pressure applied during the injection of the resin can be up to 2 bar which requires the mould construction to be resistant against the loads.

RTM is widely used for producing truck panels, aerospace and automobile parts, car body, medical composites and bathroom fixtures.

Advantages of resin transfer moulding

- Parts produced with RTM are lightweight and have a strentgh against impact, corrosion, flame and abrasion.
- Direct labour cost is low especially when compared with hand lay-up.
- RTM is usually described as an intermediate process between the relatively slower hand lay-up process and the faster compression moulding process [24].
- Variable materials such as polyester, nickel shell, aluminum or mild steel can be used for the tooling of RTM upon the production volume, life of program and budget. The tooling cost is moderate to high.
- As in RIM and compression moulding processes, two smooth finished surfaces can be figured out by RTM that minimizes the trimming and finishing costs.
- As less than 3% of scrap occurs, the material utilization is good [23].
- The lead time for dies are lower than injection moulding.
- Parts having close tolerances and complex shapes are possible to be produced with RTM.
- Metal or ceramic inserts can be put inside the gap of the mould. Thus, it is possible to build up parts strengthened with inserts.

Disadvantages of resin transfer moulding

- There is no opportunity for in-mold trimming.
- The labour requirement is higher when compared with RIM.

- The variation in resin/fiber concentration is difficult to control in sharp corners [21].
- As the production time with RTM takes longer than injection moulding, RIM and compression moulding, RTM is a proper process for only low to medium production amounts [24].
- The equipment cost is moderate.

A summary for comparison of the production methods stated under section “6.2.1 Production methods of automotive bumpers” is summarized in Table 2.2. The methods except hand lay-up is evaluated by taking the hand lay-up as base.

Table 2.2 : Comparison of automotive bumper production methods [26,27,28].

Method	Mould Cost	Production Rate	Unit Cost[1]	Part Complexity	Part Strength
Hand Lay-up	Low	Low	High	Medium	Medium
Injection Moulding	High	High	Low	High	High
RIM	Low	Medium	Low	High	High
Compression Moulding (SMC)	High	High	Low	High	High
Compression Moulding (BMC)	High	High	Low	High	High
RTM	Medium	Medium	Medium	Medium[2]	High

2.7 Future of Automotive Bumpers

As the automotive industry today is very competitive, plastics have become an important key that opens the challenges for the automobile manufacturers. What the automobile users expect from todays’ automobiles are high performance, comfort, safety, fuel efficiency, attractive designs and of course low prices [29]. At the other side, the society demands lower air pollution and a cleaner environment.

Due to these expectations, automobile manufacturers carry on with the research of new bumper materials and manufacturing processes. Lighted PP, blended thermoplastic materials and recyclable plastics are some examples of these innovations [29]. Beside new material variants, it is also a challenge for the plastic producers to develop new

[1] The evaluation of unit cost performance is done according to the maximum production amounts that can be reached depending on each method’s capacity.
[2] In case that smooth inner surfaces are not required with RTM, instead of two mould structure, vacuum bags can be used as the upper tool in RTM. In this situation, the part complexity is evaluated as medium.

variations of plastic processes. Due to the advantages such as lower production cost for higher production volumes, no assembly cost, water resistancy, lightweight, etc., especially multimaterial injection moulding or over moulding technologies are the most challenging methods that plastic processors investigate for innovations of future [29].

Safety and recycling of parts are prior challenges for automotive manufacturers on which plastic parts take a special role. Especially, recycling is an important scope that the automotive industry focuses on today. Designing vehicles with recycling materials does not only increase the waste stream, it also reduces the cost of dismantling a vehicle at the end of its life. Therefore, developing new assemblies which do not only satisfy cost and performance expectations but also enabling easy dismantling and recycling is recently a key challenge for automotive manuufacturers.

3. STRUCTURAL ANALYSIS AND DESIGN SOLUTION OF A REAR MIDDLE BUMPER USING FINITE ELEMENTS METHODS

3.1 Definiton and Approach of Finite Elements Methods

Finite Elements Method (FEM) is a numerical method that divides complex problems of structures having complicated geometries, loadings and material properties into basic sub-problems in order to come up to the whole solution by solving these basic sub-problems separately [30, 31]. FEM splits a complex structure into several pieces, in other words elements, and then reconnects these pieces at nodes which act as pins that hold these pieces together as shown in Figure 3.1.

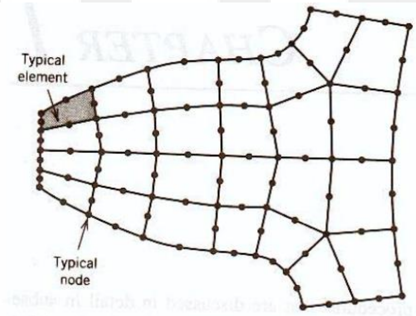


Figure 3.1 : An example of typical elements and nodes in FEM [30].

Pieceweise polynomial interpolation is used as concept in FEM and structures are analyzed by applying a set of simultaneous algebraic equations. The degree of the selected polynomial depends on the degree of the problem equation and the number of nodes of the element to be solved.

The field variables such as stress, displacement, pressure, temperature, etc. in a continuous environment can have infinitely many different values. If it is known that a given region of a continuous environment also has the same continuous property, the change of field variables in this sub-region can be defined by a function whose unknown elements are finite. Depending on the number of unknowns, the selected function may be linear or higher order. Since the subfields of the continuum are also regions with the same characteristic features, when the sets of field equations belonging to these regions are combined, a set of equations defining the whole system is obtained [12]. By the solution of the equation set, field variables in the continuous environment are achieved numerically.

With the use of FEM and widespread use of computers in the industry, it has become possible to easily investigate and analyze many machine systems or components whose strength and functionality were analyzed by costly experimental methods until today.

The main principle of the finite element method is firstly to define the equations presenting the system properties of each element and then to obtain the set of linear equations that represents the whole system by combining the equations of each elements. There are number of ways to formulate the properties of the individual elements of the whole system. The main approaches used in FEM are defined below.

3.1.1 Direct approach

This approach is more suited to single-dimensional and simple problems.

The main idea of FEM is designed from the physical procedure used in framed structural analysis and network analysis such as pipe network and electric network [32]. As the chosen elements may lead to a precise representation of the problem in certain applications, the element properties are obtained from the fundamental physics and nature of the problem in the direct approach. The stiffness method analysis can be given as an example of the direct approach applied in structural mechanics [32].

3.1.2 Variational approach

In variational approach, the boundary forces and displacements are calculated from the displacement distribution function and afterwards the nodal values are estimated, in other words the element matrix is figured out [33]. The variational approach can be defined as the extremity of a function, in other words maximization and minimization of a function. The most commonly used functions in solid body mechanics are the potential energy principle, the complementary potential energy principle and the Reissner principle [12,31]. At the point where the first derivative of the function is zero, the extreme values of the function are calculated. Depending on the second derivative being greater or less than zero, it is understood that this value is the maximum or minimum.

3.1.3 Energy approach

It depends on the uniformity of the thermal or mechanical energies entering and leaving a system [31]. The commonly applied method of energy approach in FEM is the minimum potential energy principle which depends on finding the consistent conditions of the body or structure related to the stationary values of a scalar quantity supposed by the loaded structures [32]. This scalar quantity is defined to be a function of another function.

3.1.4 Weighted residual approach

The weighted residual is a technique that aims to minimize the sum totals of the values calculated by multiplying the differences between the approximate solution and the real solution by a function [12]. In this approach, the base field is first divided into suitable elements. Then, the general functional behavior of the dependent field variable is assumed to approximately satisfy the differential equations given on the elements. In beginning, an approximation is applied to each element and then this approach is substituted for the original differential equation and summed over the entire field [32]. The advantage of obtaining element properties using this approach is that it can be applied to problems where functions can not be achieved.

3.2 Steps of Solution in Finite Elements Methods

The approach to be used in problem solving with the finite element method does not change the way to be followed in the solution process. The steps that should be followed in FEM can be summarized as stated below:

1) Splitting the body or structure into finite elements,
2) Selection of the interpolation functions,
3) Obtainig the stiffness matrix of the elements,
4) Calculation of the system stiffness matrix,
5) Finding forces acting on the system,
6) Determination of boundary conditions,
7) Solution of system equations.

3.3 Advantages of Finite Elements Methods

Due to the advantages stated in the followig, FEM is widely used in mechanical, aerospace, civil and automotive engineering.

- Due the variability of the dimensions and shapes of the selected finite elements, the geometry of the whole part can be represented very close to its original [30].
- FEM can overcome a variety of engineering problems such as solid mechanics, dynamics, heat, fluid and electrostatic problems.
- Fields with one or more holes or corners can be easily examined [31].
- Objects having different material and geometric properties can be examined.
- Problems of cause-effect relations can be formulated by a general stiffness matrix in terms of generalized interconnected forces and displacements. This feature of FEM makes it both possible and easy to understand and solve the problems [12].
- Border conditions can easily be applied.

3.4 Computer Applications Using Finite Elements Methods

Many computer aided design (CAD) softwares such as CATIA, ANSYS, Siemens NX, Solidworks, AutoCAD, etc. are commonly used in industry in order to simulate the functions of any system or component during product development phases and to reduce the time and costs spent for releasing the systems or components on market by implementing virtual prototyping.

In this thesis, Siemens NX is used during the design and product development process of the rear middle bumper design for a raised floor bus. Siemens NX software is an integrated product design, engineering and manufacturing tool that enables solutions for conceptual design, 3D modeling, multi-discipline simulation for structural, motion, thermal, flow and multi-physics applications and complete part manufacturing solutions for tooling, machining and quality inspection [34].

