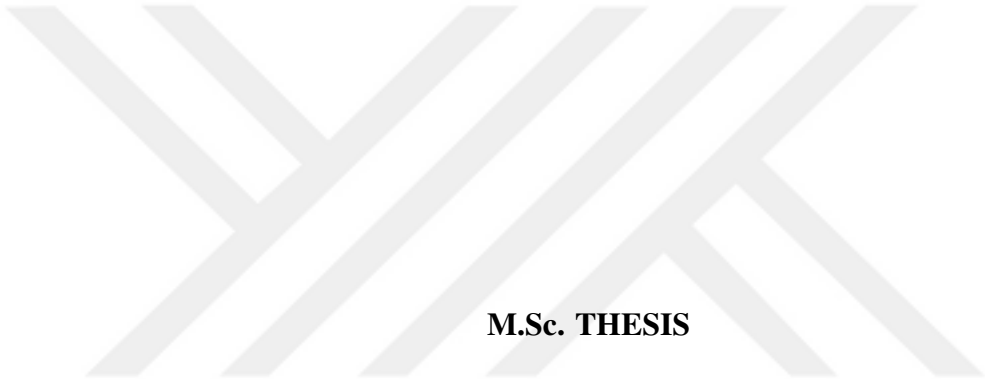


ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**OPTIMIZATION OF CFRP PREPREG COMPOSITE RIM
BY USING MOGAI GENETIC ALGORITHM**



M.Sc. THESIS

Berkay KUŞKIRA

Department of Mechanical Engineering

Solid Mechanics Programme

JUNE 2022

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

**KARBON FİBER TAKVİYELİ PLASTİK PREPREG KOMPOZİT JANTIN
MOGAIİ GENETİK ALGORİTMA KULLANILARAK OPTİMİZASYONU**

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HAZİRAN 2022

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To my spouse,



FOREWORD

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Berkay KUŞKIRA
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ABBREVIATIONS

CAD	: Computer Aided Design
CFRP	: Carbon Fiber Reinforced Plastic
DNA	: Deoxyribonucleic Acid
DOE	: Design of Experiments
ETRTO	: European Tyre and Rim Technical Organisation
FE	: Finite Element
FSAE	: Formula Society of Automotive Engineers
FT	: Failure Theory
GA	: Genetic Algorithm
ISO	: International Organization for Standardization
LGFT	: Long Glass Fiber Reinforced Thermoplastic
LHS	: Latin Hypercube Sampling
MCDM	: Multi Criteria Decision Making
MID	: Material Identification Number
MOGA	: Multi Objective Genetic Algorithm
MOGAII	: Multi Objective Genetic Algorithm II
NSM	: Nonstructural Mass
OFAT	: One Factor at Time
PID	: Property Identification Number
RBE2	: Rigid Body Element Form 2
RSM	: Response Surface Methodology
SAE	: Society of Automotive Engineers
SO	: Structural Optimization
UD	: Unidirectional



SYMBOLS

b	: Bead Seat Width
C_R	: Theoretical Rolling Circumference
d_{ovr}	: Overall Rim Diameter
d_r	: Nominal Rim Diameter
e	: Offset from Rim Center
E₁₁, E₂₂, G₁₂	: Elastic and Shear Modulus Components
ε₁₁,	: Strain Component in Fiber Direction
ε₂₂, γ₁₂	: Strain Components
F	: Torsion Loading Constant
F₁₁^{tu}, F₁₁^{cu}	: Tension and Compression Stress Limit 11 Component
F₂₂^{tu}, F₂₂^{cu}	: Tension and Compression Stress Limit 22 Component
F₁₂^{su}	: Shear Stress Limit
F₁₃^{su}	: Bonding Shear Stress Limit
F_r	: Total Radial Load
F_R	: Static Loaded Radius Constant
F_v	: Maximum Vertical Static Load
K	: Accelerated Test Factor
μ	: Friction Coefficient
M_C	: Cornering Moment
M_T	: Torsion Moment
m_v	: Maximum Mass per Tire
ν₁₂	: Poisson Ratio 12
p₁₂⁺, p₁₂⁻, p₂₂⁻	: Puck Failure Parameters
P_i	: Inflation Pressure
P_{max}	: Maximum Pressure at Center
P_θ	: Theta Dependent Pressure Load
ρ	: Density
r_b	: Bead Seat Radius
R_D	: Nominal Tire Radius
r_{dyn}	: Dynamic Tire Radius
R_S	: Theoretical Static Loaded Tire Radius
S₁₂	: Shear Strength in Plane Component
S₂₃, S₁₃	: Shear Strength Components
σ₁₁	: Stress Component in Fiber Direction
σ₂₂, σ₃₃	: Stress Components
τ₁₂	: Shear Stress in Plane Component
τ₁₃, τ₂₃	: Shear Stress Components
θ₀	: Half Angle of the Contact Patch
w_{ovr}	: Overall Rim Width
X_C, X_T	: Compression and Tensile Strengths in Fiber Direction
Y_C, Y_T	: Compression and Tensile Strengths in Transverse Direction
Z_C, Z_T	: Compression and Tensile Strengths in Thickness Direction



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OPTIMIZATION OF CFRP PREPREG COMPOSITE RIM BY USING MOGAI GENETIC ALGORITHM

SUMMARY

In the automotive industry, lightweight design is of great importance, as in other industries. Especially in performance vehicles, different material technologies have become widespread with the development of simulation and production techniques. Automotive rims are an example of these structures. Lighter rims can be obtained by using composite materials.

This thesis study was carried out in order to determine the most suitable lamina sequence and number that will ensure the strength of the automobile rim under various loads, which is aimed to be developed within the scope of Carre Wheel Design Company's composite wheel development project. In the study, a 19-inch diameter and 8.5-inch wide ten-spoke rim were used as a reference. A plain weave and resin-impregnated fabric prepreg material were used in the composite wheel.

The composite wheel was designed according to ETRTO standards using CATIA V5 software and the required reference surfaces for analysis were obtained. The rim is designed with a metallic plate and is inserted in the hub joint area.

The finite element model of the rim was modeled with Hypermesh software. Radial, cornering, and torsion loads are applied to the composite wheel model. For the analysis to be carried out using the MSC Nastran solver, the prepreg material card was used as MAT8 in the model, and the definition of composite laminate was made with PCOMP cards.

Rim optimization was performed with MOGAI (Multi Objective Genetic Algorithm II) provided by the ModeFrontier software. In the optimization study conducted with elitism, ply orientation and ply number were used as input variables. In the multi-objective optimization study, minimization of the maximum deformation and minimization of the total composite mass were performed. The maximum Tsai-Wu failure index value was defined for three different load cases as constraints. A total of 60 generations of evolutionary optimization were carried out with the initial population produced with the Sobol design of experience algorithm.

The Pareto front set was created from the designs obtained as a result of 60 generations. The created Pareto set was analyzed with linear multi-criteria decision making and genetic algorithm multi-criteria decision making methods. The analysis of the design with the highest grade was repeated and the results were shown.



KARBON FİBER TAKVİYELİ PLASTİK PREPREG KOMPOZİT JANTIN MOGAI GENETİK ALGORİTMA KULLANILARAK OPTİMİZASYONU

ÖZET

Otomotiv endüstrisinde bir çok farklı malzeme ve üretim tekniği, daha hızlı üretim daha ucuz maliyet politikası baz alınarak değerlendirilmektedir. Otomotiv sektöründe bir diğer bakış açısı ise yüksek performans odaklı ürün geliştirmektir. Bu bakış açısında araç üzerinde yapılacak herhangi bir ağırlık kazancı performans ve yakıt tüketimi açısından avantaj yaratacaktır. Araç üzerinde yapılabilecek en efektif ağırlık azaltımı yaylanmayan kütle üzerinden yapılan azaltımlardır. Yaylanmayan kütle sınıfına giren başlıca yapılar; lastik, aks, yataklar ve jant olarak sayılabilir.

Kompozit malzemeler gün geçtikçe yaygınlaşan kullanım alanlarına sahip olmaktadır. Özellikle modelleme tekniklerinin gelişimi, hesaplama gücündeki artış, imalat ve test kabiliyetlerinin gelişmesi ile havacılık ve otomotiv gibi ağırlık hafifletmenin yüksek önemini bulduğu endüstrilerde sıklıkla kullanılan bir malzeme haline gelmiştir. Otomotiv endüstrisi içinde kompozit malzemelerin avantajlarından yararlanılabilecek en önemli parçalardan birisi janttır. Yaylanmayan kütle sınıfına girdiği için yapılacak hafifletme ile otomobil performansında ve yakıt tüketiminde iyileşme gözlemlenir.

Bu tez çalışması Kare Metal Form San. ve Tic. A.Ş. firmasının başlatmış olduğu kompozit jant geliştirme projesi kapsamında geliştirilmesi hedeflenen ve 750 kg yük altında çalışması beklenen otomobil jantının çeşitli yüklemeler altında dayanımını sağlayacak en uygun lamina diziliminin ve sayısının belirlenmesi amacıyla gerçekleştirilmiştir. Tez çalışmasında 19 inç çapa ve 8,5 inç genişliğe sahip 10 adet koldan oluşan bir jant referans olarak kullanıştır. Elle serim yöntemiyle üretilmesi hedeflenen kompozit jantta düz örgülü ve reçine emdirilmiş kumaş prepreg malzeme kullanılmıştır.

Referans jant yüzeylerine elde etmek amaçlı CATIA V5 yazılımı kullanılmış ve 10 adet koldan oluşan jant geometrisi ETRTO (European Tyre and Rim Technical Organisation) standartlarına göre tasarlanmıştır. Yapılan birçok endüstriyel denemede metalik yapılar ile hibrit tasarımlar olduğu gözlemlenmiştir. Özellikle göbek bölgesinde bijon ve araç bağlantı arayüzde metalik yapıların kullanılması kompozit yapının dezavantajlarını yok etmeye yönelik bir girişimdir. Kompozit jantın araç ile arayüzüne ve bijon yuvalarına metalik yapılar eklenerek boyutlandırma çalışmasında etkileri hesaba katılması planlanmıştır. Jantın değişmeyecek olan yüzeyleri kalıp ve referans yüzey olarak belirlenmiştir.

Jantın referans yüzeyleri kullanılarak sonlu elemanlar modeli, kabuk elemanlar vasıtasıyla Hypermesh yazılımı üzerinde modellenmiştir. Kabuk elemanlara MAT8 malzeme kartı ve PCOMP eleman özellik kartı tanımlanmıştır. ISO standartları ile belirlenmiş test durumları analiz modeline yükleme koşulu olarak eklenmiştir. Jant

üzerinde oluşacak viraj, radyal ve torsiyon yüklemeleri ile toplam üç adet yük koşulu için üç adet model hazırlanmıştır.

Malzeme serim yönleri jant üzerindeki göbek ve kasnak bölgeleri için farklılaştırılmıştır. Göbek bölgesinde viraj ve torsiyon yükünün karşılanacağı radyal yön rozetin x yönü olarak tanımlanmıştır. Kasnak tarafında ise kasnak silindirini takip edecek şekilde x yönü belirlenmiştir. Jantın belli bölgelerindeki karmaşık yapısından dolayı, temel iki rozet yönü takip edilecek şekilde, sonlu elemanlar modelinde birçok PCOMP parçaları oluşturulmuş, malzeme oryantasyon tanımlamaları ayrı ayrı yapılmıştır.

Jantın optimizasyonunu gerçekleştirebilmek adına girdi ve çıktı değişkenleri belirlenmiştir. Jant geometrik olarak 6 bölgeye ayrılmış ve bu bölgelerin farklı laminat yapılarına sahip olabileceği kabul edilmiştir. Ancak fiberlerin sürekliliğini sağlamak adına tüm yapının bir lamina ile kaplanabileceği varsayılmıştır. İki tabakadan oluşabilecek göbek ve kol kısımları için plaka başına 20 lamina, göbek ve kol kısmında gelen laminatların birleşimiyle oluşacak kasnak yapısının ise toplam 40 lamina olması maksimum malzeme durumudur.

Simetrik durumdan dolayı 10 adet laminanın oryantasyonlarının belirlenmesi jantın diğer bölgelerinde de aynı oryantasyona sahip laminanın kullanılmasına sebebiyet verecektir. İki adet temel rozetin x yönü arasında 90 derece fark vardı. Jant geometrisi incelendiğinde göbek ile kasnak arasında da 90 derecelik fark olduğu gözlemlenir. Kasnak ile kol bağlantılarındaki geçiş için özel rozet tanımlamaları yapılarak süreklilik sağlanmıştır. Böylelikle 10 adet lamina tasarımın ortaya çıkması için yeterli olmakta ve alabileceği farklı oryantasyon açıları bir oryantasyon girdi değişkeni ifade etmektedir. Her bir lamina 0, 45, 90 ve 135 derece oryantasyon değerlerinden birini alabilecek şekilde girdi değişkeni tanımlanmıştır.

Girdi parametresi olarak verilen 10 adet lamina oryantasyonu ile maksimum malzeme durumu düşünüldüğünde simetrik bir laminat 20 lamina içerecektir. Ancak kütle hafiflemesini sağlamak adına belirlenmiş 6 adet bölgede laminaların her birinin var olup olmadığı bilgisi tanımlanmalıdır. Bu nedenle PCOMP eleman özelliği kartında kürlenmiş lamine kalınlığı değerinin sıfıra çok yakın veya kalınlığı kadar olması şeklinde ifade edecek olan bir diğer girdi değişkeni tanımlanmıştır.

Çalışmada jantın maksimum malzeme koşulunda statik analizleri yapılmıştır. Analiz sonuçları MSC Nastran çözücüsü kullanılarak elde edilmiştir. Tsai-Wu hasar kriteri ve maksimum deplasman değerleri istenerek ve MSC Patran yazılımı kullanılarak üç yük koşulu için sonuçlar yansıtılmıştır.

Girdi değişkenlerin parametre haline getirilebilmesi adına MSC Patran yazılımının kodlanması hedeflenmiştir. Bu amaçla MSC Patran uyumlu betikler hazırlanmıştır. Betikler sayesinde farklı tasarımlardaki lamina dizilimi ve sayısı PCOMP kartının güncellenmesi ve tekrar tanımlanması gerçekleştirilmiş olmaktadır. Ayrıca analiz girdi dosyalarının oluşturulması, analiz sonrası hasar kriteri, deplasman ve kütle bilgisinin alınması için ayrı betikler yazılmıştır.

Jantın optimizasyon çalışmasını gerçekleştirmek amacıyla ModeFrontier yazılımı kullanılmıştır. ModeFrontier yazılımı üzerinde; girdi değişkenlerinin betiklerde tanım-

lanması, yazılımlar arasındaki iletişimin sağlanması ve optimizasyon çalışmasındaki analizlerin dosyalama sisteminin oluşturulması sağlanmıştır.

Jantın optimizasyon çalışmasını yapmak üzere elitizm içeren MOGAII (multi objective genetic algorithm II) algoritması kullanılmıştır. Üç farklı yük koşulu için Tsai-Wu hasar kriteri ve oluşan maksimum deplasmanları kullanılmıştır. Jantın rijitliğinin artırılması adına deformasyonun minimizasyonu, kütleminin azaltılması hedefi ile de kütle minimizasyonu amaçları tanımlanmıştır. Aynı zamanda viraj, radyal ve torsiyon yüklemeleri altında Tsai-Wu hasar kriterinin 1'in altında olması durumu sınır koşulu olarak tanımlanmıştır.

İlk popülasyonun üretilmesi adına Sobol algoritması kullanılmış ve tasarım uzayında 100 adet nokta oluşturulmuştur. İlk popülasyon dahil 60 jenerasyon maksimum jenerasyon olarak tanımlanmıştır. Her jenerasyonda klasik çaprazlama, yönlü çaprazlama, mutasyon ve seçim ile bireyler oluşturulmuştur. Her jenerasyonda 100'er adet olmak üzere toplam 6000 adet tasarım sonucu elde edilmiştir.

Çok amaçlı optimizasyon çalışmasının sonucunda deformasyon ve kütle ilişkisi kapsamında Pareto tasarımları elde edilmiştir. Elde edilen tasarımlar lineer çok kriterli karar verme ve genetik algoritma ile çok kriterli karar verme metotları ile değerlendirilmiş ve derecelendirmede en yüksek puan alan tasarımın analizleri tekrar edilip sonuçları yansıtılmıştır.



1. INTRODUCTION

In the automotive industry, weight is a very important factor affecting vehicle performance. Especially for high-performance vehicles, even the smallest possible reduction in weight should not be neglected. In addition to advances in material technology; production and test capabilities, virtual analysis methodologies and non-destructive testing methods have led to enabling weight reduction for critical parts by using different material types in automobiles.

The masses that affect the vehicle's performance can be divided into basically two groups. These groups are called sprung and unsprung masses. The suspension systems of vehicles can be regarded as the separating part of the vehicle's sprung and unsprung masses. Sprung mass is the parts of the vehicle that are carried by the suspension. Vehicle's frame, body, passengers, and equipment can be given as an example of this mass group. All other types of equipment and parts between the suspension and the road are called unsprung masses. Tires, wheel hubs, axles, and bearings are included in the unsprung mass category.

Reducing unsprung masses provides further improvements in vehicle performance and fuel consumption. One of the main components in unsprung masses is the rim. It is possible to reduce the rim mass by using composite materials in rim technology. However, composite materials do not have isotropic behavior like metallic materials. By providing strength in certain directions, it is possible to obtain optimum lightweight designs. It is obvious that it will cause difficulties in composite production, especially with its complex structure. For this reason, it will be more advantageous to use ready-made fabric composites on the rim. The prepreg orientations and number of prepregs to be used in a composite rim should be investigated for the lightest rim design.

1.1 Literature Review

A literature review has been carried out and many studies have been found on composite wheel design and optimization. Some of these studies include designs made especially for SAE (Society of Automotive Engineers) racing vehicles.

Peters, B. (2019) aimed to develop a composite wheel for an SAE Racing vehicle. Metal rims were modeled and examined under different loads for the CFRP (carbon fiber-reinforced plastic) rim to be developed. Static loading approaches have been made for dynamic forces. It is aimed to make future tests by producing a CRFP rim prototype [1].

Bhagwat, P.G. G. (2017) designed a 10" carbon fiber rim for Formula SAE in his study. The design was based on Tire and Rim Association guidelines and analyzed under 2G cornering loading and 3G bump loading. Simulations were applied for different configurations. A selection of configurations was made taking into account the safety factor, weight, and displacements. In the study, the design and analysis of the modular rim mold was also examined [2].

Walter, H. W. (2016) developed a laminated composite wheel for the FSAE (Formula Society of Automotive Engineers) race car using finite element programs and physical testing. The load conditions that will affect the existing metallic rim during the race were obtained, the load conditions were applied to different composite designs and the results were compared. For the same load conditions, a lighter composite rim was obtained compared to the metallic rim. A rim prototype was produced using a metallic connection interface and prepreg material on its body. Tests were conducted on the produced rim and compared with the finite element results. In addition, the temperature values seen during the operation were obtained [3].

Dhage, M. B., Shah, S., Barche, Y., Shiledar, N., & Gore, S. (2020) In the study, the rim designed with CAD (Computer Aided Design) software was analyzed with the finite element method. Analyses were performed under longitudinal, normal, and lateral loads. The Formula Student race car wheel is manufactured using the vacuum bagging technique [4].

Some of the studies include the idea of using metal and composite together. In the studies carried out, more durable products were created by combining the advantages of metal and composite materials as hybrids.

Hong, J. H., Yoo, S. H., & Chang, S. H. (2013) proposed a passenger car wheel design obtained by using carbon fiber composite and aluminum structures together. The prototype was produced and tested. The analysis of the adhesion surface and thickness required for the bonding of metal and composite areas were carried out using the finite element method. Various FE (Finite Element) analyzes have been conducted to evaluate the wheel performance [5].

Rohan, C. D. (2015) made a comparison by creating many hybrid configurations in various parts of the wheel using aluminum and composite materials in the study. Tire data was collected by performing tests on the tire in order to obtain the loads on the rim. Load scenarios were created by processing the tire load data. Simulations were made for wheel rim designs in different configurations [6].

Schweizer, N., Giessl, A., Schwarzhaupt, O., & Büter, A. (2012) developed a carbon fiber wheel with an integrated electric motor. Considering the structural strength, it is aimed to develop an optimum lightweight structure. Besides, the technical difficulties that may arise during the realization of the multifunctional design have been taken into consideration [7].

In the literature, there are also researches and comparisons of different types of materials on wheel performance and strength.

Chandrashekhar, E., & Rishi, J. P. (2015) investigated the deformation, equivalent stress, fatigue life and natural frequencies of automotive wheels with light alloy materials and composite materials. By designing the rim, analyzes were made on the finite element program. Static and fatigue analyzes were performed for magnesium, titanium, aluminum and carbon fiber materials by applying boundary and load conditions. Likewise, natural frequencies have been obtained for all materials. As a result of the study, it was suggested that carbon epoxy material is the most suitable for automotive rims compared to other materials [8].

There is also a lot of research on the optimization of composite wheels. Various optimization methods have been studied for different composite materials.

Xiaoyin, W. et al., (2016) aimed to design a composite rim by using long glass fiber reinforced thermoplastic (LGFT) material. A structure that will provide strength has been obtained by performing multi-objective topology optimizations in multi-design space and under multi-load scenarios. The effects of loading scenarios on topological results have been examined by changing their weights. The design obtained is detailed with the use of metal inserts. Analyses were carried out using the finite element method to simulate material anisotropy and strength performance. The analysis and optimization methods used in the study are suggested to be used for other structures aimed to be made of thermoplastic composites [9].

In the literature, there are also studies that apply evolutionary optimization methods on composite wheels. Many different evolutionary algorithms and methods have been tried in the studies.

Oliver König and Marc Wintermantel (2004) have achieved the optimization of the car rim with the Catia V5 software with evolutionary algorithms. While minimizing rotational inertia and mass in their studies, it is aimed at keeping the stress values within a certain margin. The work done has provided the shape of the wheel and hub part of the rim geometrically [10].

Giger, M and Ermanni, P (2005) developed a racing motorcycle rim using evolutionary optimization method in their study. Tsai-Wu failure indice and deformation constraints were used while minimizing the mass of the front and rear CRFP rims. Mechanical properties were simulated with the finite element analysis package ANSYS. In the study simulation program is integrated with DynOPS and performed the wheel optimization study [11].

Lei F., Qiu R., Bai Y., Yuan C. (2018) performed the evolutionary optimization of a racing car rim according to the effective laminate thickness and then performed the ply-based optimization. In their studies, the minimization of the wheel weight and the maximization of the stiffness were aimed. Static and impact situations were included in the analysis as loading [12].

Wang D, Xu W, Wang Y, Gao J. (2021) made a hybrid composite wheel optimization in their studies. First of all, bending radial and impact loads were applied to the rim they designed with a symmetrical layup. Layup thickness and angle parameters were defined as design variables and optimization was carried out with non dominated sorting genetic algorithm. The design was chosen with the entropy weighting method by obtaining Pareto optimal solutions [13].

1.2 Purpose of Thesis

The aim of the thesis is to make an optimization study of the composite wheel for use in high-performance vehicles. Required rim geometry information and technical details have been provided by Carre Wheel Company. As a result of the study, it is aimed to obtain a 19-inch diameter rim design that can carry a load of 750 kg per rim.

The MOGAI (Multi Objective Genetic Algorithm II) was used for sizing the rim. In particular, it aims to maximize the rigidity of the rim and minimize its mass. During the optimization study, it was also expected to provide strength against radial, cornering, and torsion loads.

1.3 Existing Carbon Fiber Rims

There are many examples of carbon fiber wheels produced and used around the world. These wheels are generally developed for high-performance vehicles. The leading companies in the production of carbon fiber wheels are companies such as Koenigsegg and Carbon Revolution. In addition to these companies, carbon fiber rim trials were carried out, especially in competitions such as Formula Student.

The first wheel designed and produced for competitions such as Formula SAE was made by the UTA Racing team in 1993. The hub part of this rim connects with the wheel part continuously and without cutout. The composite wheel and vehicle are shown in Figure 1.1. As you can see, although it has complex geometry, the design has become final with a hollow design. Another point that can be drawn attention is the central connection area. A design often used in racing cars was used. The larger diameter of the composite connection will allow the loads to be distributed over a larger area.



Figure 1.1 : 1993 UTA Racing's car with composite rims [2].

When different composite wheel designs of Formula SAE teams are examined, different spoke and hub designs can be observed. One of these designs is the hollow one-piece rim with three spokes developed by Graz University of Technology. The rim and the cross-section view of the rim produced by the trapped rubber molding technique are shown in Figure 1.2.



Figure 1.2 : Graz's composite rim: (a)Rim. (b)Section of rim [2].

Joanneum Racing, one of the Formula SAE teams, used non-hollow composite wheels. In this design, it has been observed that the spoke design consists of a U-shaped laminate structure. The structure is shown in the Figure 1.3.



Figure 1.3 : Joanneum Racing's composite rim [2].

Carbon Revolution and Koenigsegg are companies that develop rims for performance vehicles. These companies have many different composite rim designs. Carbon Revolution has developed a carbon fiber rim for the Ford Mustang GT350R. This rim has been produced by the resin infusion method and has passed all fatigue and destructive tests. The rim used in the vehicle is shown in Figure 1.4.

Koenigsegg has developed composite wheels for high-speed vehicles. This rim has a central locking system. The composite rim, which can be produced as a single piece, has a hollow spoke design. The rim is shown in Figure 1.5.

Another example of composite rims is the 20-inch diameter rim developed by Porsche for the 911 Turbo model. The rim is shown in Figure 1.6. There is a central locking system in the middle of the rim with 7 spokes. It is claimed that the wheels are 20% lighter and 20% more durable with the use of composites in the rim [14]. Such examples found today show that great progress has been made in the field of composite automobile rims, especially in performance vehicles. Carre Wheel Design Company wants to be among these companies with its composite rim project. With the sizing and optimization study to be done, the design phase of the project will be realized.



Figure 1.4 : Ford Mustang GT350R composite rim [2].



Figure 1.5 : Koenigsegg's composite rim [2].



Figure 1.6 : Porsche 911 Turbo composite rim [14].



2. COMPOSITE MATERIALS

Composite materials are materials that are formed by combining two or more materials at a macro level without dissolving them and have strength properties different from the properties of the combined materials.

Composite materials have two different components. The component called the reinforcement element is known as the component carrying the main load and is embedded in the matrix element. The matrix element, on the other hand, is the component that ensures uniform distribution of the incoming loads to the reinforcement element and that the structure stays together [15].

The use of composite materials has a long history. In ancient times, the Egyptians began to use plywood to prevent the wood from expanding and curling caused by the absorption of moisture. Recently, fiber-reinforced, resin-matrix composites have been widely used in the automotive and aerospace industries, where the weight criterion is very important due to their strength and stiffness relative to their weight [16].

2.1 Classification of Composite Materials

Composite materials can be classified according to material type, geometrical properties of reinforcement elements, and matrix elements. K Friedrich, AA Almajid (2013) classified composite materials as seen in the Figure 2.1.

2.1.1 Composite materials by reinforcement element

Composite materials are classified in three different ways according to the reinforcement element. These are fiber-reinforced, particle-reinforced, layered composites.

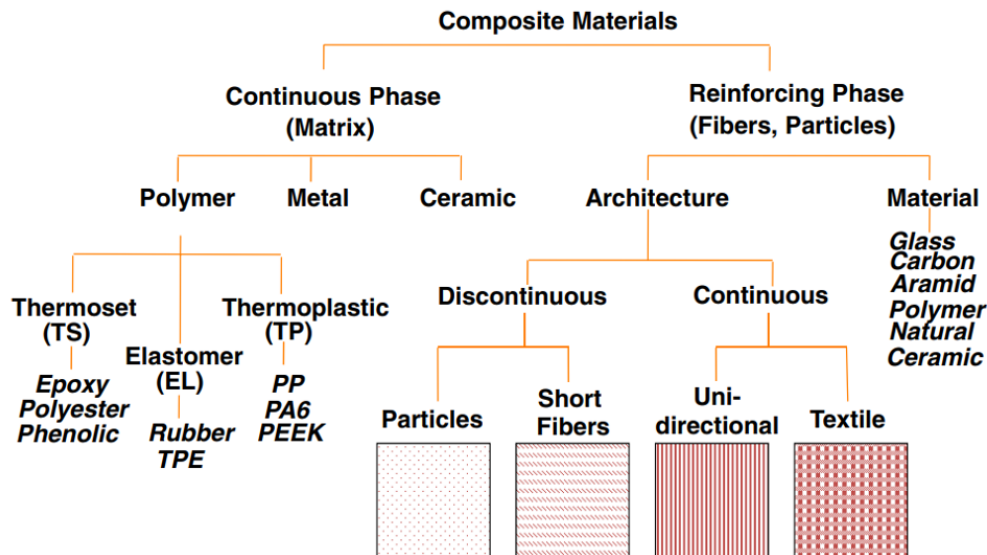


Figure 2.1 : Principle composition of composite materials [17].

2.1.1.1 Fiber reinforced composites

Fiber-reinforced composites are obtained when more rigid fibers are added into the relatively ductile matrix. When fiber is added, tensile strength, fatigue strength, specific modulus, and specific strength properties are improved [18].

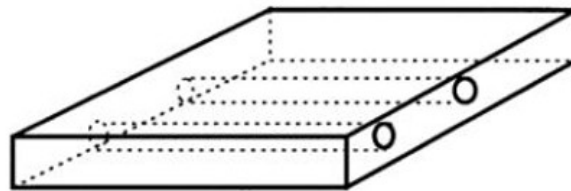


Figure 2.2 : Fiber reinforced composite [19].

Fibers can be placed in the matrix in a short or long way. Fibers can be incorporated into the matrix in various orientations. According to these orientations, the properties of fiber reinforced composite materials change. Fiber reinforced composites also show very low mechanical properties in other directions perpendicular to the fiber direction. Its mechanical properties change according to the density of presence in the matrix [20]. An example of a fiber-reinforced composite is given in the symbolic sketch Figure 2.2.

2.1.1.2 Particle reinforced composites

Particle-reinforced composites are structures in which one or more macroscopic or microscopic particles, which are considered zero-dimensional, are added into the matrix material.

The materials added into the matrix material are usually ceramics, metals, and polymers. The strength properties vary according to the properties and proportions of the materials used. An example of a fiber-reinforced composite is given in the symbolic sketch Figure 2.3.

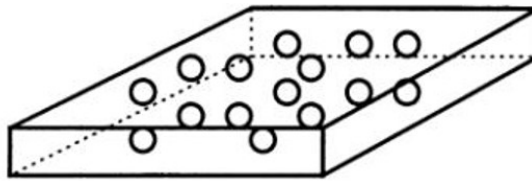


Figure 2.3 : Particle reinforced composite [19].

2.1.1.3 Layered composites

Layered composites are formed as a result of combining at least two layers. Layered composites can be formed in different material directions and numbers according to the needs. These layers can be polymer, metal, or glass.

It is the most common type of composite used in applications today. It is frequently used in the aviation and space industries. Various production methods exist to form layered composites. These layers are often combined into polymer-based matrices. A simple sketch of a layered composite is shown in Figure 2.4.

Composite materials can be classified as polymer, metal and ceramic matrix composite materials according to the type of matrix material.

2.1.1.4 Polymer matrix composites

The most common advanced composites are polymer matrix composites consisting of polymers (epoxy, polyester, urethane) reinforced with fine-diameter fibers (graphite, aramids, boron).

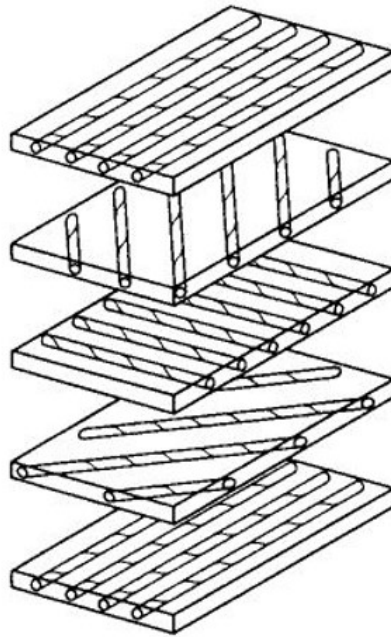


Figure 2.4 : Layered composites [16].

2.1.2 Composites by matrix material

Their low cost, high strength, and simple production can be cited among the reasons why they are the most common composites. Disadvantages of polymer matrix composites include low operating temperatures, high coefficients of thermal and moisture expansion, and low elastic properties in certain directions [15].

2.1.2.1 Metal matrix composites

Metal matrix composites, as the name suggests, have a metal matrix. Examples of materials for metal matrix composites are aluminum, magnesium, and titanium. Typical fibers include carbon and silicon carbide.

They are used as monolithic steel and aluminum for the advantage of metal matrix composites. Higher specific strength and modulus by reinforcing low-density metals such as aluminum and titanium. By being reinforced with fibers with low expansion coefficients such as graphite, it has lower thermal expansion and its properties are preserved at high temperatures.

Metal matrix composites have some advantages over polymer matrix composites. Their higher elastic properties can be shown as being more insensitive to moisture, higher electrical and thermal conductivity, better wear and fatigue resistance [15].

2.1.2.2 Ceramic matrix composites

Ceramic matrix composites can be composed of materials such as alumina calcium, aluminosilicate reinforced with fibers such as carbon or silicon carbide.

Advantages of ceramic matrix composites include high strength, stiffness, high service temperature limits for ceramics, chemical inertness, and low density. However, ceramics by themselves have low fracture toughness. Reinforcing ceramics with fibers such as silicon carbide or carbon increases fracture toughness as it causes gradual deterioration of the composite. This combination of a fiber and ceramic matrix makes ceramic matrix composites more usable for applications where high mechanical properties and extreme service temperatures are desired [15].

2.2 Prepreg Composite Materials

Prepreg materials are resin-impregnated composite materials reinforced with fibers. Prepreg materials have high value added and performance compared to other composite materials. Prepreg materials are a type of composite material used in large industries such as aviation and automotive. Prepreg materials can work at high temperatures, provide lightness and high strength. Comparison of prepreg materials with other composites according to performance and production volume is shown in Figure 2.5.

The materials used for reinforcement are the determining factor in the mechanical properties of the composite. Many materials such as carbon, glass, aramid, and polyethylene can be used for reinforcement. Among these materials, the highest strength is provided by carbon fibers. The tensile strength and tensile modulus of different fiber materials are given in Figure 2.6.