3.5 Systematic Design Solution of A Rear Middle Bumper

In order to develop a systematic design solution for the rear middle bumper in the scope of this thesis, the steps stated below were followed:

1) Task clarification and preparation of the requirements list,
2) Selection of the production method and material alternatives,
3) Modeling of part: Surface and 3D modeling,
4) Structural analysis of alternatives,
5) Improving the design based on the weak results of analysis,
6) Repeating the structural analysis of alternatives after every design improvement,
7) Selection of optimum alternative.

During the design phase of the rear middle bumper, iteration process was used to develop a systematic solution according to the structural analysis results of the alternatives. By iteration process, a solution is approached step by step. One or more steps are repeated according to the results of the previous loop in order to get the optimized information to receive a solution and enable continuous improvement as seen in Figure 3.2 [35]. According to the complexity of the structures, these iterations may be needed to be applied frequently during the problem solving process.

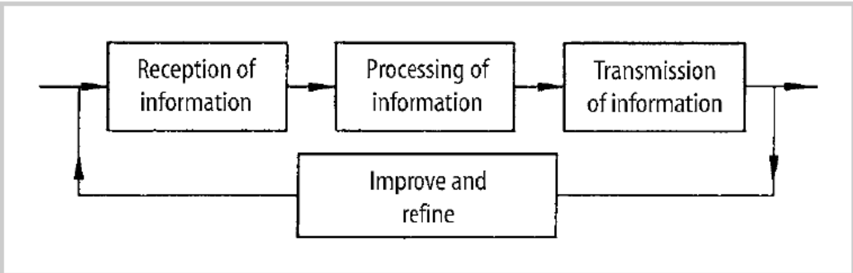


Figure 3.2 : The conversion of information using iteration [35].

3.5.1 Task clarification and preparation of the requirements list

As stated in “2.1. Definition and Functions of Automotive Bumper Systems”, the driver and passenger compartments of a raised floor bus are in a higher position than the frontal and rear collision height. Therefore, the risk of injury and death of the driver and passengers is lower in a raised floor bus when compared with passenger cars. Due to this lower risk, the priorities expected from a bus bumper system differ from a passenger car.

By taking the main functions of a bus bumper system stated in section “2.1. Definition and Functions of Automotive Bumper Systems” into consideration, the main expectations from a rear middle bumper in a raised floor bus that is addressed in this thesis can be summarized as below:

- Minimizing the injury of the pedestrians in case of a rear collision with pedestrians.
- Keeping its form against the strain occuring during the production, transport, carriage, storage and assembly processes.
- Carrying the park sensors fixed on it.
- Resisting against the oven temparature during painting processes and the temperature conditions of the countries where the buses are supplied to.
- Beautifying the bus body design.

Unlike a front bus bumper, behind which components such as electrical devices, cable harness, sensors and spare tire fixations are placed, there are no components fixed on the chassis behind a rear middle bumper. Therefore, it is not expected from the rear middle bumper to protect any components behind it.

In order to enable the functions expected from the rear middle bumper that is analyzed this thesis, firstly the requirements were defined and stated in a list as seen in Figure 3.3. During preparation of the requirements list, the steps stated in Appendix A were followed and the checklist given in Appendix B was taken as reference.

		Requirements list for a rear middle bumper of a raised floor bus	Issued on 15/03/2018
Changes	D (Demand) W (Wish)	Requirements	Responsible
		1. Geometry:	
	D	Length: 1,990 mm	
	D	Height: 355 mm	
	D	Thickness: 3-3.5 mm	
	D	Holes on part for assembly on the bus chassis with bolts M10	
	D	Space on part for tow bar cover	
	D	Space on part for plug cover	
		2.Kinematics:	
	D	Maximum displacement during being carried by hand: 15 mm for composites except of DCPD	
	D	Maximum displacement during being carried by hand: 20 mm for DCPD	
	D	Maximum tensile strength: 55 Mpa	
		3. Forces:	
	D	Maximum load affected on the part during carriage by hand: 40 N	
	W	Being carried by two people as being longer than 1,200 mm	
	D	Stiff enough for being able to carry the park sensor mounted on it	
	W	Vandalismus being out of scope	
		4. Material:	
	D	Plastics due to lightweight and stress resistance	
	D	A smooth outer surface suitable for being painted	
	D	Resisting against the oven temparature (max. 110 °C) during painting processes	
		5. Production:	
	D	Yearly production amount > 1,000 units	
		6. Quality:	
	D	A standardized and repeatable quality level at each part	
		7. Operation:	
	D	Multi-demountable part due to maintenance of park sensors that are mounted on it	
		8. Costs:	
	D	Minimization of tooling cost in order not to exceed the budget	
	D	Minimization of unit cost	
	D	A more economic part than the previous models	

Figure 3.3 : Requirements list of a rear middle bumper.

3.5.2 Selection of the production method and material alternatives

The design phase of the rear middle bumper was firstly started with proposing the production method and material alternatives. In the requirements list stated in Figure 3.2, the yearly production amount of the rear middle bumper is determined as higher than 1,000 units and a minimized tooling and unit cost enabling a more economic part than the previous models is expected. At that point, to decide on the alternative production methods, the information about the most commonly used bumper production methods and Table 2.2 given under section "2.6.1 Production methods of automotive bumpers" were evaluated.

The hand lay-up method, supplying limited production amounts with high unit costs and variable quality levels between its products, and the injection moulding process that requires a high mould and equipment cost were directly eliminated among the alternatives. According to the experiences of the company and part suppliers, as RTM does not satisfy an economic solution for amounts higher than 700 units per year, RTM also did not be chosen as an alternative to be investigated in the scope of this thesis.

According to the informations given under the section "2.6.1 Production methods of automotive bumpers" and the experiences of the company, RIM and compression moulding methods that offer high production rates with relatively lower unit costs and enable a standardized and repeatable quality level, were chosen as the production method alternatives.

A summary for the criteria taken into consideration during the selection of the production method alternatives can be seen in Table 3.1.

Table 3.1 : Evaluation of production method alternatives for the rear middle bumper of a raised floor bus.

Production Methods	**Alternative?**		**Main Reason of Selection as an Alternative**	**Main Reason of Not Being Selected as an Alternative**
	Yes	**No**		
Hand Lay-up		x	-	Limited production amounts with high unit costs, variable quality levels between parts
Injection Moulding		x	-	A very high mould and equipment cost
RIM	x		High production rates with relatively lower unit costs, standardized and repeatable quality level	-
Compression Moulding	x		High production rates with relatively lower unit costs, standardized and repeatable quality level	-
RTM		x	-	Not satisfying an economic solution for amounts higher than 700 units per year

In order to decide on the proper material types that are capable of satisfying the material needs, such as lightweight, strength, a smooth outer surface and heat resistance, which are stated in the requirements list in Figure 3.3, the bumper materials of the previous and current bus types of the company and also the industry applications have been analyzed. UP GF30 SMC (30% glass fiber reinforced unsaturated polyester sheet moulding compound) was selected as the material for the compression moulding alternative and DCPD was selected as the material for the RIM alternative. As a summary, the alternatives for the production method and materials that were proposed for the rear middle bumper in the scope of this thesis are given in Table 3.2.

Table 3.2 : Production method and material selection of the rear middle bumper alternatives [19,36].

		Material Properties						
	Production Method	Material Type	Density (g/cm^3)	Ultimate Tensile Strength (MPa)	Elastic Modulus (GPa)	Impact Strength (kJ/m^2)	Maximum Service Temperature
Alternative 1	RIM	DCPD	1.02-1.20	43-76	1.76-2.57	22-30	180 °C
Alternative 2	Compression Moulding	UP GF30 SMC	1.4-2	50-80	7-11.5	50-90	150 °C

3.5.3 Modeling of the rear middle bumper

Surface modeling can be defined as representing the skin of any object without projecting any thickness and material type information. In order to figure out the main structure and turn the surface data into the model of a mountable part, firstly the surface model of the rear middle bumper was obtained using the computer aided design (CAD) software Siemens NX as seen in Figure 3.4.

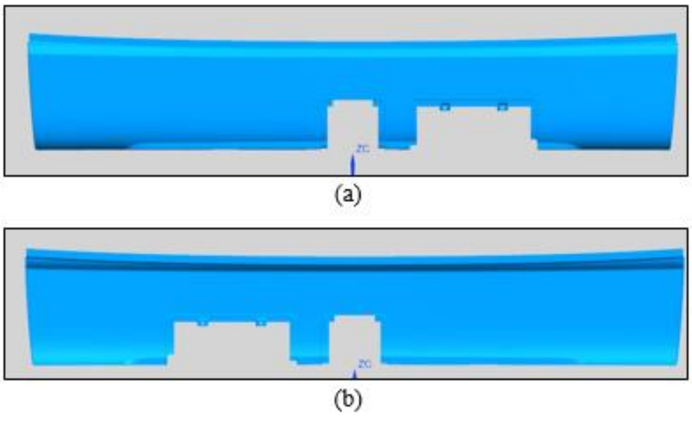


Figure 3.4 : Surface modelling of the rear middle bumper: (a) Rear view. (b) Front view.

After the surface model was represented, the 3D models for both alternatives of the rear middle bumper stated in Table 3.2 were derived by adding a volume on the surface model using Siemens NX. For creating the models of the material alternatives DCPD and UP GF30 SMC, a pre-prepared tool which is integrated in Siemens NX and enables the designer to select the materials from a list was used to introduce the material properties in the models. During the 3D modeling, each element belonging to the model was modeled separately so that the entire model will not be affected in case of any change in a certain region of the model.

Based on the experiences and the risks foreseen, horizontal and vertical axial ribs in order to prevent the structure against the risk of bending in the vertical direction, were partially modeled near the emptied sections opened for the tow bar and plug cover assembly areas. The reason of the partial modeling of the reinforcing ribs beforehand the analysis of the ribless model was to save time during the iterations on the model in case that the analysis results of the ribless model do not meet the displacement and stress limit requirements.

Before the structural analyses were applied on the models using FEM in Siemens NX, for each alternative, the whole model was divided into meshes of 10mm to 10mm squares, in other words into small elements having 100 mm^2 areas.

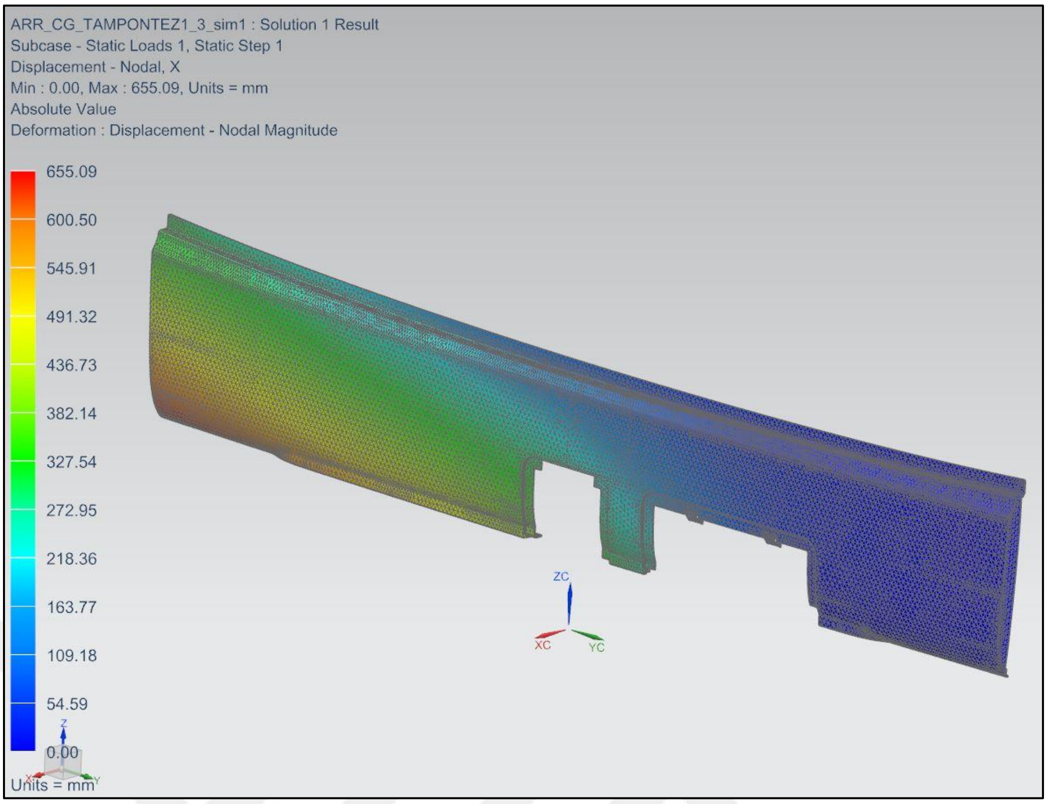
3.5.4 Structural analysis of the rear middle bumper model

As stated in the requirements list given in Figure 3.3, as the length of the rear middle bumper is above 1,200 mm, it is foreseen that the part will be carried by two persons during the production and transport processes in order to minimize the displacement occurred on the part during carriage. Additionally, the maximum load affected on the rear middle bumper during being carried is demanded to be 40 N. Eventhough it is foreseen that the bumper will be carried by two persons, in order to minimize the workmanship for carriage, the case of carriage by one person was also investigated.

By taking the requirements stated above into consideration, two conditions as explained in the following were simulated during the structural analysis of the model.

- Condition A: Applying 40 N force on the model from its center of gravity while it is fixed from 2 vertical corners on same side (simulation of carriage by one person)
- Condition B: Applying 40 N force on the model from its center of gravity while it is fixed from all 4 corners (simulation of carriage by two persons)

First of all, the bumper models without reinforcing ribs were investigated. The analysis results for the ribless models simulating Condition can be seen in Figure 3.5 and Figure 3.6.



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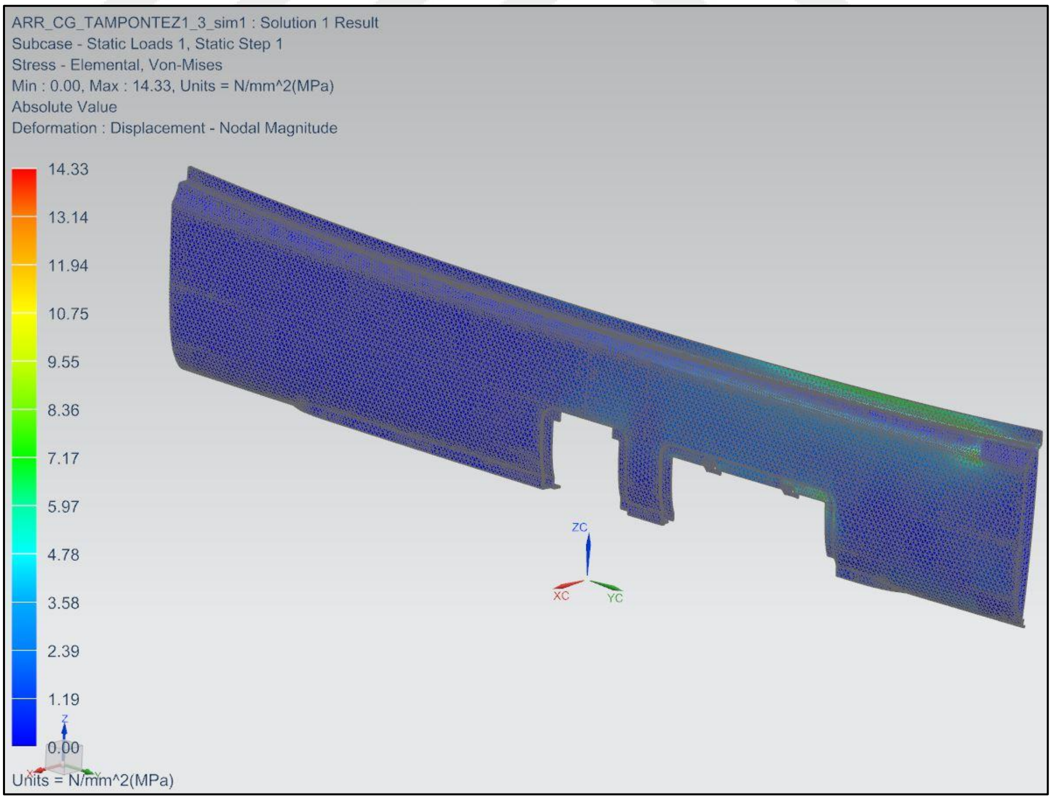
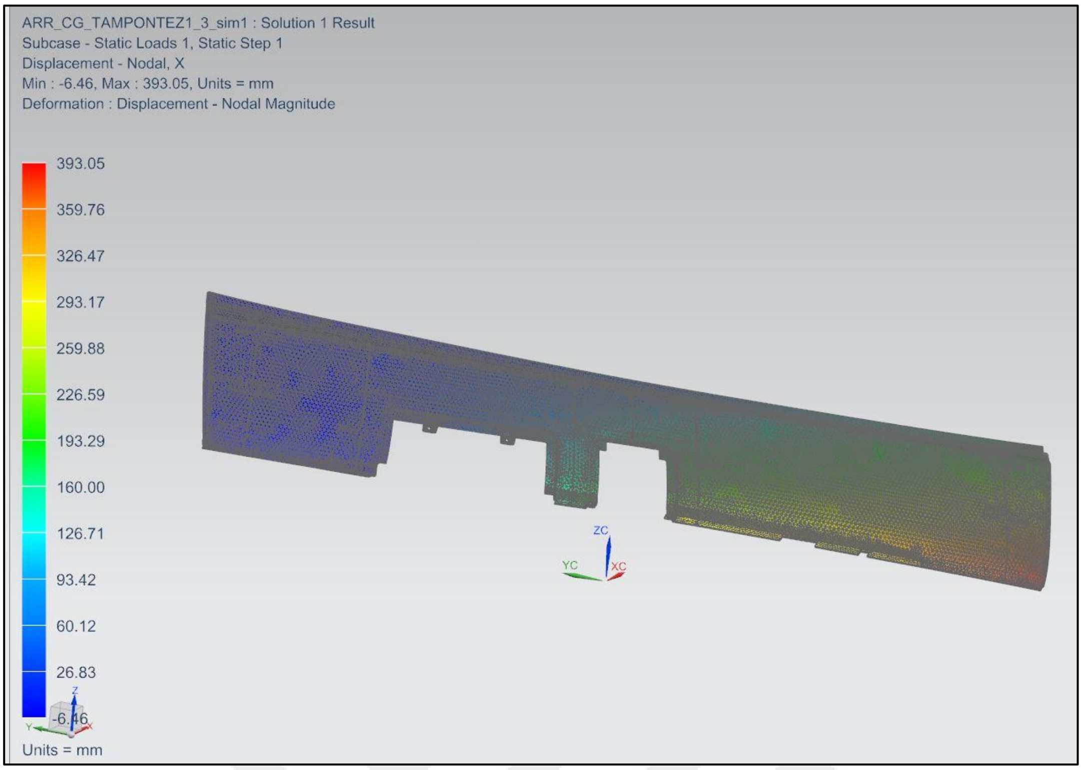


(b)

Figure 3.5 : Structural analysis of the ribless model for DCPD material alternative in case of carriage by one person: (a) Displacement. (b) Stress.