Prepreg materials have different names according to their fiber configurations. There are basically two types of prepreg materials, unidirectional (UD) and fabric. In

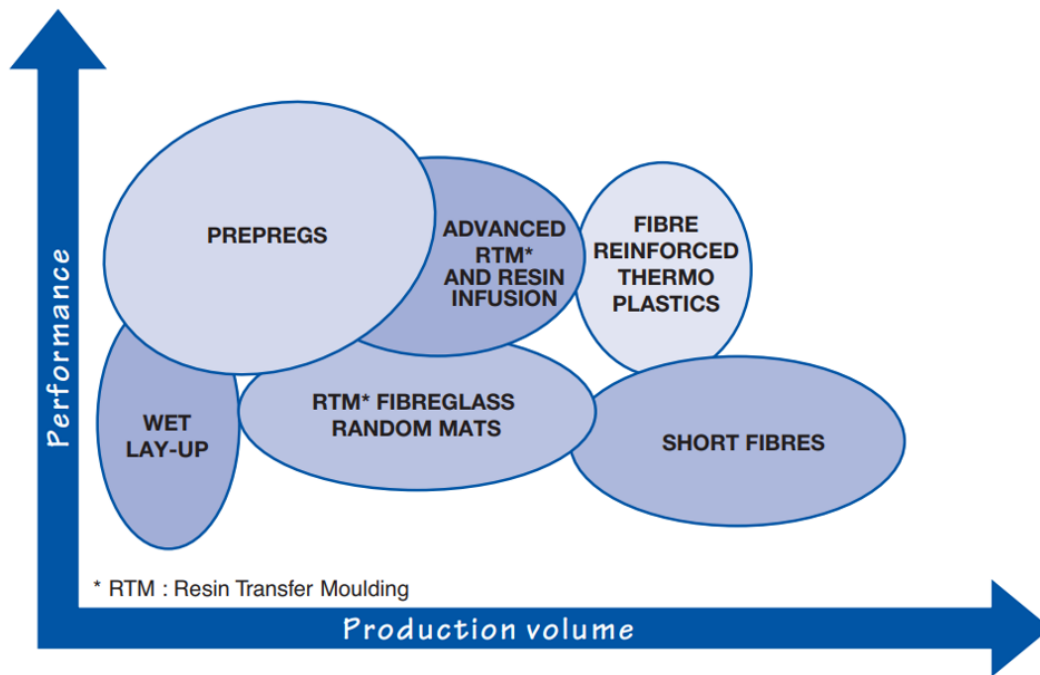


Figure 2.5 : Prepreg materials performance versus production volume [21].

unidirectional materials, the fibers are arranged in one direction. Fabric materials have fiber arrays in warp and weft directions. UD and fabric materials are shown in the Figure 2.7.

Fabric prepreg materials differ according to the fiber configurations in the warp and weft directions. These differences create various advantages or disadvantages in fabric prepreg material. Crimp and drapeability are the two main criteria. While low crimp provides better mechanical properties, the material with good drapeability is easy to lay up. Different types of fabric prepreg materials are shown in the Figure 2.8. Low drapeability and high crimp are seen in plain weave materials. Good drapeability and low crimp are observed in satin weave prepregs, while average drapeability and average crimp are observed in twill weave fabric material [21].

2.3 Failure Criteria for Composite Materials

Since the properties of composite materials vary according to direction, they are classified as anisotropic materials. Composite materials are anisotropic materials and are more specialized versions of them. A fiber-reinforced composite sheet is

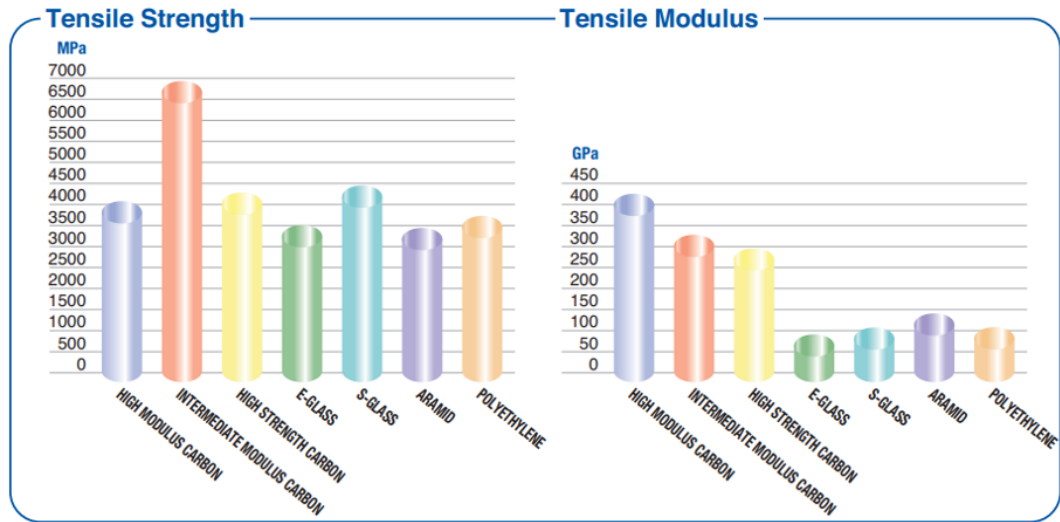


Figure 2.6 : Comparison of fiber materials [21].

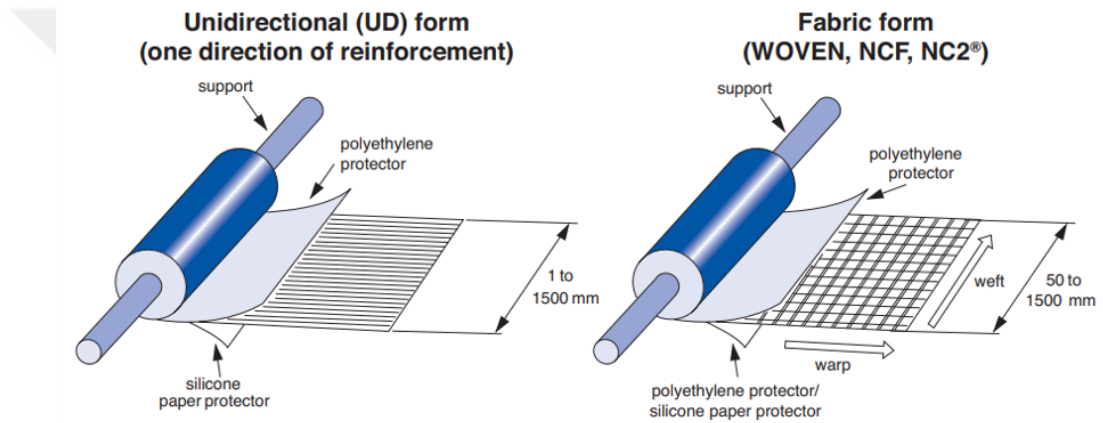


Figure 2.7 : UD and fabric prepregs [21].

symmetrical to all three planes at the macro level and can be considered as an orthotropic material at the macro level.

There are three material aspects in orthotropic materials. The axis number 1 from these material directions is the axis extending parallel to the fiber direction. The strength properties of the composite material in this direction are better than in other directions. Material direction number 2 is perpendicular to the fiber direction, that is, material direction number 1. The strength properties in material direction number 2 are quite low compared to material direction number 1. Material direction number 3 is in the direction of the thickness of the layer. Material directions are shown in Figure 2.9.

In composite materials, stress and strain strengths were defined according to fiber directions and failure criteria were determined. These strengths are tensile and

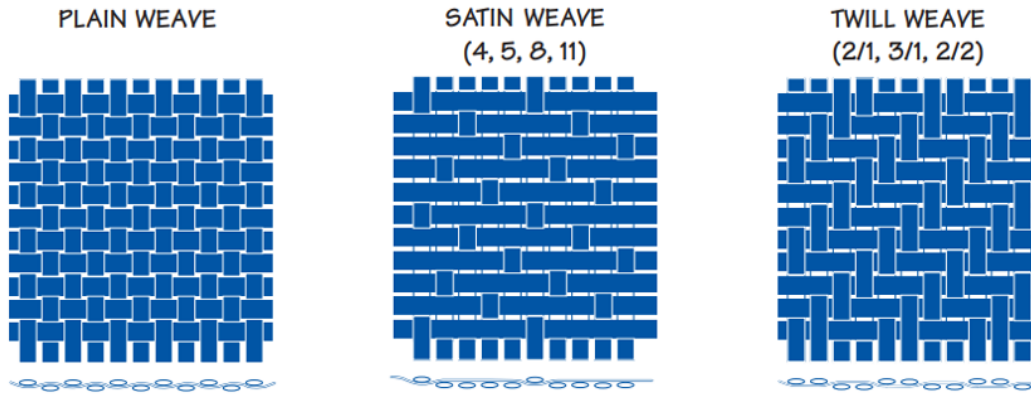


Figure 2.8 : Different weave styles of fabrics [21].

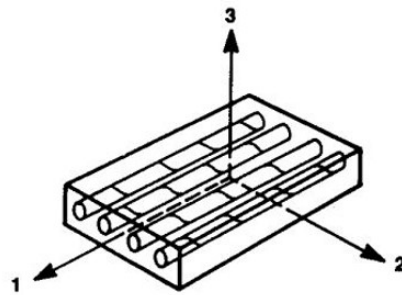


Figure 2.9 : Main material orientations of lamina [16].

compressive stress and strain in the fiber direction, tensile and compressive stress and strain perpendicular to the fiber direction, and shear stress and strain in the plane of the layer. Strain and stress components in composites are shown in Figure 2.10.

Failure criteria developed for composite materials are divided into three main groups. These are non-interactive failure criteria, interactive failure criteria, and failure criteria that relate to failure modes. Classification of failure criteria are shown in Figure 2.11.

2.3.1 Non-interactive failure criteria

Non-interactive failure criteria do not interact between tensile and compressive stress and strain components in different directions. The resulting stress or strain values in a certain direction are compared with the strength stress and strain values of the composite material. These failure criteria can lead to incorrect evaluations in cases of multi-axial stresses. Non-interactive failure criteria are maximum stress and maximum strain criteria.

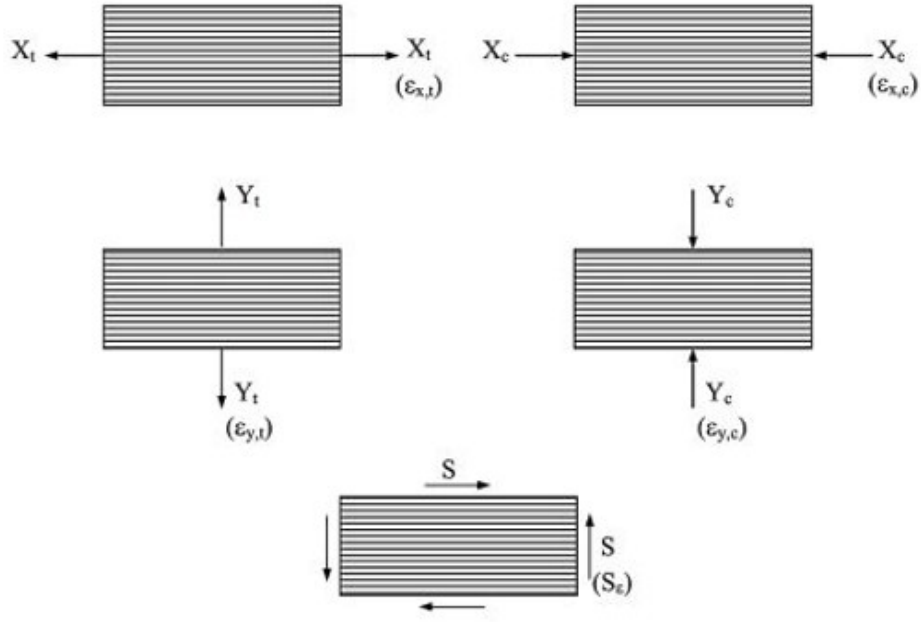


Figure 2.10 : Strain and stress components in composites [22].

2.3.1.1 Maximum stress failure criteria

This theory is similar to the application of Rankie's maximum stress and Tresca's maximum shear stress theories to isotropic materials. The stresses acting on a layer are converted into normal and shear stresses in the local axes. Failure occurs when any of the normal or shear stresses in the local axes of a layer equal or exceed the strengths of the unidirectional layer.

$$-X_C < \sigma_{11} < X_T \quad (2.1)$$

$$-Y_C < \sigma_{22} < Y_T \quad (2.2)$$

$$-S_{12}^C < \tau_{12} < S_{12}^T \quad (2.3)$$

The negative signs in the normal stresses in the equations 2.1, 2.2 and 2.3 indicate the compressive stress, and the positive stresses indicate the tensile stress. Each of the stress components is compared with its respective strength value. Therefore, each stress component does not interact with other components.

The maximum stress criterion is more useful in brittle failure situations. It gives results that are not very close to reality, especially in the case of multi-axial surface tension in experimental studies.

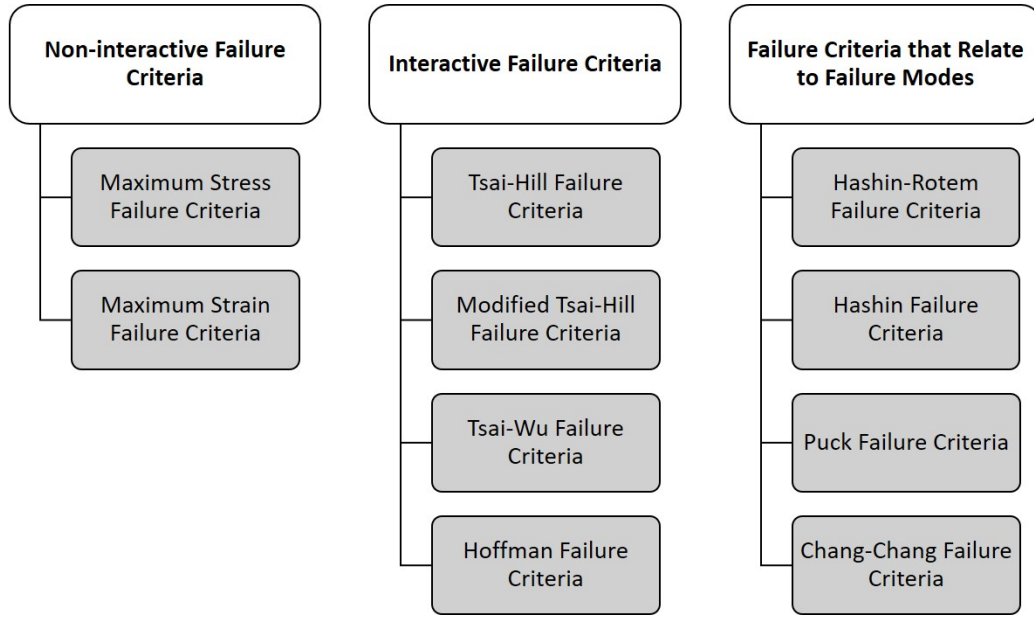


Figure 2.11 : Failure criteria in composite materials [20].

2.3.1.2 Maximum strain failure criteria

This theory is based on St. Venant's theory of maximum normal strain and Tresca's theory of maximum shear stress applied to isotropic materials. The strains applied to a layer are converted to strains in the local axes. Failure can be said to occur if any of the normal and shear strains in the local axes of a lamina are equal to or exceed the corresponding maximum strain of the unidirectional layer.

$$-\epsilon_{11}^C < \epsilon_{11} < \epsilon_{11}^T \quad (2.4)$$

$$-\epsilon_{22}^C < \epsilon_{22} < \epsilon_{22}^T \quad (2.5)$$

$$-\gamma_{12}^C < \gamma_{12} < \gamma_{12}^T \quad (2.6)$$

The maximum stress failure theory is similar to the maximum stress failure theory in that the components do not interact with each other. However, the two failure criteria give different results. Because local stretching of a lamina has an effect of passion ratio. If the position ratio is zero in the unidirectional layer, two different failure theories will give the same results.

2.3.2 Interactive failure criteria

In the interactive failure criteria, failure assessment is made by considering the stresses in different directions. It is accepted that failure to the structure occurs in cases where the failure criteria are exceeded.

2.3.2.1 Tsai-Hill failure criteria

The Tsai-Hill failure criterion [23] is the von-Mises distortion energy failure criterion applied to isotropic materials, adapted to anisotropic materials. If the distortion energy is higher than the failure distortion energy of the material, the material is considered to be failed.

Hill applied von-Mises' distortion energy criterion to anisotropic materials. Then Tsai adapted it to a one-way lamina. The material will fail if the following equation 2.7 is not satisfied.

$$\begin{aligned} & (F_2 + F_3) \sigma_{11}^2 + (F_1 + F_3) \sigma_{22}^2 + (F_1 + F_2) \sigma_{33}^2 - 2F_3 \sigma_{11} \sigma_{22} - 2F_2 \sigma_{11} \sigma_{33} \\ & - 2F_1 \sigma_{22} \sigma_{33} + 2F_4 \tau_{23}^2 + 2F_5 \tau_{13}^2 + 2F_6 \tau_{12}^2 < 1 \end{aligned} \quad (2.7)$$

Here, the equation constants F_1, F_2, F_3, F_4, F_5 , and F_6 are found as follows:

$$F_1 = \frac{1}{2} \left(-\frac{1}{X_T^2} + \frac{1}{Y_T^2} + \frac{1}{Z_T^2} \right) \quad (2.8)$$

$$F_2 = \frac{1}{2} \left(\frac{1}{X_T^2} - \frac{1}{Y_T^2} + \frac{1}{Z_T^2} \right) \quad (2.9)$$

$$F_3 = \frac{1}{2} \left(\frac{1}{X_T^2} + \frac{1}{Y_T^2} - \frac{1}{Z_T^2} \right) \quad (2.10)$$

$$F_4 = \frac{1}{2} \left(\frac{1}{S_{23}^2} \right) \quad (2.11)$$

$$F_5 = \frac{1}{2} \left(\frac{1}{S_{13}^2} \right) \quad (2.12)$$

$$F_6 = \frac{1}{2} \left(\frac{1}{S_{12}^2} \right) \quad (2.13)$$

2.3.2.2 Modified Tsai-Hill failure criteria

Tensile stresses are used in the Tsai-Hill failure criterion. Since the compressive strength of the fibers is generally higher than the tensile strength, the compression strength value is used in the equation when compressive stress is applied. The resulting new criterion is called the modified Tsai-Hill failure criteria.

$$\begin{aligned} & \left(\frac{\sigma_{11}}{X}\right)^2 + \left(\frac{\sigma_{22}}{Y}\right)^2 + \left(\frac{\sigma_{33}}{Z}\right)^2 - \sigma_{11}\sigma_{22}\left(\frac{1}{X^2} + \frac{1}{Y^2} - \frac{1}{Z^2}\right) \\ & - \sigma_{11}\sigma_{33}\left(\frac{1}{X^2} - \frac{1}{Y^2} + \frac{1}{Z^2}\right) - \sigma_{22}\sigma_{33}\left(-\frac{1}{X^2} + \frac{1}{Y^2} + \frac{1}{Z^2}\right) \\ & + \left(\frac{\tau_{12}}{S_{12}}\right)^2 + \left(\frac{\tau_{23}}{S_{23}}\right)^2 + \left(\frac{\tau_{13}}{S_{13}}\right)^2 < 1 \end{aligned} \quad (2.14)$$

$$X = \begin{cases} \sigma_{11} > 0 \Rightarrow X = X_T \\ \sigma_{11} < 0 \Rightarrow X = X_C \end{cases} \quad (2.15)$$

$$Y = \begin{cases} \sigma_{22} > 0 \Rightarrow Y = Y_T \\ \sigma_{22} < 0 \Rightarrow Y = Y_C \end{cases} \quad (2.16)$$

$$Z = \begin{cases} \sigma_{33} > 0 \Rightarrow Z = Z_T \\ \sigma_{33} < 0 \Rightarrow Z = Z_C \end{cases} \quad (2.17)$$

2.3.2.3 Tsai-Wu failure criteria

The Tsai-Wu failure theory is more general than the Tsai-Hill failure theory. Because it distinguishes the difference between the compressive and tensile strength of the lamina. Tsai and Wu applied for the first time the general second-order failure criterion developed by Gol'denblat and Kopnov [24] for anisotropic materials on composite plates subjected to plane stress [25].

$$\begin{aligned} & F_1\sigma_{11} + F_2\sigma_{22} + F_3\sigma_{33} + F_4\tau_{23} + F_5\tau_{31} + F_6\tau_{12} + F_{11}\sigma_{11}^2 + F_{22}\sigma_{22}^2 \\ & + F_{33}\sigma_{33}^2 + F_{44}\tau_{23}^2 + F_{55}\tau_{31}^2 + F_{66}\tau_{12}^2 \\ & + 2F_{12}\sigma_{11}\sigma_{22} + 2F_{13}\sigma_{11}\sigma_{33} + 2F_{23}\sigma_{22}\sigma_{33} \leq 1 \end{aligned} \quad (2.18)$$

$$F_1 = \frac{1}{X_T} - \frac{1}{X_C} \quad (2.19)$$

$$F_2 = \frac{1}{Y_T} - \frac{1}{Y_C} \quad (2.20)$$

$$F_3 = \frac{1}{Z_T} - \frac{1}{Z_C} \quad (2.21)$$

$$F_4 = F_5 = F_6 = 0 \quad (2.22)$$

$$F_{11} = \frac{1}{X_C X_T} \quad (2.23)$$

$$F_{22} = \frac{1}{Y_C Y_T} \quad (2.24)$$

$$F_{33} = \frac{1}{Z_C Z_T} \quad (2.25)$$

$$F_{44} = \frac{1}{S_{23}^2} \quad (2.26)$$

$$F_{55} = \frac{1}{S_{31}^2} \quad (2.27)$$

$$F_{66} = \frac{1}{S_{12}^2} \quad (2.28)$$

There is not enough experimental data about the parameters F_{12} , F_{13} and F_{23} . This is due to the difficulty in performing bi-axial tensile tests. Assuming that the failure strengths of the biaxial tensile tests are $\sigma_{11} = \sigma_{22} = \sigma_{b12}$, $\sigma_{11} = \sigma_{33} = \sigma_{b13}$ and $\sigma_{22} = \sigma_{33} = \sigma_{b23}$, the parameters F_{12} , F_{13} and F_{23} are found as follows:

$$F_{12} = \frac{1}{2\sigma_{b12}^2} [1 - \sigma_{b12}(F_1 + F_2) - \sigma_{b12}^2(F_{11} + F_{22})] \quad (2.29)$$

$$F_{13} = \frac{1}{2\sigma_{b13}^2} [1 - \sigma_{b13}(F_1 + F_3) - \sigma_{b13}^2(F_{11} + F_{33})] \quad (2.30)$$

$$F_{23} = \frac{1}{2\sigma_{b23}^2} [1 - \sigma_{b23}(F_2 + F_3) - \sigma_{b23}^2(F_{22} + F_{33})] \quad (2.31)$$

2.3.2.4 Hoffman failure criteria

In the Hoffman failure criterion [26], the linear term is added to the Tsai-Hill failure criterion equation to account for the different tensile and compressive strengths. According to this criterion, if equation 2.32 is not met, the material is considered to be failure.

$$\begin{aligned} & \frac{1}{2} \left(\frac{1}{X_T X_C} - \frac{1}{Y_T Y_C} - \frac{1}{Z_T Z_C} \right) (\sigma_{22} - \sigma_{33})^2 \\ & + \frac{1}{2} \left(-\frac{1}{X_T X_C} + \frac{1}{Y_T Y_C} - \frac{1}{Z_T Z_C} \right) (\sigma_{33} - \sigma_{11})^2 \\ & + \frac{1}{2} \left(-\frac{1}{X_T X_C} - \frac{1}{Y_T Y_C} + \frac{1}{Z_T Z_C} \right) (\sigma_{11} - \sigma_{22})^2 \\ & + \left(\frac{1}{X_T} + \frac{1}{X_C} \right) \sigma_{11} + \left(\frac{1}{Y_T} + \frac{1}{Y_C} \right) \sigma_{22} + \left(\frac{1}{Z_T} + \frac{1}{Z_C} \right) \sigma_{33} \\ & + \frac{\tau_{12}^2}{S_{12}^2} + \frac{\tau_{13}^2}{S_{13}^2} + \frac{\tau_{23}^2}{S_{23}^2} < 1 \end{aligned} \quad (2.32)$$

2.3.3 Failure criteria that relate to failure modes

There are various failure modes in the failure criteria that relate to the failure modes. These are fiber tension, fiber compression, matrix tension, matrix compression and delamination modes.

The delamination failure mode can be thought of as the separation of two layers. When this failure mode occurs in the structure, the structure loses its rigidity significantly and failure occurs. In the fiber tensile failure criterion, on the other hand, due to the very high tensile strength of the fibers, in case of failure, very high energy occurs and causes sudden breaks. In fiber compression failure, matrix shear failure or fiber failure is seen. Since matrix failure is usually perpendicular to the fiber direction, fiber splits are seen [20].

2.3.3.1 Hashin-Rotem failure criteria

Hashin-Rotem failure criterion [27] is one of the first failure criteria used in composite materials and was developed in 1973. This failure criterion calculates fiber tension, fiber compression, matrix tension and matrix compression failure modes separately.

Fiber in tension $\sigma_{11} < 0$:

$$\left(\frac{\sigma_{11}}{X_T} \right) < 1 \quad (2.33)$$

Fiber in compression $\sigma_{11} < 0$:

$$\left(\frac{\sigma_{11}}{X_C} \right) < 1 \quad (2.34)$$

Matrix in tension $\sigma_{22} + \sigma_{33} \geq 0$:

$$\left(\frac{\sigma_{22}}{Y_T} \right)^2 + \left(\frac{\tau_{12}}{S_{12}} \right)^2 < 1 \quad (2.35)$$

Matrix in compression $\sigma_{22} + \sigma_{33} < 0$:

$$\left(\frac{\sigma_{22}}{Y_C} \right)^2 + \left(\frac{\tau_{12}}{S_{12}} \right)^2 < 1 \quad (2.36)$$

2.3.3.2 Hashin failure criteria

Hashin failure criterion [28] is a modified version of Hashin-Rotem failure criterion. It was created in 1980. Hashin failure criterion is an interactive failure criterion in which multiple stress components are used to evaluate different failure modes. It was developed to take into account the effect of compressive stress on matrix strength. Generally, the Hashin criterion is used in the classical two-dimensional lamination approach for point stress calculations with sheet reduction as the material failure model.

The Hashin criterion was originally developed for polymeric unidirectional composites. Therefore, its application to other types of composites may not give satisfactory results. The Hashin criterion deals with fiber and matrix failures and includes four failure modes. The criterion has been extended to 3-dimensional problems where the maximum stress criterion is used for the transverse normal stress component. If one of the following equations is satisfied, it is concluded that the material will fail.

Fiber in tension ($\sigma_{11} \geq 0$) :

$$\left(\frac{\sigma_{11}}{X_T} \right) + \frac{\tau_{12}^2 + \tau_{13}^2}{(S_{12})^2} < 1 \quad (2.37)$$

Fiber in compression ($\sigma_{11} < 0$) :

$$\left(\frac{\sigma_{11}}{X_C} \right) < 1 \quad (2.38)$$

Matrix in tension ($\sigma_{22} + \sigma_{33} \geq 0$) :

$$\frac{(\sigma_{22} + \sigma_{33})^2}{Y_T} + \frac{\tau_{23}^2 - \sigma_{22}\sigma_{33}}{(S_{23})^2} + \frac{\tau_{12}^2 + \tau_{13}^2}{(S_{12})^2} < 1 \quad (2.39)$$

Matrix in compression ($\sigma_{22} + \sigma_{33} < 0$) :

$$\left[\left(\frac{Y_C}{2S_{23}} \right)^2 - 1 \right] \left(\frac{\sigma_{22} + \sigma_{33}}{Y_C} \right) + \left(\frac{\sigma_{22} + \sigma_{33}}{2S_{23}} \right)^2 + \frac{\tau_{23}^2 - \sigma_{22}\sigma_{33}}{(S_{23})^2} + \frac{\tau_{12}^2 + \tau_{13}^2}{(S_{12})^2} < 1 \quad (2.40)$$

Delamination in tension ($\sigma_{33} > 0$) :

$$\left(\frac{\sigma_{33}}{Z_T} \right)^2 < 1 \quad (2.41)$$

Delamination in compression ($\sigma_{33} < 0$) :

$$\left(\frac{\sigma_{33}}{Z_C} \right)^2 < 1 \quad (2.42)$$

2.3.3.3 Puck failure criteria

Puck failure criterion is among the widely used and advanced criteria for strength analysis of composite laminates. The Puck theory is based on observations of laminates breaking under loading. Based on these observations, it was concluded that the fracture of composites is similar to the fracture of a brittle material.

The Puck failure criterion was first published in 1969 [29]. Later, using the Hashin failure criterion, the failure criterion was developed in 1992 [30] and 1996 [31].

Fiber in tension ($\sigma_{11} > 0$) :

$$\frac{\sigma_{11}}{X_T} < 1 \quad (2.43)$$

Fiber in compression ($\sigma_{11} < 0$) :

$$\frac{|\sigma_{11}|}{X_C} < 1 \quad (2.44)$$

Matrix failure:

Mod A - matrix in tension ($\sigma_{22} > 0$) :

$$\sqrt{\left(\frac{\tau_{12}}{S_{12}} \right)^2 + \left(1 - p_{12}^+ \frac{Y_T}{S_{12}} \right)^2 \left(\frac{\sigma_{22}}{Y_T} \right)^2} + p_{12}^+ \frac{\sigma_{22}}{Y_T} < 1 \quad (2.45)$$

Mod B - matrix in compression ($\sigma_{22} < 0$) :

$$\frac{1}{S_{12}} \sqrt{\tau_{12}^2 + (p_{12}^- \cdot \sigma_{22})^2} + p_{12}^- \cdot \sigma_{22} < 1 \quad (2.46)$$

Mod C - matrix in compression ($\sigma_{22} < 0$) :

$$\left[\left(\frac{\tau_{12}}{2(1 + p_{22}^-) S_{12}} \right)^2 + \left(\frac{\sigma_{22}}{Y_C} \right)^2 \right] \left(\frac{Y_C}{-\sigma_{22}} \right) < 1 \quad (2.47)$$

The results obtained from the Puck criterion are consistent with the results found in experimental studies. It examines matrix failure with three modes. It examines fiber failure with two modes. Three modes can be seen in Table 2.12.

The empirical p_{12}^- , p_{12}^+ and p_{22}^- material parameters can be found experimentally. Puck published in 2002 on the calculation of these parameters [32]. The – sign in the parameters indicates the compression side and the + sign indicates the tension side.

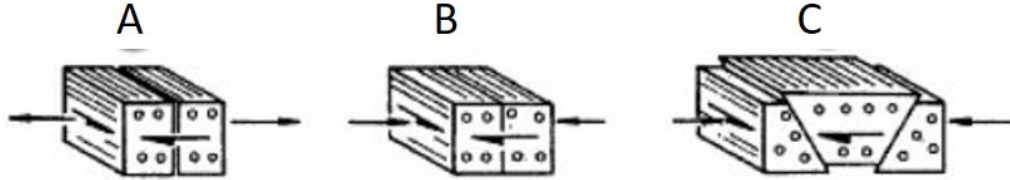


Figure 2.12 : Failure modes of composite matrix [31].

2.3.3.4 Chang-Chang failure criteria

The Chang-Chang failure criterion was developed in 1987 [33,34]. It is a preferred criterion in composite failure analysis. It was developed to calculate the effects of through holes and impact loads in fiber reinforced composites [20].

Fiber in tension ($\sigma_{11} > 0$) :

$$\left(\frac{\sigma_{11}}{X_T}\right)^2 + \alpha \frac{\tau_{12}}{S_{12}} < 1 \quad (2.48)$$

Fiber in compression ($\sigma_{11} < 0$) :

$$\left(\frac{\sigma_{11}}{X_C}\right)^2 < 1 \quad (2.49)$$

Matrix in tension ($\sigma_{22} > 0$) :

$$\left(\frac{\sigma_{22}}{Y_T}\right)^2 + \alpha \left(\frac{\tau_{12}}{S_{12}}\right)^2 < 1 \quad (2.50)$$

Matrix in compression ($\sigma_{22} < 0$) :

$$\left(\frac{\sigma_{22}}{2S_{12}}\right)^2 + \left[\left(\frac{Y_c}{2S_{12}}\right)^2 - 1\right] \frac{\sigma_{22}}{Y_c} + \left(\frac{\tau_{12}}{S_{12}}\right)^2 < 1 \quad (2.51)$$

The α coefficient in the equations indicates the weight of the shear stress in the calculations.



3. OPTIMIZATION

Finding the best that can achieve a particular objective under constraints is called optimization. Mathematical or rule-based algorithms are used to solve such optimization problems. There is no exact method among the optimization methods, and the solution is not guaranteed. However, there is the best solution within a certain time interval and with a certain degree of accuracy [35].

3.1 Classification of Optimization Problems

Different types of optimization problems have different kinds of solutions. Optimization varies according to the type of problem. There are many types of classification for optimization problems. There are different types of optimization problems, such as constrained or unconstrained problems, linear or non-linear, and discrete or continuous optimization [36,37]. There are also different types of optimization problems, such as deterministic or stochastic optimization problems, and single or multiple objective optimization problems [38].

3.2 Basic Concepts of Optimization

3.2.1 Objective function

Objective function is a function that transforms into a value that can express the comparison of different designs and the degree of goodness of the design. The objective function is used to classify and characterize designs. This function is the quantity that expresses the minimization or maximization. The design in which the objective function is minimized or maximized is an optimized design.

In general, in a structural optimization problem; weight, displacements, stresses, buckling loads, vibration frequencies, cost, etc. criterias or their combinations are used as objective functions.

When formulating the design goal, two issues must be considered. The first is that the objective function works with sufficient precision for each variable. The second is the comparison and consideration of values in absolute value.

3.2.2 Design variables

Design variables are parameters that must be changed in order for the design to reach the objective. These variables can be continuous or discrete values. Continuous design variables are variables that are within a certain range or a series and can take any parameter within this array. Discrete design variables, on the other hand, take a value from the array separately from each other in a permissible array.

In structural optimization, there are three types of variables in terms of design. These are size design variable, shape design variable and topology design variable.

The size design variable is related to the quantities of a particular construct. For example, the section inertia of a beam can be the thickness of a plate, the value of a particular dimensional measure. In optimization studies using this design variable, the modeling area does not change. Therefore, the shape of a reference surface used in optimization is not expected to change.

The shape design variable is related to the actual model. For example, in a truss system, the orientation and length of a rod are shape variables. In three-dimensional models, the positions of holes or variations of a structural element in different positions are examples of shape variable parameters.

Topology design variables are actually design solutions that are realized by the decision of whether a concept exists or not. Examples such as the amount of material desired to be created in the place where a load will pass, and the presence or absence of a finite element representing this material are seen in topology optimizations.

3.2.3 State variables

State variables are functions that contain the answers to a design solution. In a structural optimization problem; Response of a mechanical structure, displacements, stresses, deformations or forces can be included in these variables.

3.2.4 Design constraints

The conditions that the design must meet in an optimization problem are the design constraints. If there is any concept to be constrained in the optimization problem, the problem becomes a constrained optimization problem. In the absence of any constraints, it is considered an unconstrained optimization problem. In structural problems, material limits are often one of the concepts that constrained optimization.