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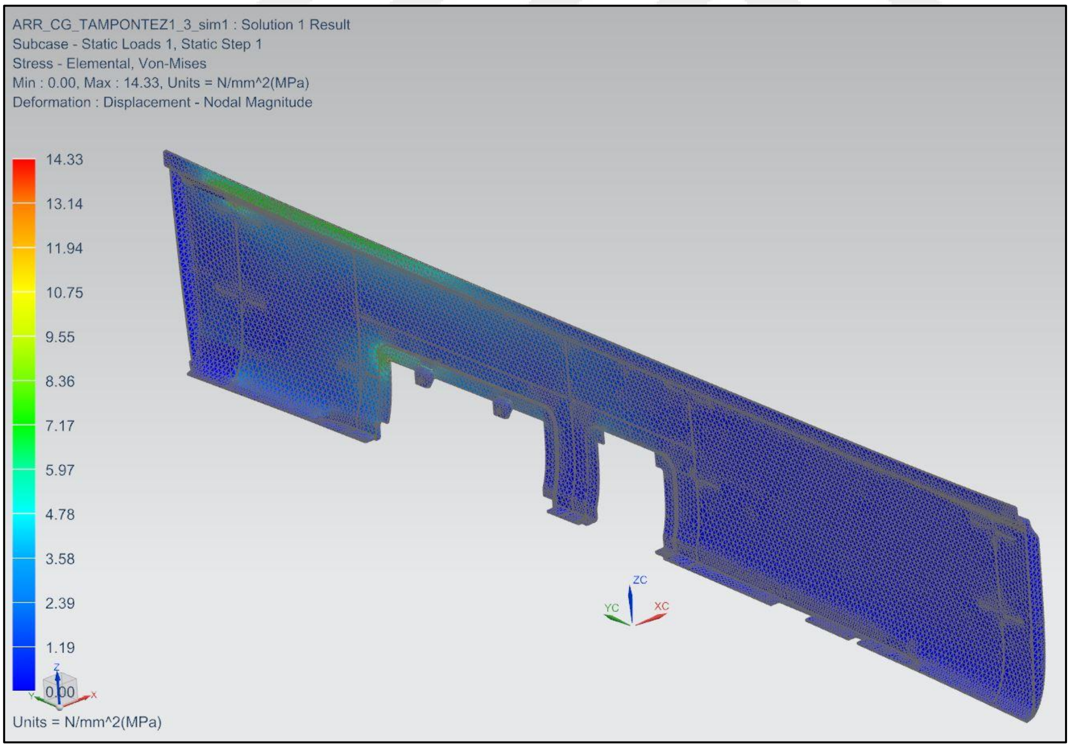


(b)

Figure 3.6 : Structural analysis of the ribless model for SMC material alternative in case of carriage by one person: (a) Displacement. (b) Stress.

As seen in Figure 3.5, in case of carriage by one person, the maximum displacement occured on the ribless model of the DCPD material alternative is 655.09 mm and the maximum stress is 14.33 MPa. The structural change of displacement that is addressed during the analyses in the scope of this thesis can be shortly defined as the distance how much a part moves out its axis under a defined stress is affected on it. Herein, stress can be defined as the force that causes the part to be displaced. Eventhough the stress calculated during the analysis in Figure 3.5 is lower than the maximum limit value of 55 MPa as stated in the requirements list in Figure 3.3, the displacement on the model is very higher than the maximum limit value of 20 mm. Therefore, as a result, if the part will be carried by one person, it was decided that the ribless model of the DCPD material alternative is not proper and does not satisfy the requirements.

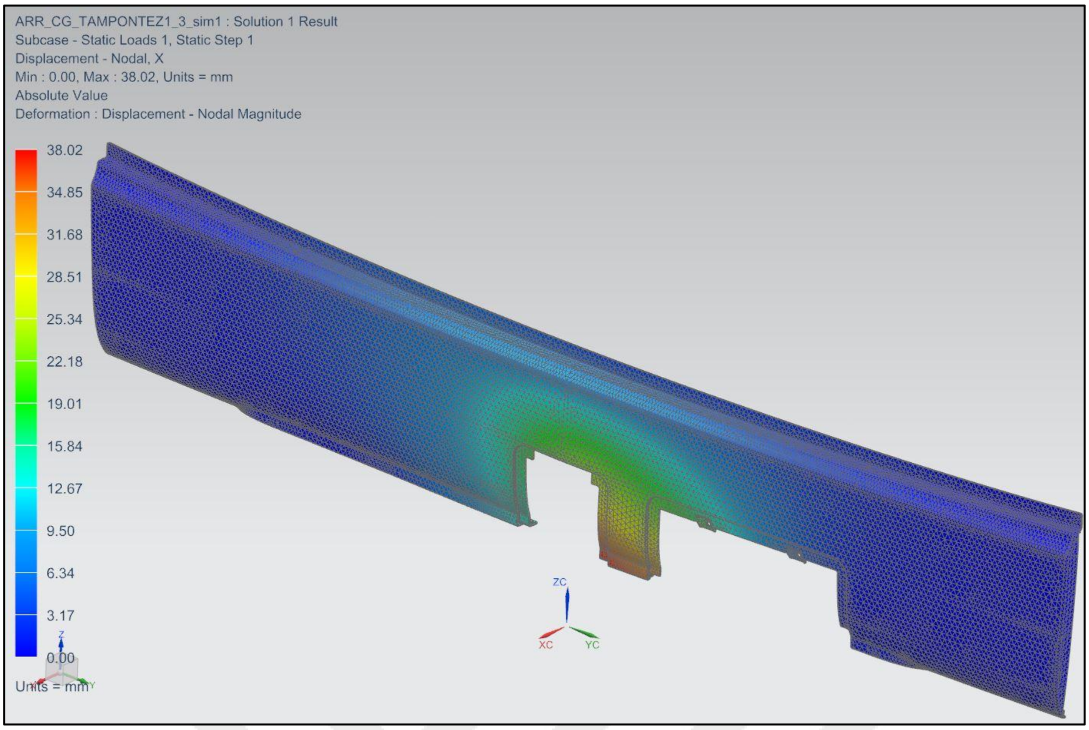
Likewise, when Figure 3.6 is analyzed, it is seen that the maximum displacement occured on the ribless model of the SMC material alternative is 393.05 mm and the maximum stress is 14.33 MPa in case of carriage by one person. As the maximum limit value of the diplacement for SMC material is 15 mm as stated in the requirements list in Figure 3.3, the ribless model of the SMC material alternative also does not meet the requirements for Condition A.

The results of the analyses done for the ribless model of both alternatives under the conditions of carriage by one person are summarized in Table 3.3.

Table 3.3 : Structural analysis results of the ribless rear middle bumper model for DCPD and SMC material alternatives in case of carriage by one person.

	Analysis Result		Allowed Max. Values	
Material Alternatives	Max. Displacement (mm)	Max. Stress (MPa)	Displacement (mm)	Stress (MPa)
DCPD	655.09	14.33	20	55
UP GF30 SMC	393.05	14.33	15	55

Due to the unsatisfying results of being carried by one person, in other words the simulation of Condition A, the same analysis were repeated for the case of carriage by two persons. The analysis results for the ribless model simulating Condition B for the DCPD alternative can be seen in Figure 3.7 and for the SMC material alternative can be seen in Figure 3.8.



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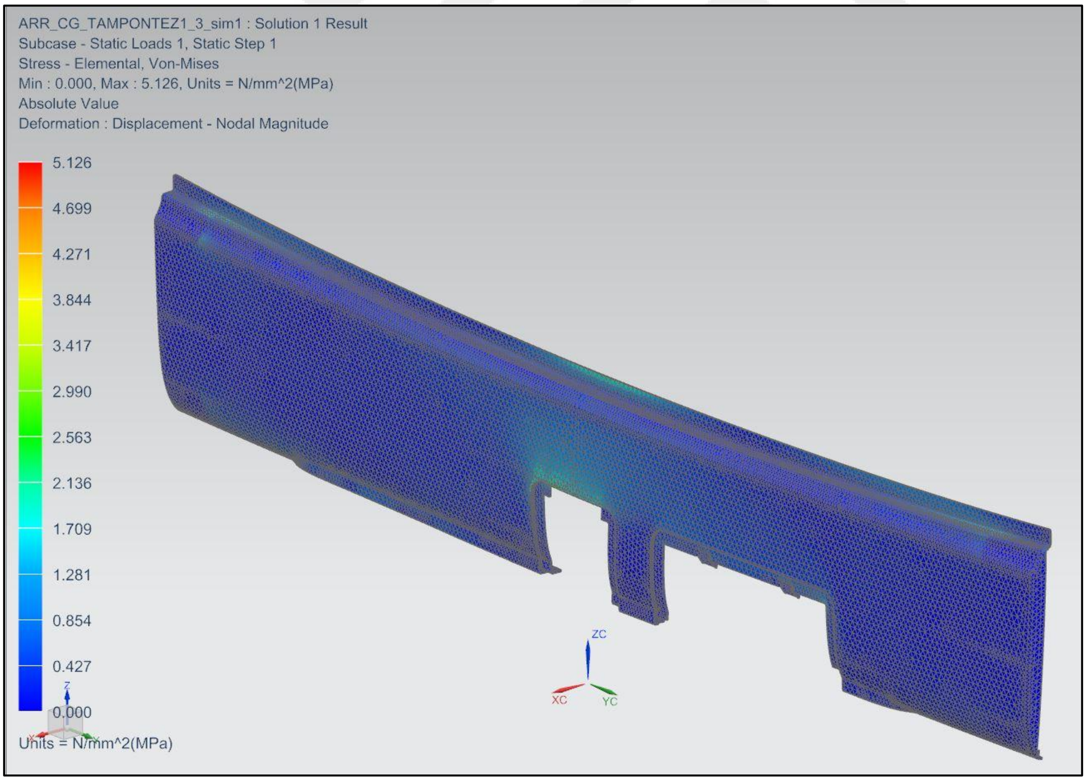
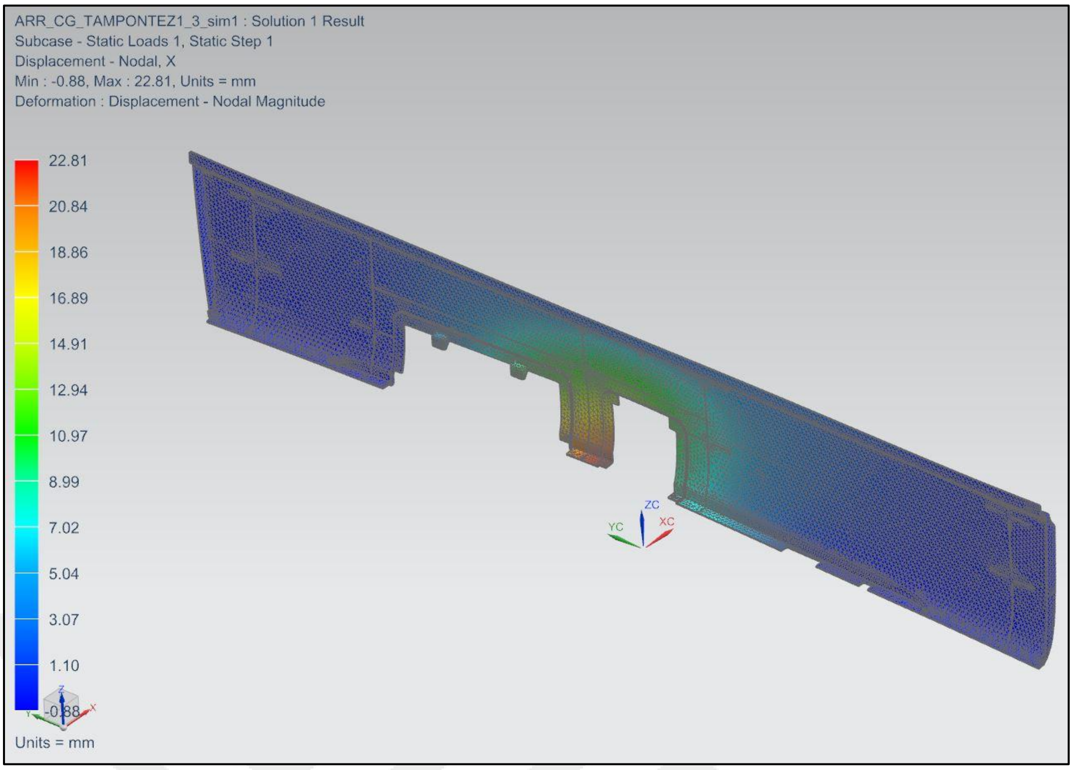