3.3 General Mathematical Form of a Structural Optimization Problem

A general structural optimization (SO) problem can be expressed in the form in equation 3.1 when the objective function f , the design variable x , and the state variable y are used in an optimization problem.

$$(SO) \begin{cases} \text{minimize } f(x, y) \text{ with respect to } x \text{ and } y \\ \text{subject to } \begin{cases} \text{behavioral constraints on } y \\ \text{design constraints on } x \\ \text{equilibrium constraint.} \end{cases} \end{cases} \quad (3.1)$$

In multi-objective problems, the objective function can be written as in the equation 3.2.

$$\text{minimize } (f_1(x, y), f_2(x, y), \dots, f_l(x, y)) \quad (3.2)$$

In general, the same x and y values cannot be optimized for all objective functions. Therefore, Pareto optimization can be attempted instead. If all objectives cannot be met with a different design, it is considered a Pareto optimal design. If there are no other (x, y) values that satisfy the constraints, the (x^*, y^*) values that satisfy the constraints are Pareto optimal.

$$f_i(x, y) \leq f_i(x^*, y^*), \text{ for all } i = 1, \dots, l \quad (3.3)$$

$$f_i(x, y) \leq f_i(x^*, y^*), \text{ for at least one } i = 1, \dots, l \quad (3.4)$$

$$\sum_{i=1}^l w_i f_i(x, y) \quad (3.5)$$

w_i are weight factors. By minimizing the equation 3.5, the Pareto optimum solution is obtained [35].

3.4 Optimization Algorithms

An optimization process can be divided into steps: design of experiments (DOE), rough optimization using stochastic algorithms, and refinement of the Pareto optimal set using deterministic algorithms. There are both stochastic and deterministic optimization algorithms in ModeFrontier software. Apart from these, there are also algorithms obtained by combining both approaches, called hybrid algorithms.

3.5 Multi-Objective Genetic Algorithm II (MOGAII)

The Multi-Purpose Genetic Algorithm (MOGA-II) is a version of the multi-objective genetic algorithm (MOGA) in which the elitism method is used for intelligent and more efficient optimization. With elitism, the algorithm converges quickly, ensuring that the fitness of each new generation is greater than that of their parents [39].

3.5.1 Optimization process in MOGAII

The first cluster is created with the algorithm and the population is started. MOGA operators are used to generate future generations. These operators are selection, classical crossover, directional crossover, and mutation.

Selection is the transfer of an existing design because it is sufficient to pass on to the next generation.

Directional crossover is performed by determining the direction of improvement based on the fitness values of designs in the same generation. Three designs are used in this process. For orientation, the fitness value of a design is compared with two designs from the same generation. A new design in the next generation is formed based on the determined direction vector.

Mutation is the random change of genetic material of a design as a new design is created in the next generation. The main purpose of this event is to reach different points in the design space.

The classical crossover is when two parents in one generation create a new design for the next generation. In this way, population diversity is preserved. A new design derived from good designs is more likely to be better. During this crossover, the

influence of other operators is added. The effect of other operators can be adjusted by the user. The high probability of classical crossover is important for exploring different points of the design space. However, this will slow down the convergence time.

Which of the designs within the generations is the best design is determined by fitness. Non-dominated designs are copied and stored as an elite set. This operation is repeated each time. Non-dominated designs are included in the set. During this process, the dominated ones are removed from the elite set each time.

The generations are multiplied using the specified operators, and the process stops when the maximum generation is reached. The population sizes found in MOGAI are dependent on the number in the design of experiment DOE dataset [39]. A simple evolution scheme is given in Figure 3.1.

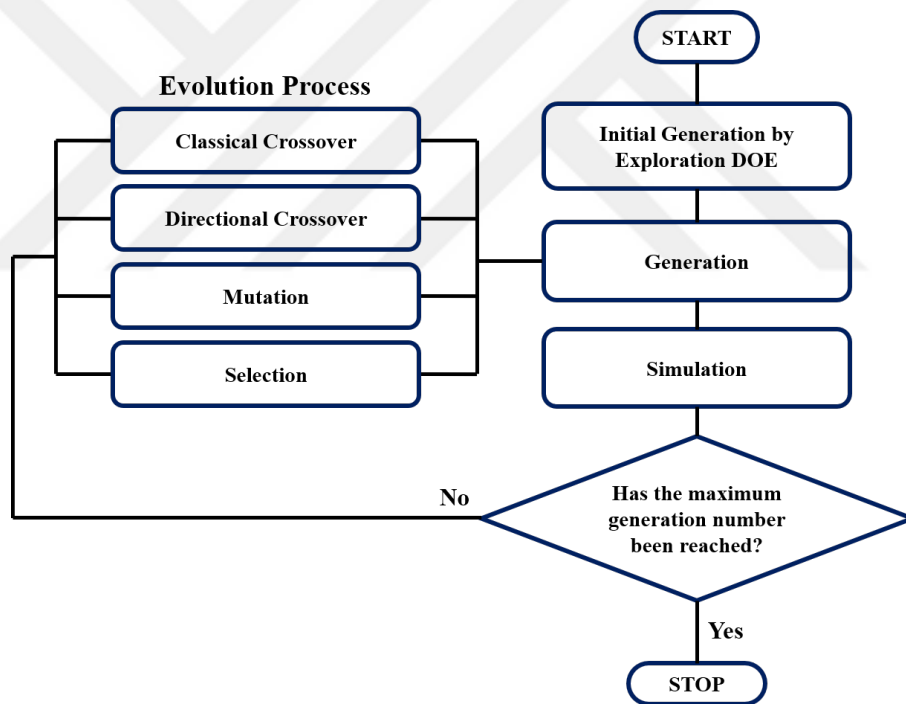


Figure 3.1 : Evolution scheme.

3.5.2 MOGAI modes in ModeFrontier

Algorithm configuration modes in the modeFrontier user interface are respectively; autonomous, self-initializing, and manual configuration modes.

In autonomous mode, no parameters are requested from the user. In this mode, the optimization process is shaped by obtaining information on the optimization established. In case Pareto cannot be developed further, the process is stopped. In self-initializing mode, only the number of evaluations is prompted from the user. The user limits the number of generations, taking into account the solution capability of the user's system. Also, in this mode, the user does not define DOE. MOGAII automatically identifies DOE. In manual configuration, all parameters are open to the control of the user [39].

3.5.3 MOGAII parameters

3.5.3.1 Number of generations

The number of generations is a parameter that defines how large the run will be. The total number of designs is calculated by multiplying the number of designs found in the first specified DOE by the number of generation [39].

3.5.3.2 Algorithm type

There are three types of algorithms that can be defined. These are generational evolution, steady evolution, and adaptive evolution.

Generational evolution is a classical algorithm. It occurs by using the previous generation and deriving the next one. If there is elitism, the population consists of the last generation and an elite cluster.

In steady evolution, a new design is created by evaluating previous designs without waiting for a generation's designs to be completed. If there is elitism, the elite set is also updated by keeping a certain design population constant. This option is advantageous when different computational resources are used simultaneously to evaluate multiple designs in parallel. In adaptive evolution, the operators' probability values are automatically updated during the search process to improve Pareto convergence. It is useful when it is not clear what kind of probability values the user will use [39].

3.5.3.3 Probability of directional crossover

It is the probability of using the directional crossover operator when creating a new design. With a high probability value, the design can be found effectively. However, the robustness of the algorithm decreases. It causes the design space to stay around the local optimum, and it becomes difficult to explore the entire design space [39].

3.5.3.4 Probability of selection

It is the parameter that defines the possibility of using the selection operator while creating a new design. It is an operator that is especially important in transferring good designs to the next generations. The value of this operator should be kept small, otherwise the number of new designs will decrease [39].

3.5.3.5 Probability of mutation

It is the parameter that defines the possibility of using the mutation operator while creating a new design. Thanks to this operator, randomness comes into the optimization. It helps in investigating different regions of the design space. Thus, the algorithm does not converge prematurely [39].

3.5.3.6 Probability of classical crossover

The classical crossover parameter is calculated using other operators. The probability of appearing as a kind of residual is defined in the classical crossover probability parameter [39].

$$ClassicalCrossover = 1 - (DirectionalCrossover + Selection + Mutation) \quad (3.6)$$

3.5.3.7 DNA string mutation ratio

It is the parameter that defines the percentage of DNA (Deoxyribonucleic Acid) that the design to be mutated will mutate. The DNA of each design is a binary string. The mutation rate also defines the number of bits to be mutated. If the mutation rate is 0, there is no mutation, while if it is 1, all bits of DNA are mutated each time [39].

3.5.3.8 Elitism

With elitism, it is ensured that the quality of a design that has been solved by the algorithm is passed on to other generations. This parameter can only be set as either active or passive [39].

3.5.3.9 Treat constraints

This constraint can be set as "penalising objectives" or "as one extra objective" [39]. The penalizing objective is penalized based on non-compliance of unfeasible designs with respect to restriction violations [39]. As one extra objective examines the optimization problem without restrictions. Instead, it defines an additional minimization objective. The value to be minimized is equal to the sum of all constraint violations. This option is most relevant when there is more than one constraint of equal importance [39].

3.5.3.10 Reject input-unfeasible designs

If this option is selected, the algorithm discards the design that violates any constraints imposed on one or more input variables. If it is not selected, it enters the solver to calculate the output values. With the maximum number of rejection parameters, the maximum number that the algorithm can reject is defined [39].

3.5.3.11 Random generator seed

With the same DOE and parameters, the design and data to be generated during operation will be the same. By changing this parameter, it is aimed to get different results when a different optimization is run [39].

3.6 Design of Experiments (DOE)

The first design data to be defined in the optimization study is effective in the rest of the optimization process. How to select the first given design examples from the design space is a problem that needs to be examined separately.

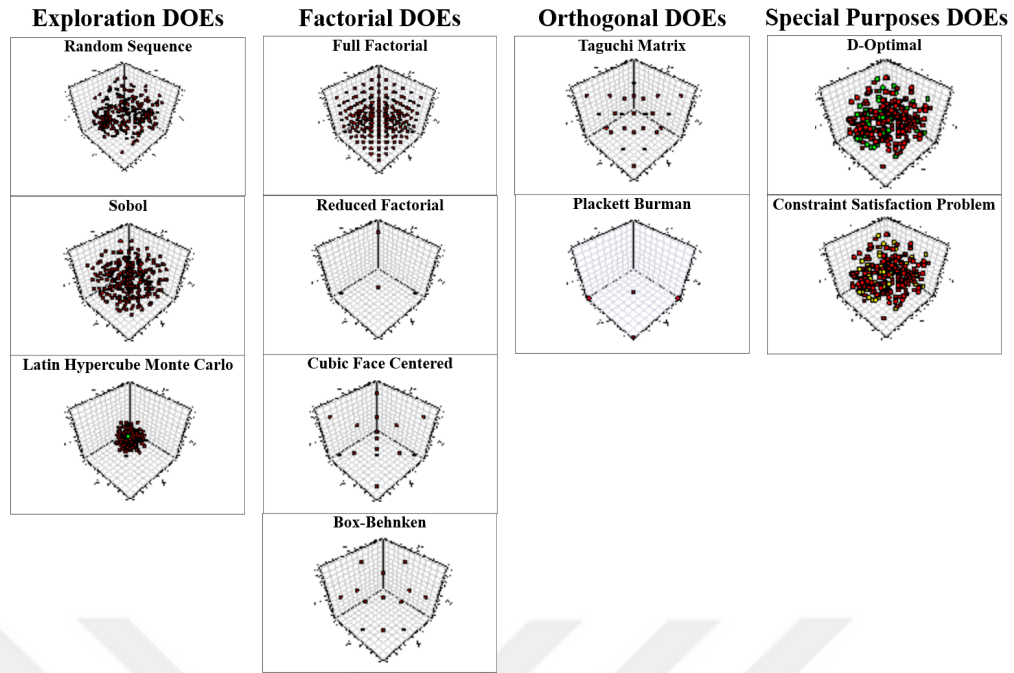


Figure 3.2 : DOE methods.

Design of experiment (DOE) was invented in 1920 by British scientist Sir R. A. Fisher to maximize the knowledge to be obtained in tests. In the traditional approach, the one factor at a time (OFAT) method is followed. In this method, one of the factors affecting the test is changed while the others are kept constant. In this way, the effects of the changing factor are observed. However, all these factors can be changed with the DOE. As it can be understood, the DOE approach allows examining all factors simultaneously, unlike OFAT.

The use of DOE in the field of optimization is usually to give the first population. Each optimization algorithm needs different versions of the DOE in different sizes. However, robust optimizers such as genetic algorithms are little affected by the quality of DOE.

DOE methods on the modeFrontier software are divided into five different classes. These are user-defined exploration DOEs, factorial DOEs, orthogonal DOEs, and special-purpose DOEs. User-defined DOEs consist of designs determined by the user according to their own user experience. Classified DOE methods other than user-defined DOEs and the positions of the designs in an example DOE with 3 variables are given in the Figure 3.2.

3.6.1 Exploration DOEs

Exploration DOEs are mostly used to produce initial designs before the optimization process. Examples of these DOEs are random DOE, sabol, and the latin hypercube Monte Carlo [40].

3.6.1.1 Random DOE

It is the DOE obtained by generating random numbers. The algorithm tries to distribute the points evenly across the design space. Randomness is managed with a seed number.

In order to obtain a uniform distribution, the input variables must be continuous. Clustering may occur, especially if there are few samples in a multidimensional variable space [40].

3.6.1.2 Sabol

Random is a deterministic algorithm similar to DOE's behavior. However, it avoids the clustering effect of random DOE. Such sequences are called semi-random. While the samples are placed in the design space, they are chosen to be at the maximum distance from each other [40].

3.6.1.3 The latin hypercube monte carlo

It generates random design configurations suitable for various statistical distributions. Latin Hypercube Sampling (LHS) is an advanced monte carlo sampling. The statistical distribution is divided into n intervals. A random value is selected in each interval according to the density function. The design points are relatively evenly distributed over the density range [40].

3.6.2 Factorial DOEs

Factorial DOEs are used to perform statistical analysis of problems and to examine the effects of variables [40].

3.6.2.1 Full factorial

It is the DOE that includes the combination of all possible factor levels. The number of design points depends on the number of input variables. It is suitable for statistical analysis because the effect of each factor on the output variable and the interaction between factors can be examined [41].

3.6.2.2 Reduced factorial

In the full factorial method, the number of experiments will increase exponentially according to the number of input variables, so it becomes inefficient in terms of time. Finney developed the reduced factorial method in 1945. This DOE features some of the full factorial designs. It is suitable for statistical analysis. However, it tends to overestimate the correlations between variables [41].

3.6.2.3 Cubic face centered

A cube has axial points at the center of each surface, and designs are available at the corner points of the cube. The distance of each axial point from the center is defined as α [40].

3.6.2.4 Box-Behnken

With this algorithm, all quadratic effects can be calculated. Therefore, it is suitable for statistical analysis. However, it is not suitable for genetic algorithms [40].

Similar to the cubic face-centered DOE, but without the use of vertices or endpoints. In general, a polyhedron is filled [40].

3.6.3 Orthogonal DOEs

Orthogonal DOEs are best used to describe the main effects. There are two methods: Taguchi matrix and Plackett Burman [40].

3.6.3.1 Taguchi matrix

Taguchi matrix DOE was developed by "Dr. Genichi Taguchi" and aims to produce high-quality designs at a low cost. Taguchi focused on finding the best values against uncontrollable noise factors [40].

First, the target is defined. The goal can be minimization or maximization. Any deviation from the target value is used to define the loss function. Design variables that affect the performance measure are determined. Orthogonal arrays are created for each variable. The effect of each different variable on performance is determined [40].

3.6.3.2 Plackett Burman

The Plackett-Burman DOE assumes that the interaction effects are negligible and identifies only the main effects. It does not provide a suitable DOE for the genetic algorithm and RSM. This algorithm is used with a minimum of 3 variables and a maximum of 59 variables [40].

3.6.4 Special purposes DOEs

Special purposes DOE is used when other methods cannot be applied. There are two methods in the ModeFrontier software. These are D-Optimal and constraint satisfaction problem [40].

3.6.4.1 D-Optimal matrix

D-optimal is used to extract a design set from an existing dataset. It filters designs and minimizes correlations between variables [40].

3.6.4.2 Constraint satisfaction problem

Classical optimization algorithms need at least one feasible design. Because they usually cannot pass from the unfeasible region to the feasible region. It is more difficult to find a feasible design for problems with too many constraints. The need for feasible design in genetic algorithms is not mandatory, but useful. This DOE method aims to find the design that satisfies the constraints [40].

4. COMPOSITE RIM DESIGN

In order to be able to conduct composite analyzes and sizing studies, a reference CAD geometry must be created initially by using CATIA. In addition to being an aesthetic aspect of automobile rims with a design concern, certain geometric parameters have been standardized from a technical point of view. The basic design parameters and their values are shown in Table 4.1. The design was made by choosing the basic design parameter values of the rim and taking into account the ETRTO [42]. The cross-section profile of the wheel rim designed according to the standards is shown in Figure 4.1.

Table 4.1 : Composite rim design basic parameters and their values.

Parameter	Value
Nominal Diameter	R19 - 487.4 mm
Number of Spokes	10
e - offset	30 mm
Center Hub Diameter	168 mm
Number of Fasteners	5
Fastener Diameter	15 mm
Center Hole Diameter	32 mm

When the load bearing capabilities of composite structures are evaluated, it is known that in-plane load carrying capabilities are better than out-of-plane load carrying capabilities. Considering the interface area between the rim and the vehicle, while the load is transferred from the rim hub with the fasteners on the vehicle interface, force bond occurs between the vehicle and the rear face of the wheel hub as a result of the preload on the fasteners. For this reason, while designing the automobile rim, it is planned that fastener holes and the connection interface area of the rim with the automobile are supported by a metallic structure. Reference CAD geometry and a section of the center hub can be seen in Figure 4.2.