(b)

Figure 3.7 : Structural analysis of the ribless model for DCPD material alternative in case of carriage by two persons: (a) Displacement. (b) Stress.



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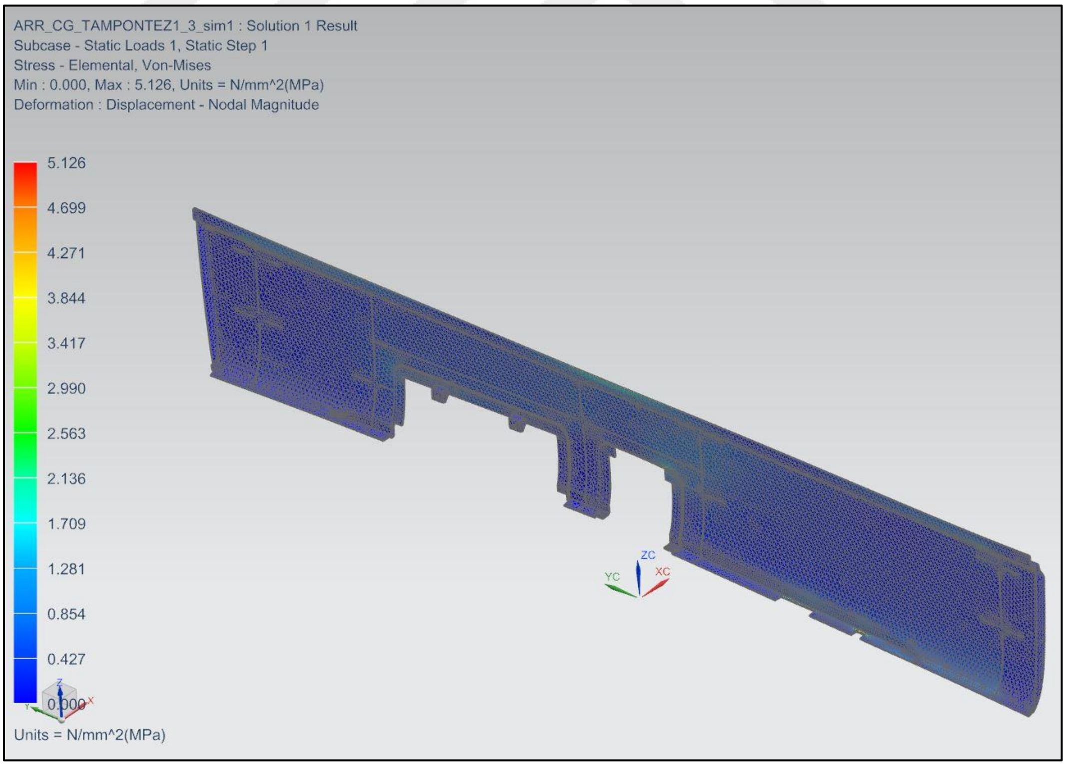


(b)

Figure 3.8 : Structural analysis of the ribless model for SMC material alternative in case of carriage by two persons: (a) Displacement. (b) Stress.

As seen in Figure 3.7 and Figure 3.8, eventhough the displacement values for the condition of carriage by two persons are lower than the results of carriage by one person, the maximum displacement values for the DCPD and SMC material alternatives are still higher than their maximum limit values. The results of the analyses done for the ribless model of both alternatives under the conditions of carriage by two persons are summarized in Table 3.4.

Table 3.4 : Structural analysis results of the ribless rear middle bumper model for DCPD and SMC material alternatives in case of carriage by two persons.

	Analysis Result		Allowed Max. Values	
Material Alternatives	Max. Displacement (mm)	Max. Stress (MPa)	Displacement (mm)	Stress (MPa)
DCPD	38.02	5.126	20	55
UP GF30 SMC	22.81	5.126	15	55

As the conditions of carriage by one and two persons for the ribless models of the two material alternatives do not satisfy the requirements, the ribless models were eliminated and it was decided to add ribs on the model in order to reinforce the structure.

As the rear middle bumper is a long part, the risk of bending occurs in vertical direction. In order to reinforce the structure against this risk, as explained in section "3.5.3 Modeling of the rear middle bumper", mainly horizontal and also vertical axial ribs were added on the 3D models near the emptied sections opened for the tow bar and plug cover assembly areas as shown in Figure 3.9. After the iterations were done on the model by adding ribs, firstly the analysis for the condition of carriage by one person, in other words Condition A, were repeated for both material alternatives. The results of these analyses can be seen in Figure 3.10 and Figure 3.11.

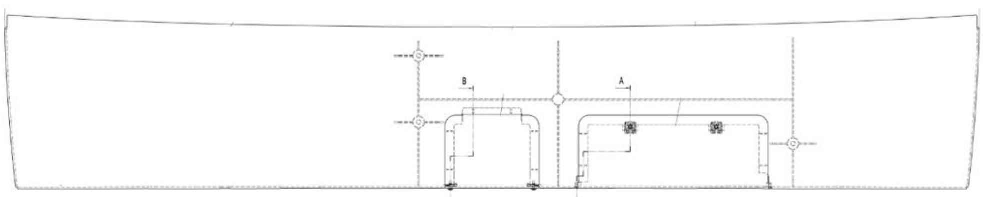
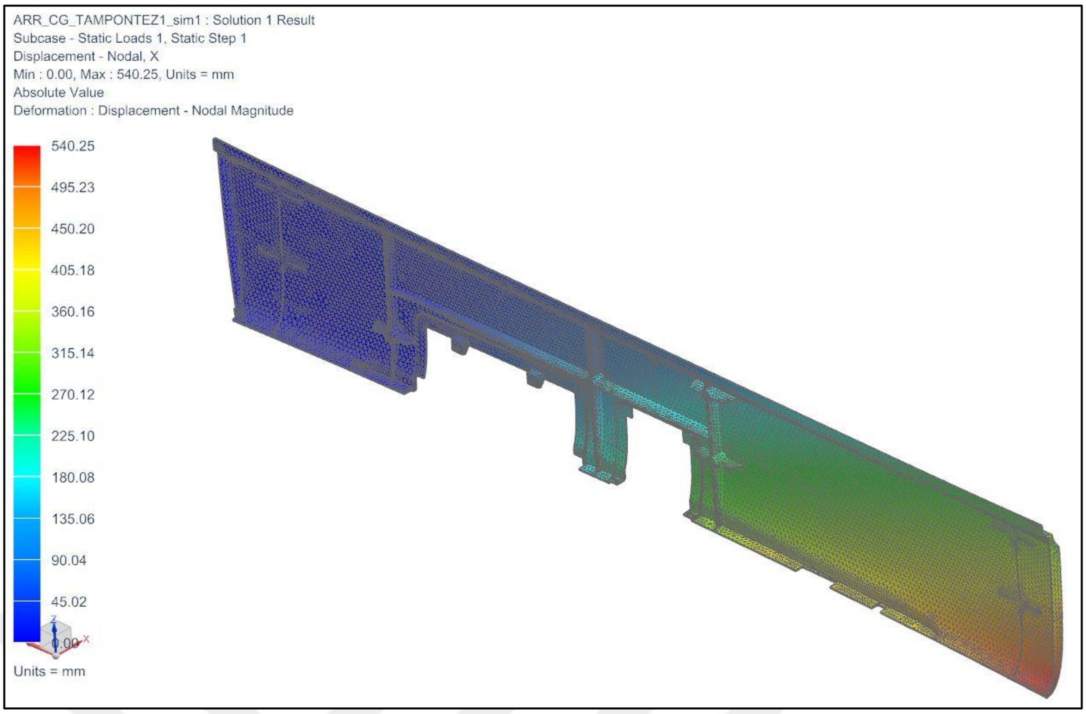


Figure 3.9 : Technical drawing showing the reinforcement ribs added on the rear middle bumper.