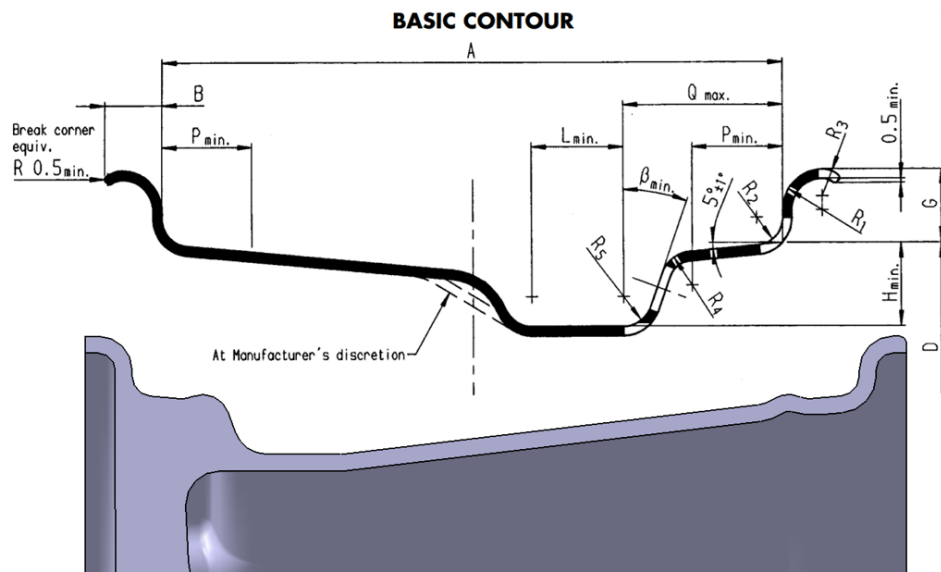


Figure 4.1 : Reference geometry rim wheel parameters.

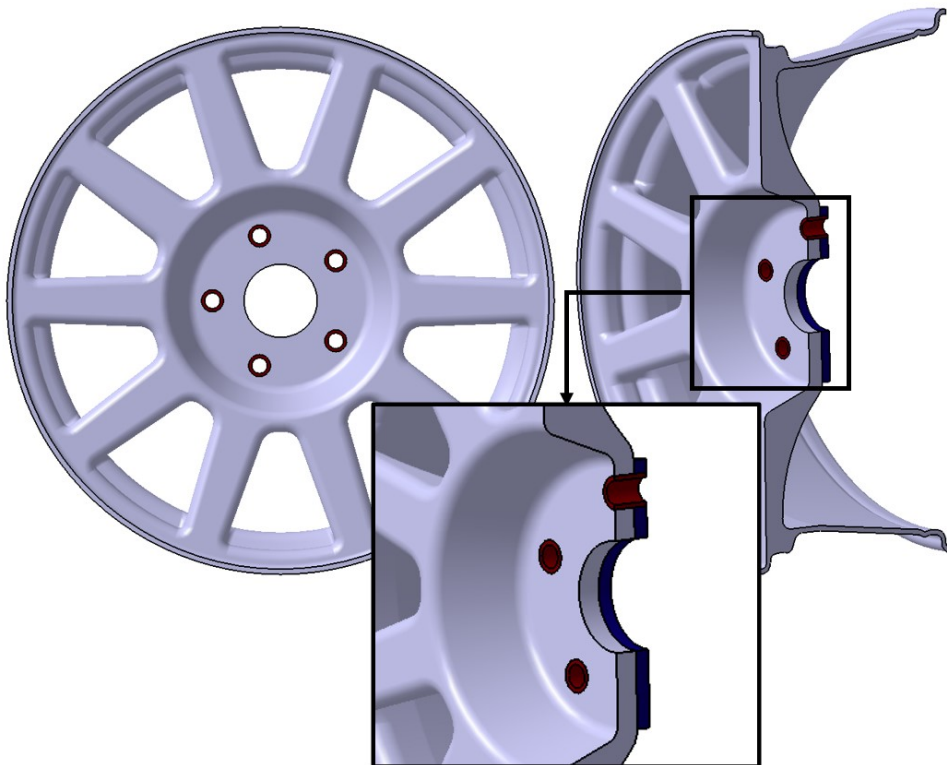


Figure 4.2 : Reference geometry for composite rim and center hub.

Table 4.2 : Tire design requirement parameters.

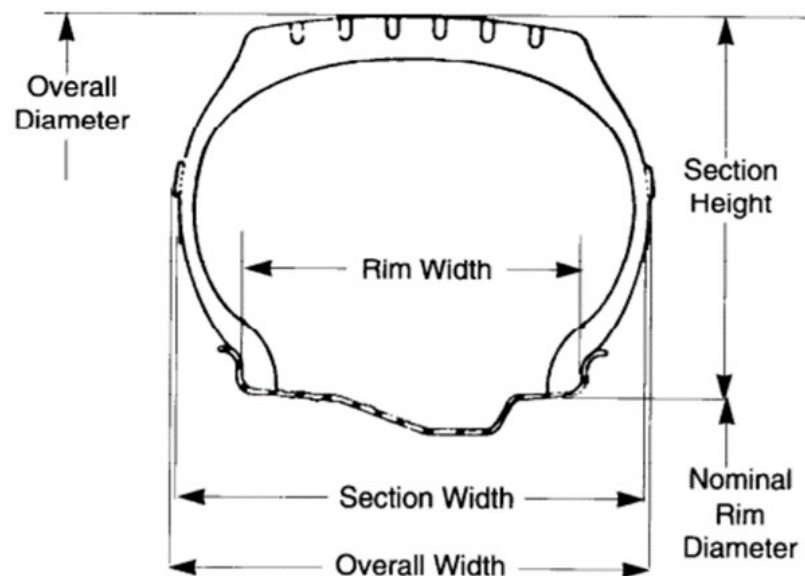
Tire Parameters	Requirement	Values
Speed Index	300 km/h Maximum Speed	Y
Load Index	750 kg per tire	98

The purpose of the targeted rim design is that it can be used on performance vehicles, and a tire that can meet certain speed and load requirements should be determined. The selection parameters for the tire to be used are given in the Table 4.2.

Tire selection should be made for the values determined in the table according to ETRTO Standards. When the standards are examined in this direction, one of the recommended tires is seen as R19 245/40. As for the tire inflation pressure, the value of 3 kPa is specified as the reference value. The nominal design parameters of the selected tire are shown in Figure 4.3 and their values are given in the Table 4.3.

Table 4.3 : Selected tire parameters.

Tire Parameters	Values
Type	245/40 R19
Inflation Pressure [bar]	3
d_{ovr} – Overall Diameter [mm]	679
w_{ovr} – Overall Width [mm]	248
Load Capacity [kg]	750

**Figure 4.3 :** Tire design parameters [42].



5. MODELING OF COMPOSITE RIM

In order to carry out the optimization study, it is aimed to create a ready-to-analyze model using reference geometry surfaces. The reference surfaces used can also be thought of as tool surfaces. For this reason, the element offset parameters are determined by considering these outer surfaces.

There are ten arms in the rim geometry designed with basic parameters. In fact, these ten arms represent ten symmetrical planes in the target design. Therefore, the 360-degree rim geometry consists of ten 36-degree parts. In order to make modeling easier, the model was created by taking a 36-degree rim piece as a reference.

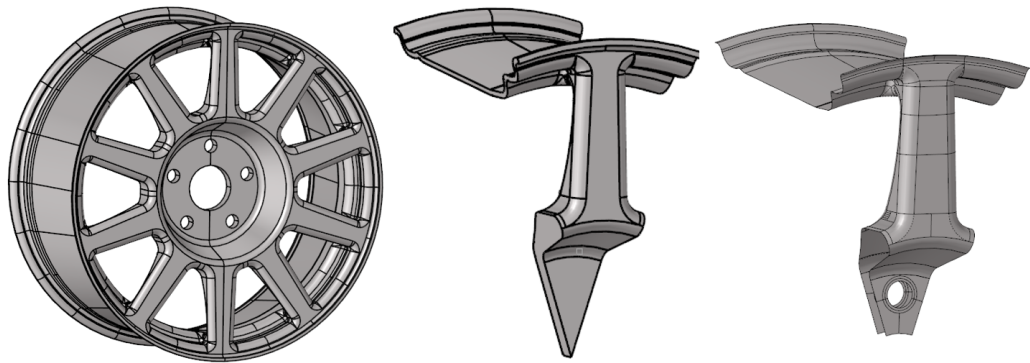


Figure 5.1 : Geometry preparation for mesh modeling.

Hypermesh was used to create the rim finite element model. The shell mesh structure created in the symmetric region is reproduced to create models of all composite regions. QUAD4 shell element type was used while creating the mesh structure. The mesh with an average of 2 mm element dimensions was realized by considering the element quality threshold values. As seen in Figure 5.1, first a 1/10 surface model was created, and then the mesh structure was obtained for the whole model. In Figure 5.2, the surface mesh and the whole model obtained by using a 1/10 slice are shown.

In order to represent the metallic structures that are planned to be placed in the body part of the car rim to support the composite structure, the inserts to be placed in the

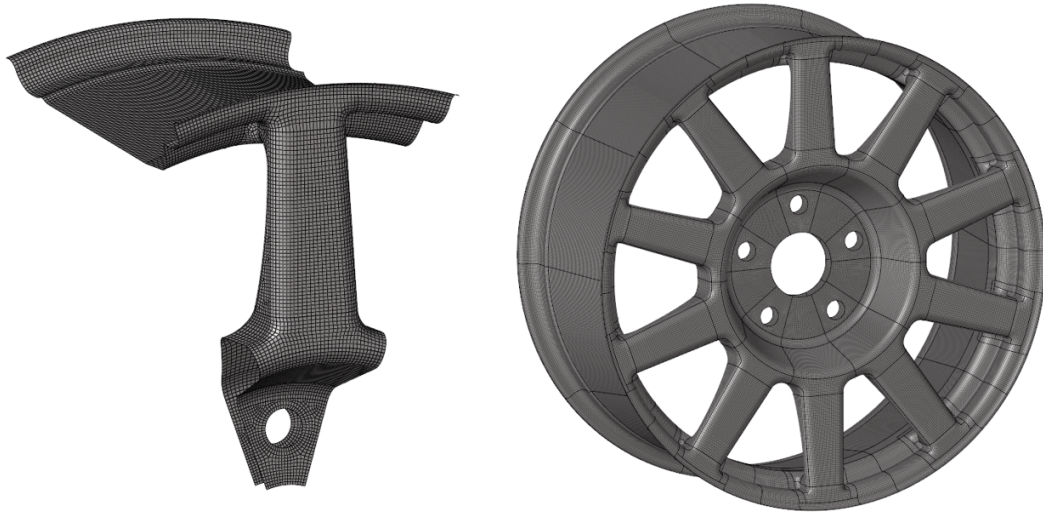


Figure 5.2 : Surface shell mesh.

holes and the metal plate are modeled as in Figure 5.3. As can be read from the Table 4.1, the "e" offset value is used as the basic design value of 30 mm. The "e" value represents the distance of the connection plane between the car and the rim to the rim center axis, as mentioned in the previous sections. While adding the metal structure design to be applied in the center of the rim to the structure, the design was carried out considering the e offset value. Metal plates with a thickness of 10 mm in the interface connection area are modeled using QUAD4 shell elements and share the same nodes with the central composite plate.

It is aimed to use special production inserts for the wheel bolts that will be attached to the wheel center. Since composite structures have low strength in out-of-plane loading, they have the risk of inter-laminar matrix failure. The forces caused by the preload and extra load conditions applied to the bolts will come perpendicular to the composite plate and will form the out-of-plane condition. For this reason, it is aimed to transfer these forces to the metallic plate placed in the center via metallic inserts, not the composite plate. Assuming the thickness of the insert to be used is 3 mm, it is modeled to be positioned on the hole surface of the composite model. The thicknesses used for metal structures were roughly determined by examining the existing designs, and the optimization of the composite structure was focused on.

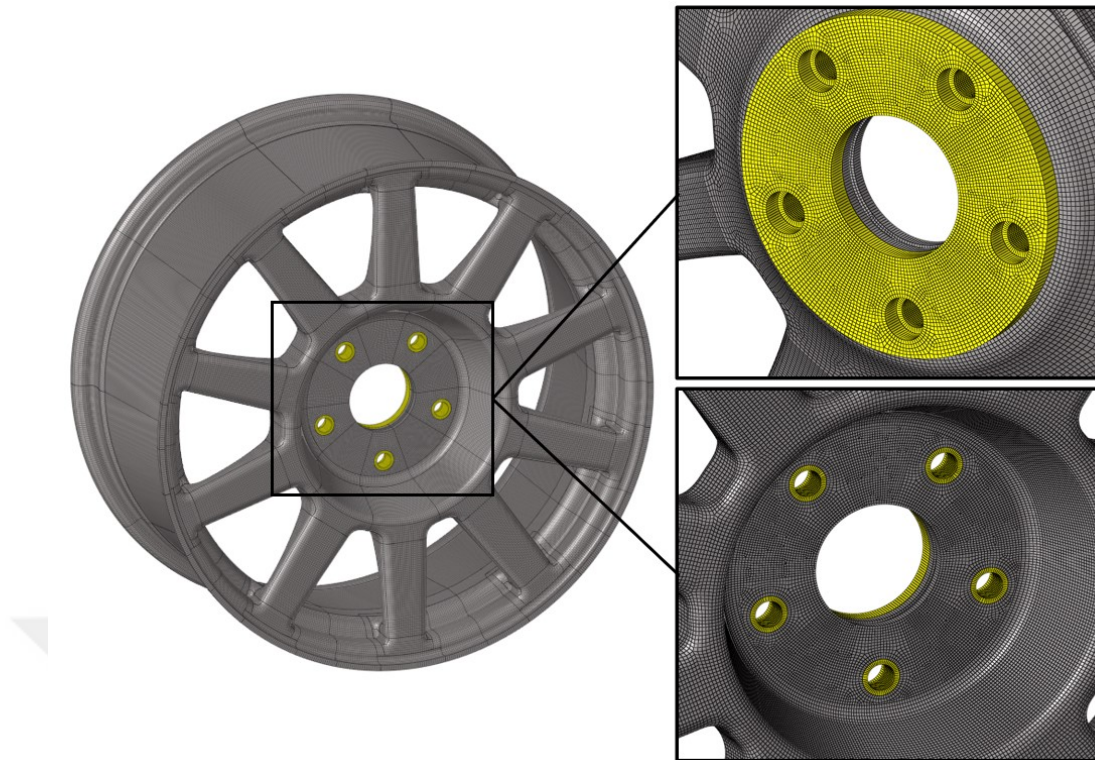


Figure 5.3 : Center hub metallic structures of rim model.

Some criteria were followed while preparing the finite element model. Elements were created by considering element size and element quality thresholds. The number of element types used and the worst quality parameter values are shown in the Table 5.1.

Table 5.1 : Mesh properties and worst quality values.

Mesh Parameters	Value
Element Type	R19 - QUAD4
Element Size	2 mm
Number of Element	190245
Number of Node	184715
Worst Aspect Ratio	3.3
Worst Warpage	40
Worst Jacobian	0.60

5.1 Loading and Boundary Conditions

Like many automobile parts, rims are subject to certain tests. These tests are specified by ISO (International Organization for Standardization). These tests are designed for steel and aluminum, which are rim materials that are already used extensively in the industry. There are tests that must be completed successfully before the wheel models

created are put into mass production. In the light of the results obtained from these tests, design and material changes can be made. Although the material used in the study is different from the test specifications, it is expected that the rim that is the subject of the project, which is planned to go into mass production, will successfully pass these tests. There are three tests that must be successfully completed in order to prove that a manufactured wheel meets the required requirements.

Since the weight of the vehicle on which the rim will be used is targeted as a maximum of 3000 kg, the mass per tire can be calculated as 750 kg.

$$F_v = m_v g \quad (5.1)$$

$$F_v = 7355.25N \quad (5.2)$$

In the equation (5.1), F_v is the maximum vertical static load determined by the rim manufacturer. g is the gravitational acceleration. In order to calculate the load distributions on the rim, the loaded radius dimension of the selected tire should be calculated. The static tire radius calculation is specified in ETRTO standards [42].

$$R_S = \frac{d_r}{2} + F_R \frac{d_{ovr} - d_r}{2} \quad (5.3)$$

In the equation (5.3), R_S is the theoretical static loaded radius. d_{ovr} is tire design overall diameter. d_r is nominal rim diameter. F_R is a constant and equals to 0.78 [42].

5.1.1 Cornering loading

The cornering test is a test applied in order to simulate the loads that will affect the rim during the cornering of the vehicle under real conditions. The test covers vehicles specified in ISO 3006:2015(E). Test setup is shown in Figure 5.4

$$M_C = (\mu R_S + e) F_v K \quad (5.4)$$

In the equation (5.4), M_C is cornering moment. μ is the assumed coefficient of friction between road and tire. R is the maximum radius of a statically loaded tire that can be applied to the rim. e is offset value of the rim in meters. F_v is the maximum vertical static load as determined by the wheel or auto manufacturer. K is the accelerated test factor.

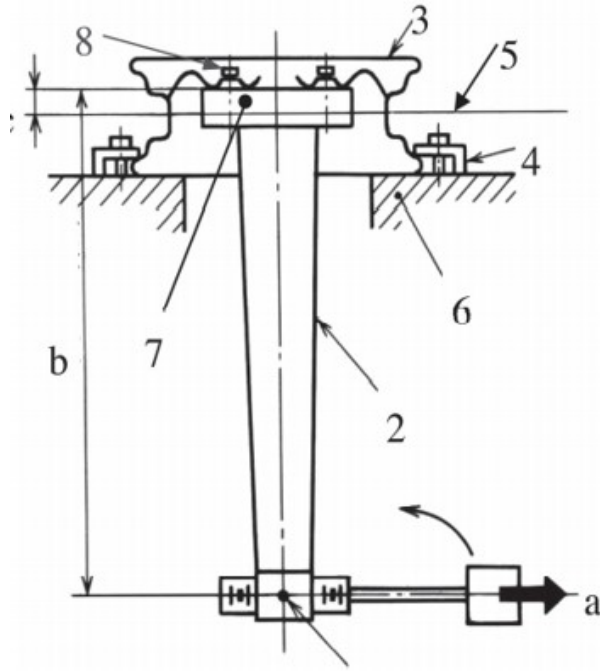


Figure 5.4 : Test setup of cornering test [43].

The values used in the calculation of the moment to be used in the study are given in Table 5.2. μ is taken 0.7 according to the standards [43]. K value is an accelerated test factor for fatigue test. In this study S is taken as 1.

Table 5.2 : Cornering moment calculation parameters.

Parameter	Value
μ	0.70
R_S	0.32m
e	0.03m
F_v	7355.25N
K	1.00

$$M_C = 1868Nm \quad (5.5)$$

The test ends in one of the following two situations. These are when the rim cannot carry the load and propagation of existing cracks or cracks prior to testing or propagation of new stress cracks into the rim section.

As seen in Figure 5.4, in the test setup, one side of the rim wheel is clamped and loaded in order to create a moment from the hub part. Similar to the test setup, the cornering load condition was created and RBE2 (Rigid Body Element Form 2) elements were

modeled to transfer the force that will create the moment to be loaded. In order to apply the boundary condition, the degrees of freedom of the nodes U1, U2 and U3 in the fixing region of the rim are set to zero. The region highlighted in red in the Figure 5.5 shows the clamped region.

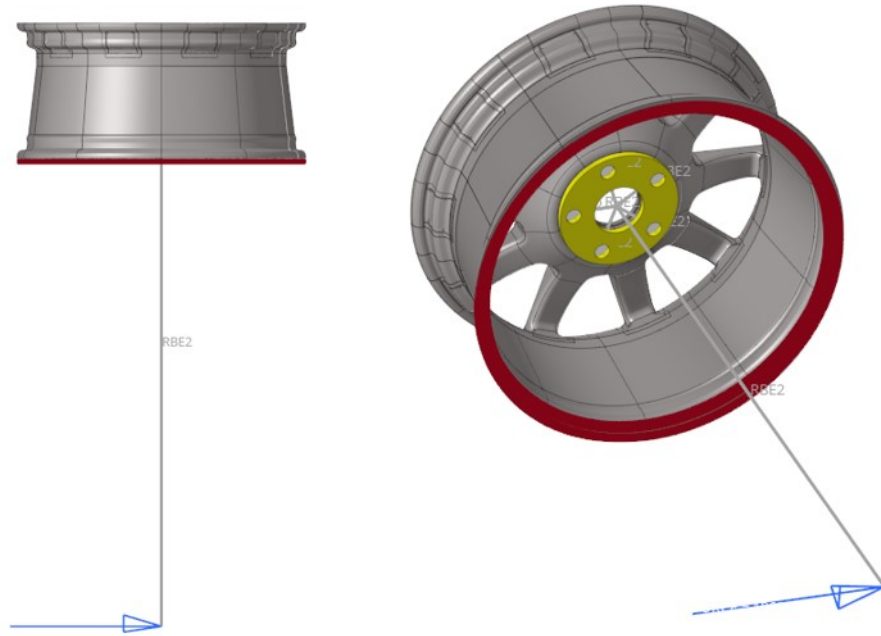


Figure 5.5 : Loading and boundary conditions of cornering load case.

5.1.2 Radial loading

The radial test is a test that aims to simulate real road conditions with the vehicle load applied to the rim and the tire mounted. While performing this test, the tire is inflated to a higher pressure than normal use. Thus, the response of the road to the vehicle and the simulation of the vehicle load are provided. The representative image of the test is given in Figure 5.6.

Table 5.3 : Test pressure to be applied.

Normal Inflation Pressure [kPa]	Test Inflation Pressure [kPa]
0-160	280
161-280	450
281-450	550

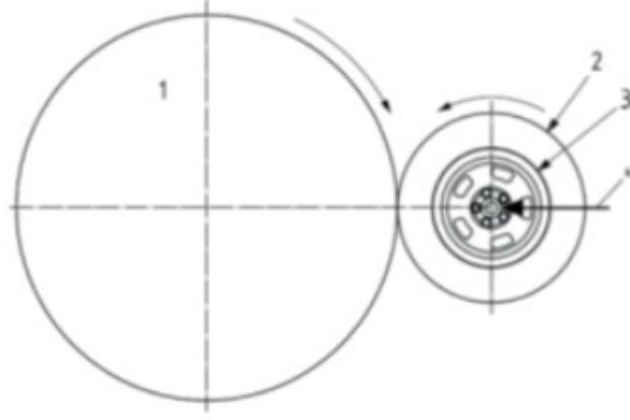


Figure 5.6 : Radial test setup [43].

$$F_r = F_v K \quad (5.6)$$

In this equation (5.6), F_r is total radial load [N]. F_v is the maximum vertical static load and K is the acceleration test factor.

As a result of the loads on the tire, a contact surface will be formed between the tire and the ground. The total force on the tire will act as a distributed load on this contact surface. In reality, the load will not affect the rim as it comes directly to the tire. If the approximation that the distributed load is in a cosine distribution is used, and it is assumed that it acts directly on the rim, this would be a conservative and sufficient approach.

The deformation on the tire can be calculated from the relationship between the resulting static loaded radius and the nominal design diameter. According to the relationship given in Figure 5.7, the contact patch angle can be calculated using these two values.

$$\theta_o = \text{Angle } AOC = \cos^{-1} \frac{R_S}{R_D} \quad (5.7)$$

In this equation (5.7), θ_o is half angle of the contact patch, R_S is the theoretical static loaded radius and R_D is nominal tire radius.

$$\theta_o = \text{Angle } AOC = \cos^{-1} \frac{318.42 \text{ mm}}{339.50 \text{ mm}} \quad (5.8)$$

$$\theta_o = \text{Angle } AOC = 20.29^\circ \quad (5.9)$$

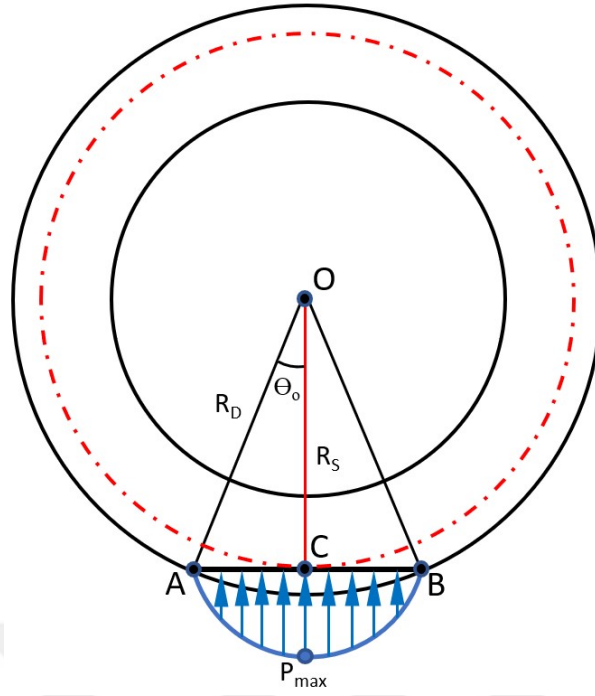


Figure 5.7 : Radial load cosinus distribution.

According to the calculations, the total contact patch angle was obtained as 40.58 degrees. If the total force is written in terms of the highest pressure value in the load distribution, the integration can be made as in the equation below.

$$P_{\theta} = P_{\max} \cos \left(\frac{\pi}{2} \frac{\theta}{\theta_0} \right) \quad (5.10)$$

$$F_r = 2b \int_{-\theta}^{\theta} P_{\theta} r_b d\theta \quad (5.11)$$

$$F_r = 2b \int_{-\theta}^{\theta} P_{\max} \cos \left(\frac{\pi}{2} \frac{\theta}{\theta_0} \right) r_b d\theta \quad (5.12)$$

In these equations (5.10),(5.11) and (5.12), $P_{\max}$ is maximum pressure at the center, b is the bead seat width of the rim, r_b is bead seat radius, and F_r is the maximum radial static load.

The tire sits on the rim surface of these bead seat areas, shown in Figure 5.8 as white surfaces. For this reason, integration has been created, considering that the load will affect both sides of the rim. According to the measurements taken on this rim design, the bead seat width is 8 mm and the bead seat radius r_b is 242,95 mm.

By solving the integration, the following equation is obtained.

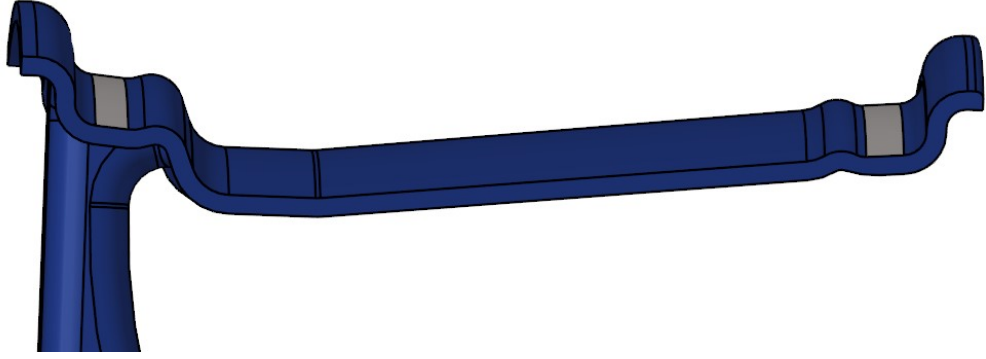


Figure 5.8 : Bead seats of the rim wheel.

$$F_r = 8br_b\theta_0 \frac{P_{max}}{\pi} \quad (5.13)$$

$$P_{max} = \frac{F_r\pi}{8br_b\theta_0} \quad (5.14)$$

If the equation is solved, the P_{max} value is obtained as 4.2 MPa. By using this value, the pressure distribution depending on the angle can be transferred to the model in the relevant bead seat area. The resulting cosine distribution is given in the equation below.

$$P_\theta = 4.2 \cos\left(\frac{\theta}{0,2254}\right) \text{ MPa} \quad (5.15)$$

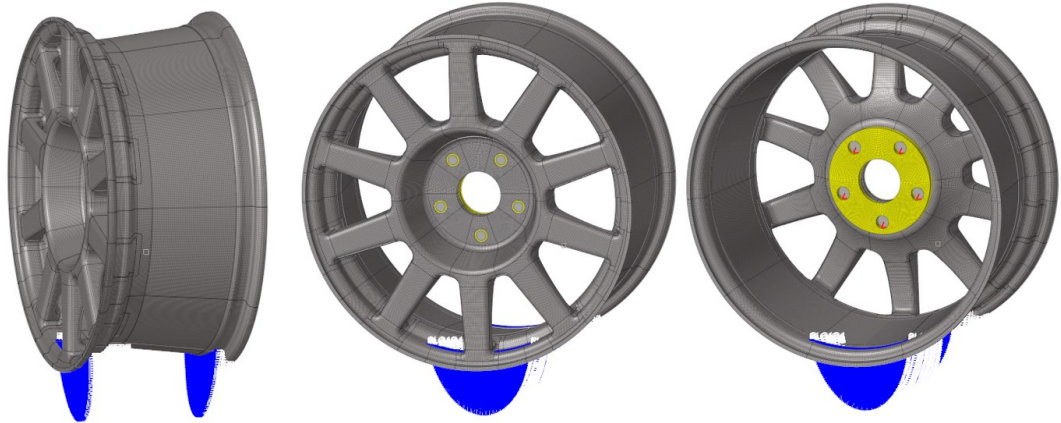


Figure 5.9 : Radial load case load distribution.

Considering the calculated load distribution, the load was applied as PLOAD4 to the relevant bead seat surface norms. It is highlighted in blue in the Figure 5.9. The cosine loading distribution applied to the two bead seat regions can be seen.

During the radial loading test, loading is performed with the reference tire mounted on the rim. Therefore, not only the radial load, but also the test inflation pressure affects the rim. The inflation pressure of the tire selected according to the Table 4.3 is specified as 3 bar. If this value is evaluated according to Table 5.3, it seems that the test inflation pressure P_i should be 550 kPa. In addition to the radial load, the test inflation pressure was applied as PLOAD4 to the surface normal of the wheel rim as shown in Figure 5.10.



Figure 5.10 : Radial load case inflation pressure loading.

In the radial test, a realistic situation is created and the rim, together with the tire on it, is connected to the test assembly with bolts. The targeted design load is applied with the mechanism connected to this region. What is desired to be created in the case of radial load is to model the reaction force on the rim and see its effect on the structure. For this reason, the model was established by fixing the fasteners from all degrees of freedom, as seen in Figure 5.11.

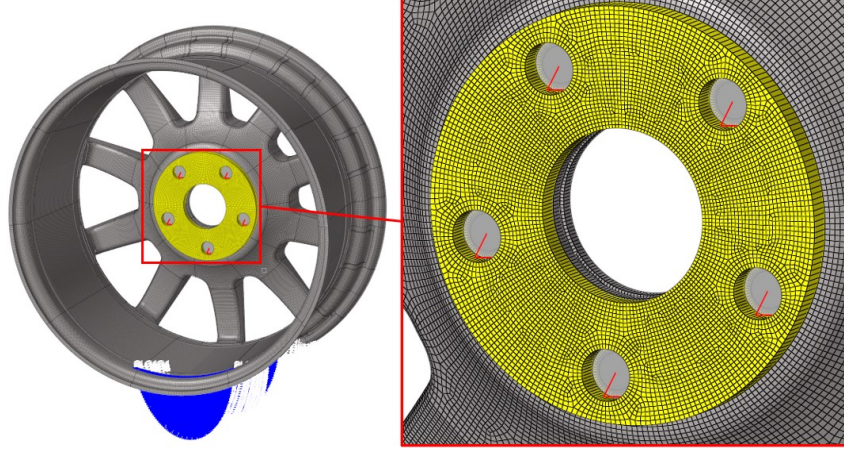


Figure 5.11 : Boundary condition of radial load case.

5.1.3 Torsion loading

The tangential forces acting on the rim during acceleration and deceleration are analyzed by the torsion test [44]. During the execution of the test, the rim is clamped, similar to the cornering load. Torque load is applied by means of fasteners located in the hub part. The test is performed by applying the M_T torsion moment.

$$M_T = KF_v r_{dyn} \quad (5.16)$$

In this equation (5.16), M_T is torsion moment [Nm], K is the acceleration test factor, F_v is the maximum vertical load [N] and r_{dyn} is the dynamic tire radius [m].

In order to solve the equation, the dynamic tire radius r_{dyn} needs to be calculated. To calculate the dynamic tire radius r_{dyn} , the theoretical rolling circumference value is divided by 2π [44].

$$r_{dyn} = \frac{C_R}{2\pi} \quad (5.17)$$

C_R the theoretical rolling circumference is calculated as [42].

$$C_R = F d_{ovr} \quad (5.18)$$

In equation (5.18), the value of F constant is 3.05 [42]. d_{ovr} is the design overall diameter.

$$C_R = 2070.95 \text{ mm} \quad (5.19)$$

The overall diameter of the design is 679 mm. Thus, the C_R value was calculated as 2070.95 mm. The dynamic tire radius is calculated using the theoretical rolling circumference value.

$$r_{dyn} = \frac{2070.95 \text{ mm}}{2\pi} \quad (5.20)$$

$$r_{dyn} = 329.6 \text{ mm} \quad (5.21)$$

The K and F_v values are 1 and 7355.25N, respectively. The torsional moment is calculated as follows,

$$M_T = 1 \times 7355.25 \text{ N} \times 329.6 \text{ mm} \quad (5.22)$$

$$M_T = 2424304 \text{ Nmm} \quad (5.23)$$

In order to simulate the torsion test, load and boundary conditions are applied to the finite element model. As in the cornering loading, the region where the clamp is applied is the region with the nodes seen in the Figure 5.12 highlighted in red. The U1, U2 and U3 degrees of freedom of these nodes are set to zero. The fasteners are modeled with RBE2 elements as in the other models and are gathered into a single node in the center of the rim. The moment to be applied is transferred to the model with RBE2 elements to be transferred from the connectors. As can be seen in Figure 5.12, the moment highlighted in blue is applied using the calculated torsional moment value M_T .

5.2 Analysis Cases Summary

The load cases and test scenarios to be considered in order to optimize the composite wheel are briefly determined as radial loading, cornering loading, and torsion loading. The results will be obtained by examining the strength of the structure under these load cases. Load conditions, loads, and load combinations are given in the Table 5.4.