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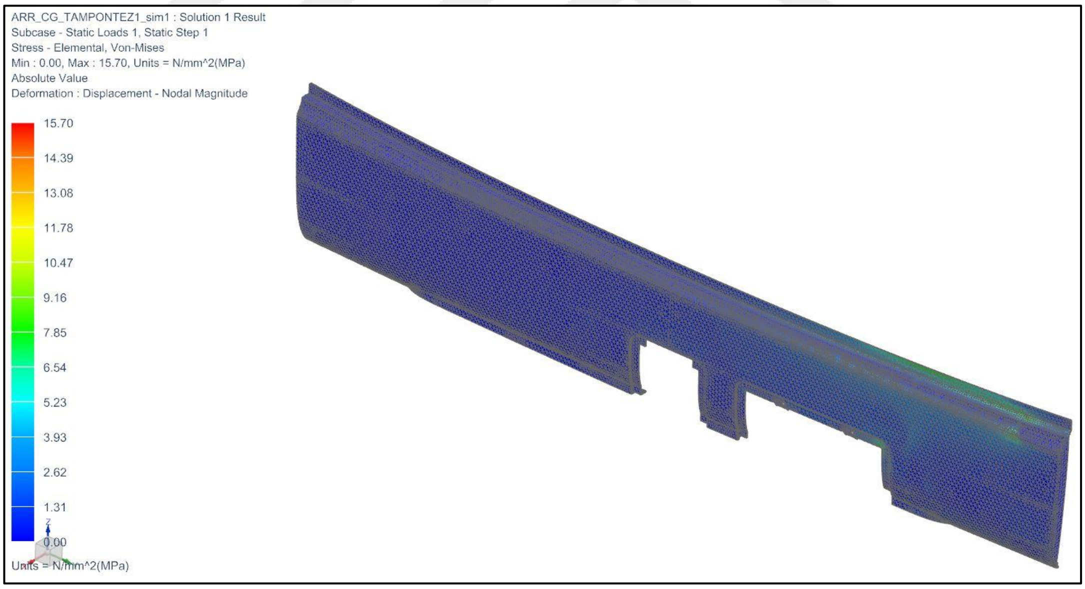
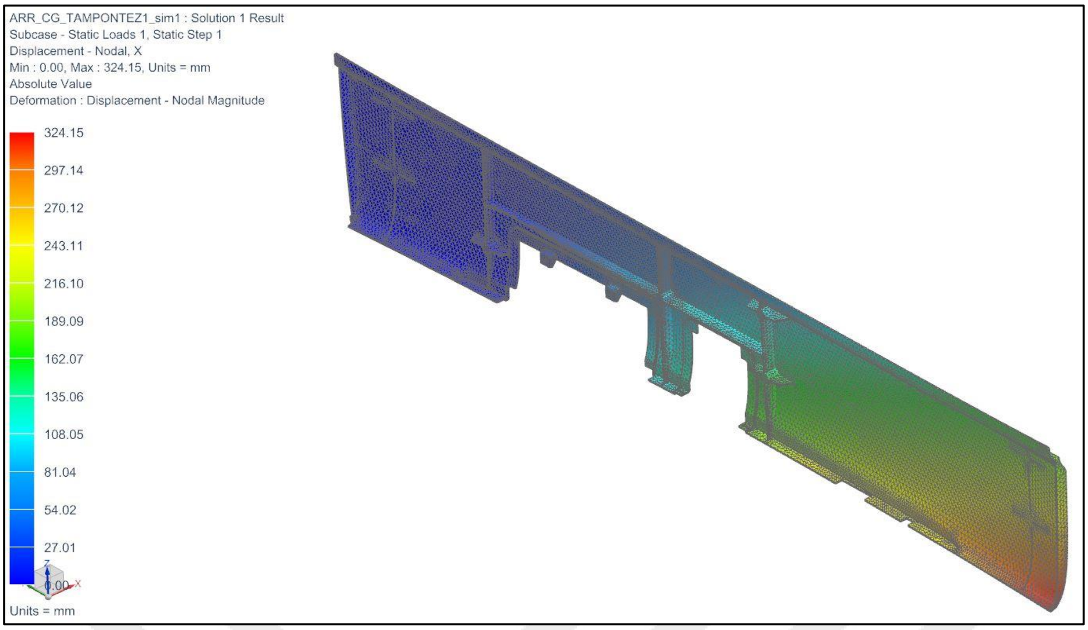


(b)

Figure 3.10 : Structural analysis of the model with ribs for DCPD material alternative in case of carriage by one person: (a) Displacement. (b) Stress.



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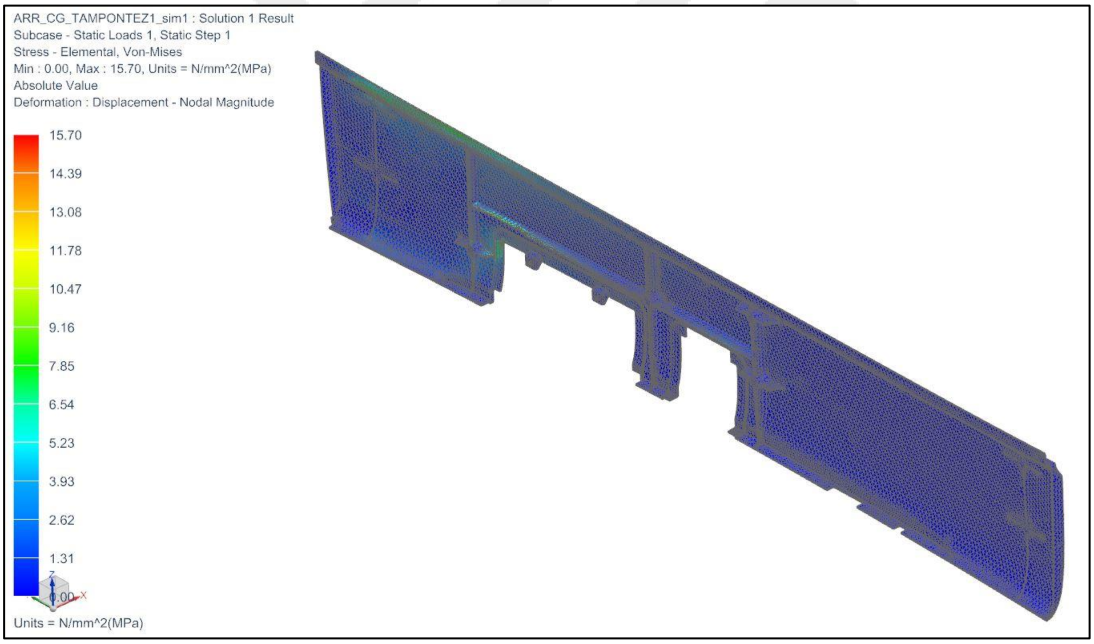


(b)

Figure 3.11 : Structural analysis of the model with ribs for SMC material alternative in case of carriage by one person: (a) Displacement. (b) Stress.

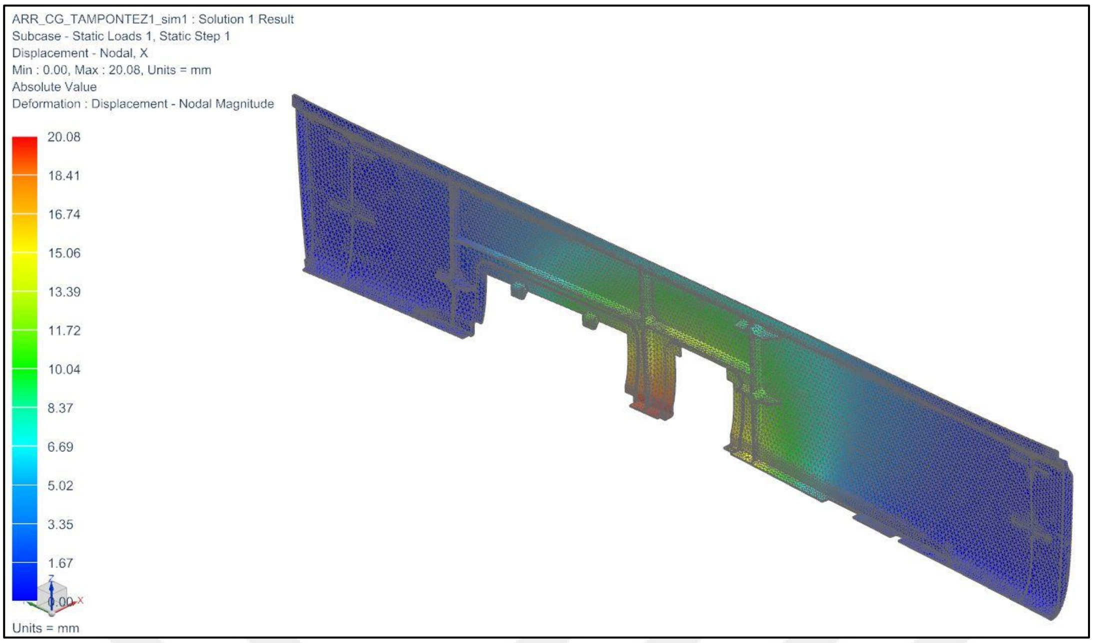
According to the results seen in Figure 3.10 and Figure 3.11, the maximum displacement of the DCPD model with ribs under the condition of carriage by one person is 540.25 mm and the stress occured is 15.70 MPa. Additionally, the maximum displacement occured on the SMC model with ribs is 324.15 mm and the stress calculated is 15.70 MPa. As the displacement results for both material alternatives of the reinforced rear middle bumper models are higher than the demanded maximum limit values stated in the requirements list in Figure 3.3, it was concluded that the reinforced models for both alternatives do not satisfy the requirements under the condition of carriage by one person.

The results of the analyses done for the reinforced models in case of carriage by one person are summarized in Table 3.5.

Table 3.5 : Structural analysis results of the rear middle bumper model with ribs for DCPD and SMC material alternatives in case of carriage by one person.

	Analysis Result		Allowed Max. Values	
Material Alternatives	Max. Displacement (mm)	Max. Stress (MPa)	Displacement (mm)	Stress (MPa)
DCPD	540.25	15.70	20	55
UP GF30 SMC	324.15	15.70	15	55

Due to these unsatisfying results, the same analysis were repeated for the case of carriage by two persons. The analysis results for the reinforced DCPD bumper model simulating the case of carriage by two persons, in other words Condition B, can be seen in Figure 3.12 and for the SMC material alternative, the results can be seen in Figure 3.13.



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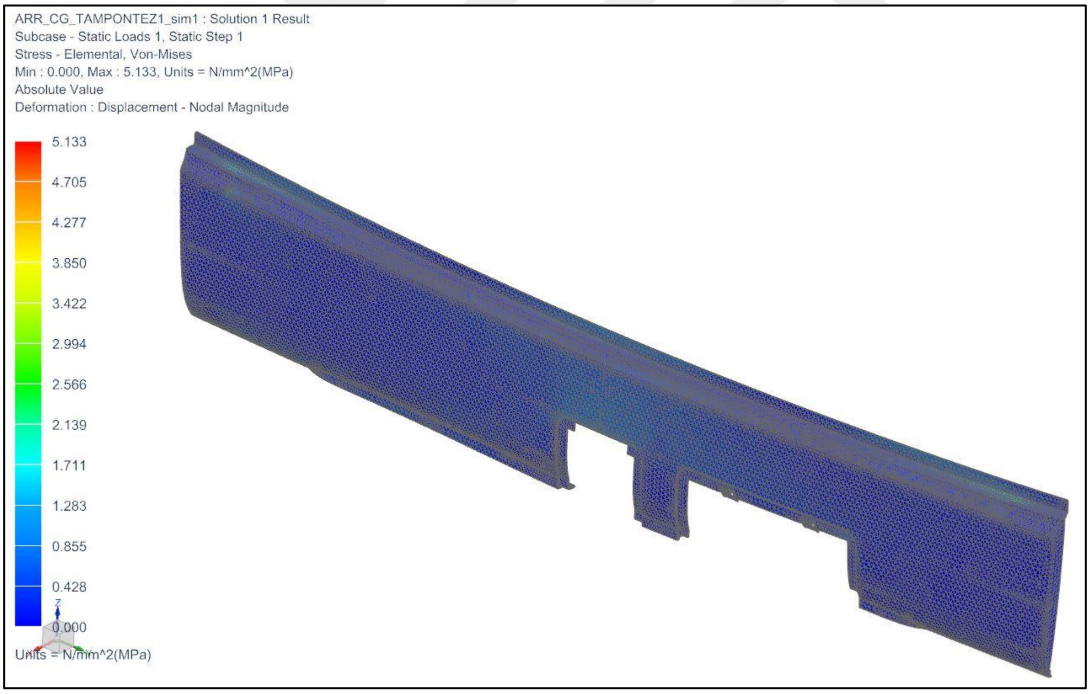
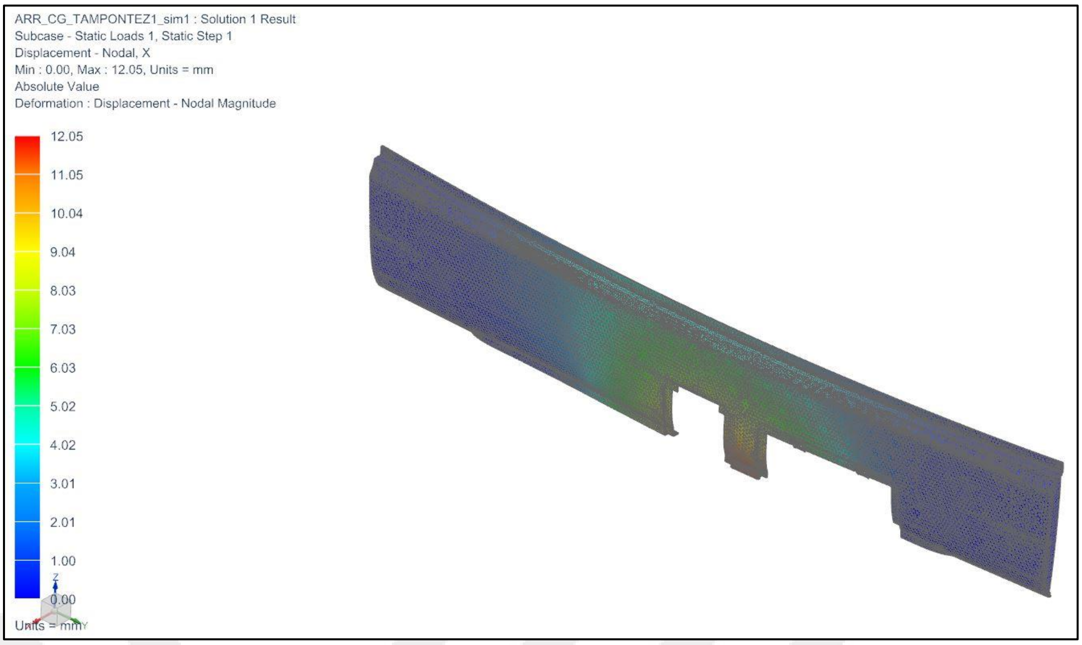


(b)

Figure 3.12 : Structural analysis of the model with ribs for DCPD material alternative in case of carriage by two persons: (a) Displacement. (b) Stress.



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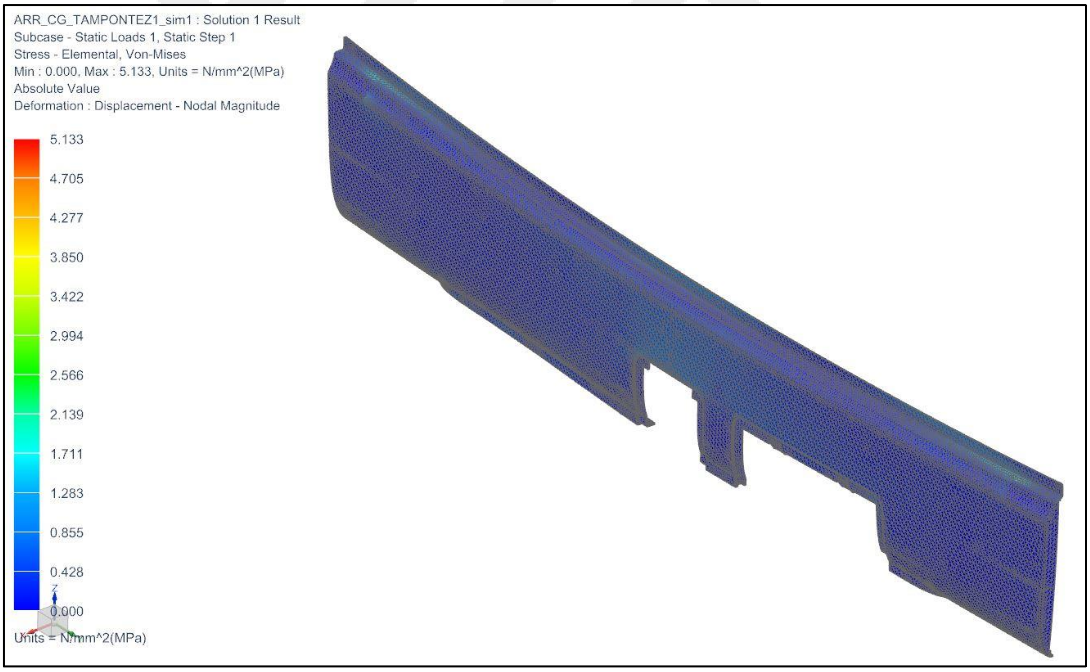

(b)

Figure 3.13 : Structural analysis of the model with ribs for SMC material alternative in case of carriage by two persons: (a) Displacement. (b) Stress.

Taking the results in Figure 3.12 into consideration, it can be seen that the maximum displacement value in case that the DCPD model with ribs is carried by two people is 20.08 mm and the maximum stress is 5.133 MPa. Likewise the previous analysis done for the DCPD model, even the stress in under the maximum limit value of 55 MPa, the displacement value is still relatively risky as it is almost at the maximum limit value of 20 mm.

On the other hand, when Figure 3.13 that shows the results of the SMC model with ribs in case of carriage by two persons is analyzed, it is seen that both the maximum displacement with the value of 12.05 mm and the maximum stress with the value of 5.133 MPa are under the maximum limit values defined for the SMC material alternative as seen in Table 3.6.

Table 3.6 : Structural analysis results of the rear middle bumper model with ribs for DCPD and SMC material alternatives in case of carriage by two persons.

	Analysis Result		Allowed Max. Values	
Material Alternatives	Max. Displacement (mm)	Max. Stress (MPa)	Displacement (mm)	Stress (MPa)
DCPD	20.08	5.133	20	55
UP GF30 SMC	12.05	5.133	15	55

Even the maximum displacement of the rib-added DCPD material alternative under the condition of carriage by two persons is only very few above its maximum allowed value as seen in Table 3.6, the rib-added model of the UP GF30 SMC material alternative as addressed in Table 3.6 was proposed as the design solution for the rear middle bumper of the raised floor bus due to the reasons summarized below:

- The maximum displacement and stress occured on the SMC model for the condition of carriage by two persons during the transport and production processes are below the allowed maximum limit values stated in Table 3.6.
- The DCPD technology is a new application used in the automotive industry. Therefore, unforeseen risks can occur during the production processes of large automotive parts by using the DCPD material. On the other hand, when compared with DCPD technology, SMC is a more widespread and reliable technology due to the wide know-how of the carmakers and their suppliers.

4. CONCLUSIONS AND RECOMMENDATIONS

An automotive bumper system, that is integrated to the front or rear end of a motor vehicle, is not only a structure that adds aesthetics to the automobile body. A bumper system also takes an important role on minimizing the injury of the pedestrians and passengers in case of a collision, protecting the components behind it and performing the car body aerodynamic requirements.

While the primary task of a bumper system in a passenger car is to minimize the injury of the passengers and pedestrians in case of a crash, as the collision height of buses is relatively in a lower level than the height of the driver and passenger compartments, the risk of injury in case a collision is very low. Thus the priority of a bus bumper system differs from a passenger car.

Due to the vital importance of the bumper systems in passenger cars, certain standards and regulations had been defined for the passenger car bumper systems in different regions of the world and revised parellel with the development of bumper systems within time. When taking a look from the point of view of the bus manufacturers, as there are no certain standards and regulations defined worldwide for the bus bumper systems, each bus manufacturer takes its own norms and priorities into consideration as criterias during the design phase of their bus bumpers.

As the rear middle bumper that is investigated in this study is a long part, it has a high risk of getting deformed during the production, transport, carriage, painting and assembly processes. Due to this high risk, one of the most important criterias that are considered during this thesis study is investigating the sufficient and financially advantageous production method, material and design solution that can perform the requested strength under defined conditions.

Today, many computer aided software programs that use Finite Elements Methods have been developed in order to make use of during the design, modeling and structural analysis phases of parts. Automobile manufacturers take the advantages of these computer aided design softwares during designing many of their parts, including the bumpers. Especially during the prototyping phase of bumpers, these software applications helps the designer to save time and money.

During the modeling and structural analysis phases of the rear middle bumper in this study, one of these widespread computer aided design softwares, named Siemens NX, was used. By the usage of the computer aided software, the 3D models of two material proposals were figured out and by using a systematic design approach, step-by-step iterations were performed on the models. Firstly, in order to minimize the complexity of part and cost, the models without adding any reinforcing ribs were investigated. Due to the insufficient results of the structural analysis applied on the ribless models, the models were reinforced with ribs at weak regions and the analyses were repeated. After the step-wise study, the rib-added model of the UP GF30 SMC material alternative finally could satisfy the requirements, which means being the design solution for the rear middle bumper.

As the competition among the automobile manufacturers is very high today, cost saving solutions are the main challenges of the actors in the automotive industry. Therefore, from today forth, bus manufacturers should start with working on cost effective design developments in order to succesfully survive in the future. In this scope, in order to reduce the complexity and correspondingly the complexity of the mould, to minimize the weight and as a result to reduce the unit cost of the rear middle bumper designed in this thesis study, alternative solutions that enables reduction of the reinforcing ribs should be investigated in the future.

Additionally, as day by day the air pollution becomes a threat for the public, solutions for protecting the environment is another important challenge for the automobile manufacturers today. In order to meet the expectations of the public, recyclable material alternatives should be investigated and these materials should substitute today’s materials in the future. Another point that automobile manufacturers should focus on in the scope of protecting the environment is of course finding new technologies or alternative solutions for reduction of fuel consumption. As a vehicle with less weight consumes less fuel, automobile manufacturers should start investigating alternative bumper materials that can lighten the total weight of the vehicles and as a result reduce the fuel consumptions.

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APPENDICES

APPENDIX A: Steps of requirements list
APPENDIX B: Checklist for requirements list

APPENDIX A

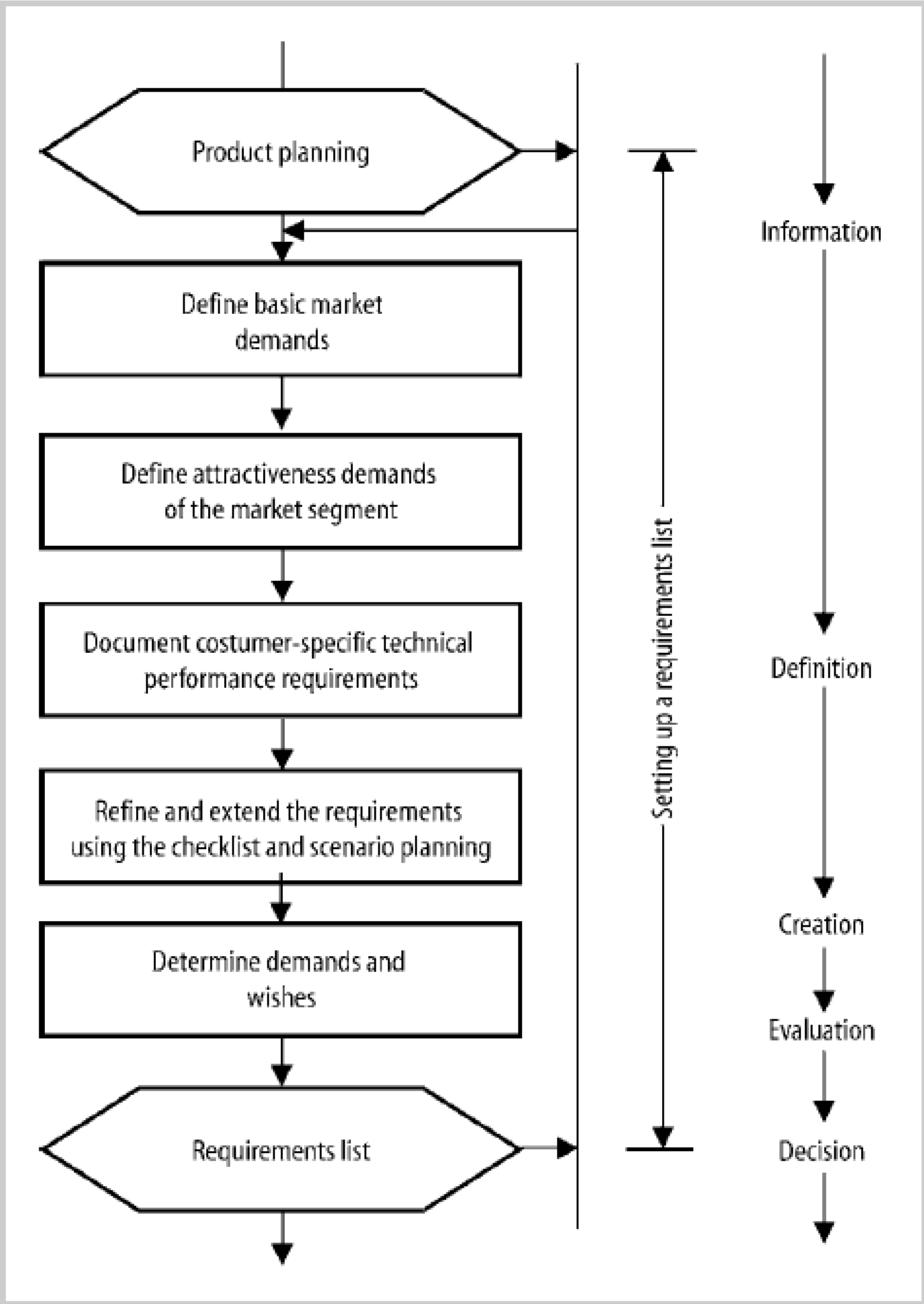


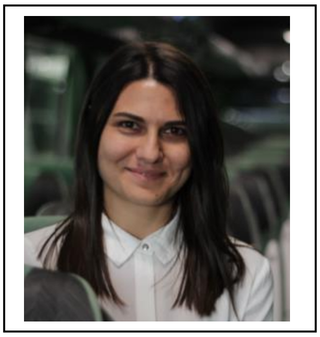
Figure A.1 : Main steps of preparing a requirements list [35].

APPENDIX B

Main headings	Examples
Geometry	Size, height, breadth, length, diameter, space requirement, number, arrangement, connection, extension
Kinematics	Type of motion, direction of motion, velocity, acceleration
Forces	Direction of force, magnitude of force, frequency, weight, load, deformation, stiffness, elasticity, inertia forces, resonance
Energy	Output, efficiency, loss, friction, ventilation, state, pressure, temperature, heating, cooling, supply, storage, capacity, conversion.
Material	Flow and transport of materials. Physical and chemical properties of the initial and final product, auxiliary materials, prescribed materials (food regulations etc)
Signals	Inputs and outputs, form, display, control equipment.
Safety	Direct safety systems, operational and environmental safety.
Ergonomics	Man-machine relationship, type of operation, operating height, clarity of layout, sitting comfort, lighting, shape compatibility.
Production	Factory limitations, maximum possible dimensions, preferred production methods, means of production, achievable quality and tolerances, wastage.
Quality control	Possibilities of testing and measuring, application of special regulations and standards.
Assembly	Special regulations, installation, siting, foundations.
Transport	Limitations due to lifting gear, clearance, means of transport (height and weight), nature and conditions of despatch.
Operation	Quietness, wear, special uses, marketing area, destination (for example, sulphurous atmosphere, tropical conditions).
Maintenance	Servicing intervals (if any), inspection, exchange and repair, painting, cleaning.
Recycling	Reuse, reprocessing, waste disposal, storage
Costs	Maximum permissible manufacturing costs, cost of tooling, investment and depreciation.
Schedules	End date of development, project planning and control, delivery date

Figure A.2 : Checklist for preparing a requirements list [35].

CURRICULUM VITAE



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