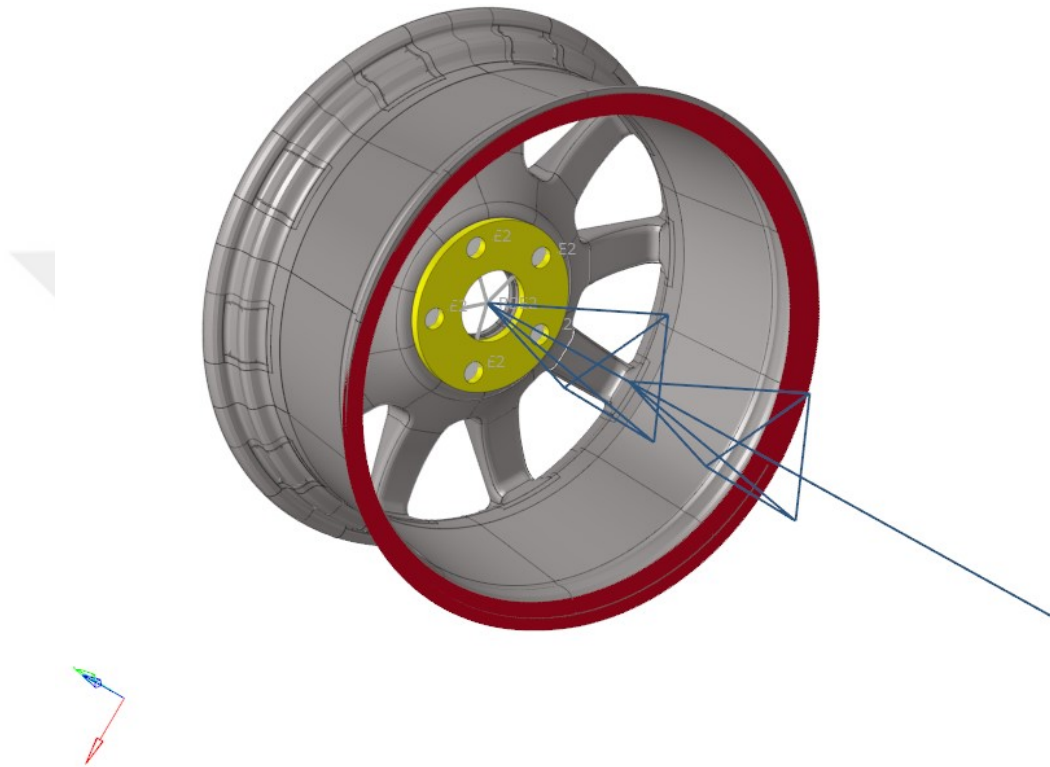
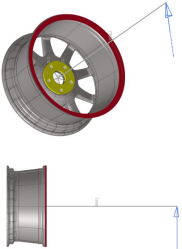
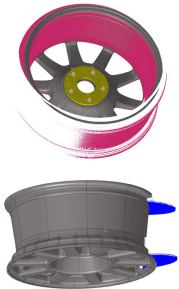
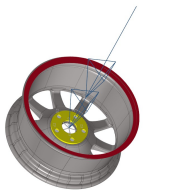


Figure 5.12 : Boundary and load condition of torsion load case.

Table 5.4 : Load case summary table.

Load Case	Representation	Magnitudes
Cornering Load Case		$M_C = 1868\text{Nm}$
Radial Load Case		$P_\theta = 4.2 \cos\left(\frac{\theta}{0.2254}\right) \text{MPa}$ $P_i = 0.55\text{MPa}$
Torsion Load Case		$M_T = 2424304\text{Nmm}$

5.3 Material

There are two kinds of materials in the automotive wheel rim world. These are metallic and composite materials. Carbon fiber reinforced prepreg material with high strength was used as the composite material type. Especially when choosing from metallic structures, titanium alloy metallic structures were preferred by considering their compatibility with carbon fiber reinforced structures.

5.3.1 Carbon fiber reinforced prepreg

As it is known, there are two types of prepreg composite materials: unidirectional and fabric. In unidirectional prepreg materials, although the strength is high in the fiber direction, the strength in the direction perpendicular to the fiber direction is very low compared to the fiber direction. In fabric preregs, on the other hand, since there is fiber orientation in two directions, strength is provided in both directions. There are differences in strength values according to fabric types.

The two prepreg types mentioned have advantages and disadvantages compared to each other. Fabric structures are more advantageous, especially in cases with complex surfaces and where the prepreg will be exposed to bending and distortion during production. Since there is no carrier other than resin in unidirectional fiber arrays perpendicular to the fiber direction, difficulties will arise in the production of structures with such complex surfaces. Prepreg cure ply thickness values are much smaller in unidirectional prepreg materials. Thus, it will be possible to obtain lighter structures with less ply numbers. However, since it is unidirectional, it is possible to line up in many different directions between 0 and 180 degrees. This will generate many variations for the optimization work to be done.

Fabric prepreg material was used in order to be more suitable for the carbon fiber wheel geometry to be optimized and to reduce the number of variables that will come from the material. As for the carbon fiber fabric type, plain weave type material with similar elastic and strength values in 0 and 90 degree orientations was chosen. The material

to be used for this purpose was chosen as TORAY T700SC-12-50C/2510 Plain Weave Fabric. Material properties of prepreg used in the study are shown in Table 5.5.

Table 5.5 : TORAY T700SC-12-50C/2510 material properties in elevated temperature wet condition [45].

	Material Property	Value
E_{11}	Elastic Modulus 11 [MPa]	56640
E_{22}	Elastic Modulus 22 [MPa]	54445
ν_{12}	Poisson Ratio 12	0.029
G_{12}	Shear Modulus 12 [MPa]	3172
ρ	Density [tonne/mm ³]	1.6347E-9
F_{11}^{tu}	Tension Stress Limit 11 [MPa]	979
F_{22}^{tu}	Tension Stress Limit 22 [MPa]	781
F_{11}^{cu}	Compression Stress Limit 11 [MPa]	404
F_{22}^{cu}	Compression Stress Limit 22 [MPa]	430
F_{12}^{su}	Shear Stress Limit [MPa]	70
F_{13}^{su}	Bonding Shear Stress Limit [MPa]	55

5.3.2 Material modeling

The MAT8 orthotropic material card was used to create the material model and assign its parameters. Orthotropic material properties are assigned to shell elements using the MAT8 card. With this card, the mechanical properties which are E_{11} , E_{22} , ν_{12} , G_{12} , ρ , and strength properties which are F_{11}^{tu} , F_{22}^{tu} , F_{11}^{cu} , F_{22}^{cu} , F_{12}^{su} of the prepreg material are defined. The material mechanical properties and strength properties defined here are fixed and unchangeable parameters in the optimization study. As it is known, there is no need for density information in static analyzes to be made. However, since weight will be a parameter in the optimization study, this information has been recorded on the material card.

With the definition of the prepreg material behavior with the MAT8 card; It is provided to use the defined features in the PCOMP element card, where the orientation and sequences of the defined features will be defined. The PCOMP element card is generally defined as a data card that describes the properties of a composite laminate with n plies [46].

The data to be included in this Table 5.6 are; PID value is property identification number, Z0 is offset value from reference geometry surface, NSM is nonstructural

Table 5.6 : PCOMP laminate definition data block [46].

PCOMP	PID	Z0	NSM	SB	FT
	MID1	T1	THETA1	SOUT1	
	MID2	T2	THETA2	SOUT2	
	...	...	...	...	

mass, SB is the allowable of inter-laminar property which is F_{13}^{su} of the material. FT is failure theory. In Nastran, only Hill, Hoffman, Tsai-Wu and Maximum Strain failure theories are applicable. These specified parameters are fixed values to be defined with reference to the material and geometry [46].

The MID (Material Identification Number), T and THETA parameters specified in the Table 5.6 are the parameters to be defined for each ply. SOUT for each ply is stress or strain output request of the analysis. The parameter value of SOUT is specified as YES for all PCOMP definitions. MID parameter is material identification parameter. This parameter is the identification number of the previously created MAT8 material card for all ply layers. T is the thickness of ply. T value is the cure ply thickness value for each prepreg material. T parameter can be considered as a variable that also defines the strength of that ply for each layer. THETA is the parameter that defines how much angle the prepreg lamina will make with respect to a reference coordinate system, whose mechanical properties are defined by MAT8. In short, it is the angle that each ply makes with respect to a certain coordinate. In this optimization study, the ply thickness T and the ply orientation THETA in the definition of PCOMP were used as optimization parameters.

5.3.3 Rosette definition

Rosette generally refers to the coordinate system to be referenced for the orientation of each ply in a composite laminate. In flat plates, when layup is performed according to a determined coordinate system, each ply takes shape by adhering to the reference coordinate system throughout the layup. However, it can be predicted that rosettes to be determined in complex structures such as rims will not be able to follow the reference coordinate system during layup due to the complex shape of the rim. In order to prevent this behavior, different PCOMP element cards have been created on

the rim, especially for the regions where distortion may occur due to its shape or ply drop off in the layup sequence.

PCOMP groups were created on the rim model in order to define the rosette and possible ply drop off regions as parameters for the analysis. As seen in Figure 5.13, many PCOMP zones have been created on the composite rim and the areas that will change the rosette and ply layup have been determined. In Figure 5.14, main rosetta system per main rim section can be seen.

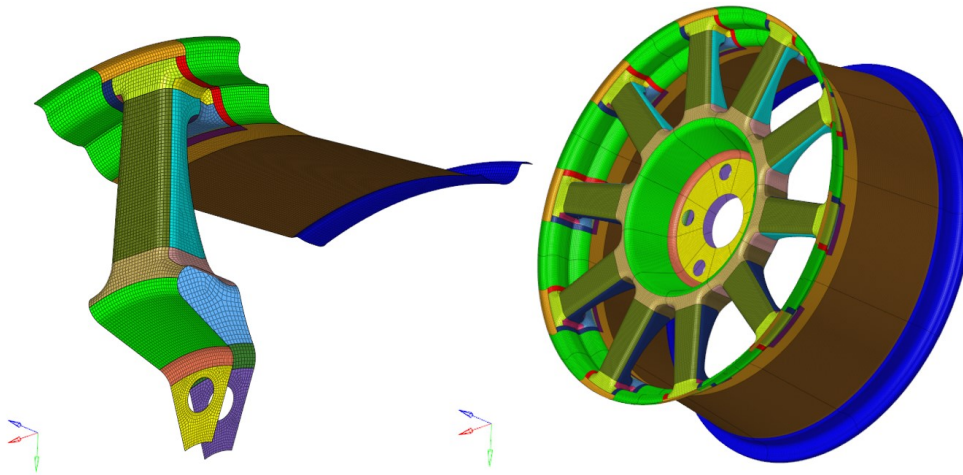


Figure 5.13 : PCOMP zones of composite rim model.

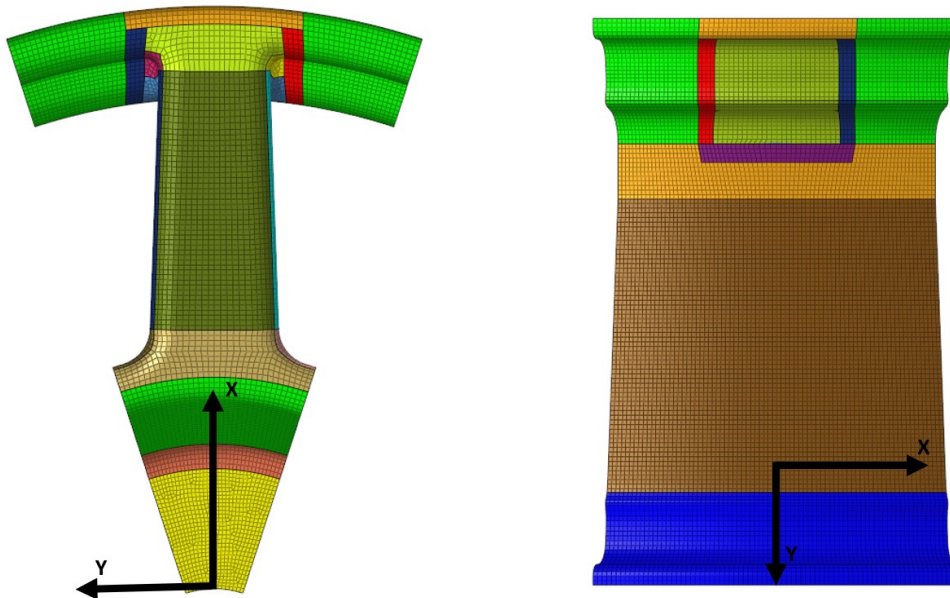


Figure 5.14 : Main rosette systems of the model.

The main orientation coordinates are referenced for each PCOMP region. Especially due to curved surfaces, the material cannot follow the reference coordinate system. Therefore, these surfaces are also defined as separate PCOMP. Definitions have been made in the direction that the prepreg material will follow with the laying. The defined material orientations in the x direction are shown in the Figure 5.15 with black lines.

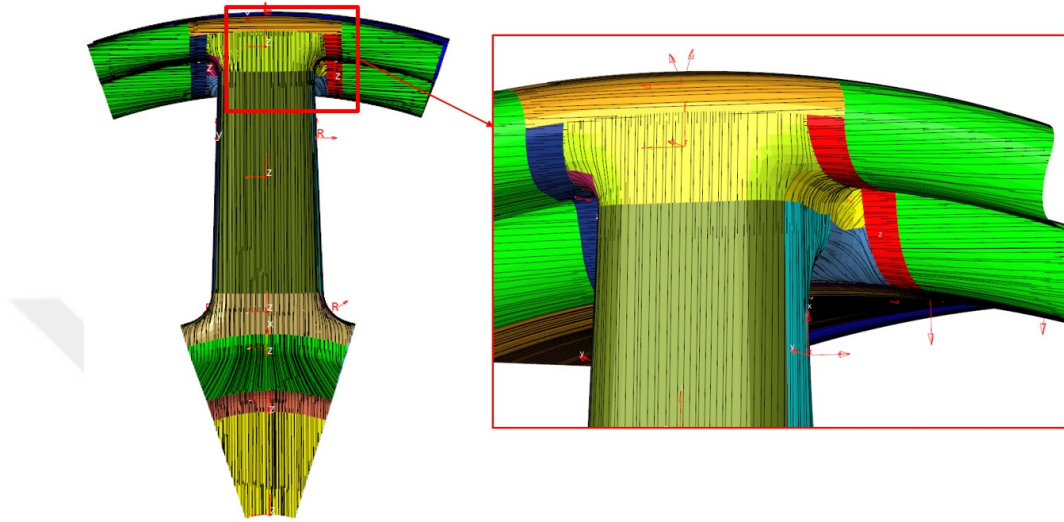


Figure 5.15 : Local rosette systems and x directions of PCOMP zones.



6. OPTIMIZATION STUDY

Composites allow lighter products to be created by taking advantage of directional strength compared to isotropic materials. Especially when considering an automotive rim, it is desired that this product should be durable as well as light. Strength and lightness are two fundamentally opposite concepts. These opposite concepts create an environment for optimization.

Although production factors and quality are involved in the strength of composite structures, there are basic components to ensure strength in composite laminate structures with prepreg material. The most important of these components are the number of plies in the laminate and the orientation of each ply. Especially in fabric prepreg materials, the number of layers greatly affects the strength, and the optimum laminate structure is obtained by determining the orientation of these layers.

The optimization study was carried out with the help of software called ModeFrontier. With the ModeFrontier software, various software and steps are defined as processes and design solutions are obtained. Optimization algorithms are provided through the ModeFrontier software. The relevant optimization process is controlled by the software.

6.1 Selection of Optimization Parameters

6.1.1 Selection of layup regions

In order to carry out the optimization study, it is important to determine the composite layup regions that will differentiate the composite. For this purpose, it is important to separate the zones that have different basic loading principles on the composite rim and that have geometrical risks.

Different colors in the Figure 6.1 represent different layup regions. The center region, coded as NB_500, is a region that has an interface with metallic plates and bolts.

For this reason, an assumption has been made that the lower and upper surfaces are symmetrical and provide the same arrangement.

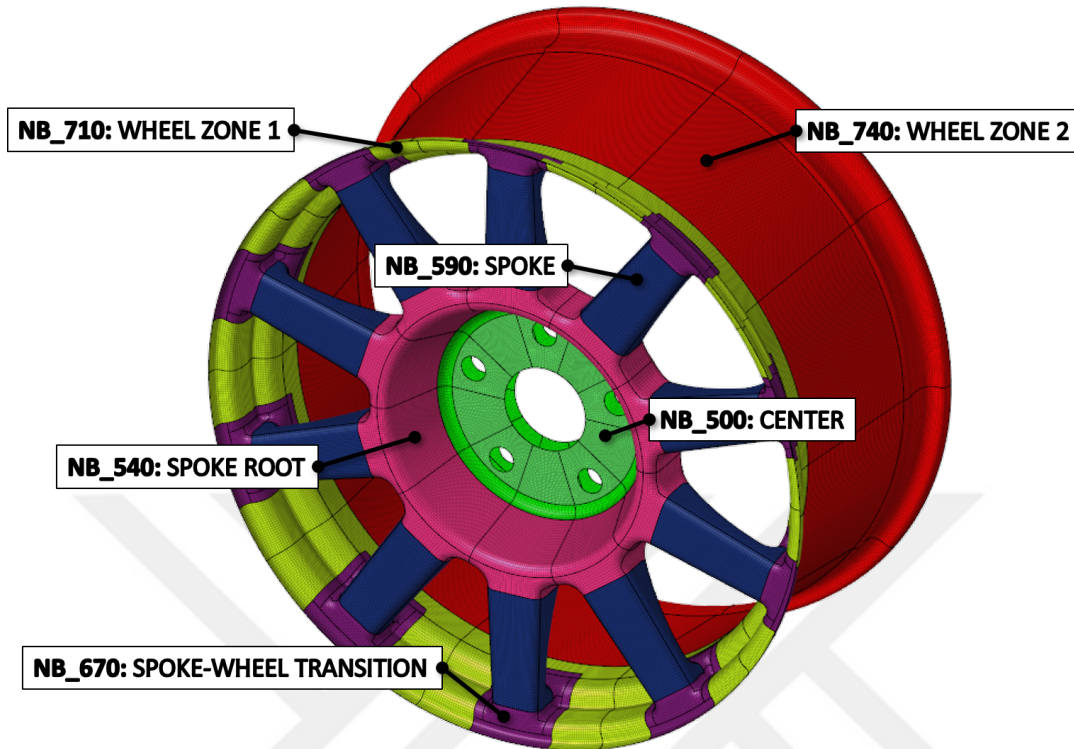


Figure 6.1 : Different layup regions to be optimized.

The pink region coded as NB_540 is the transition region between the spoke and the center. It has a complex shape to realize the required design volume, especially for the spoke area. It needs to be differentiated at the sizing stage.

The blue area coded as NB_590 is reserved for spoke sizing. This region, which operates mostly in bending and radial loads, is also an optimization region.

The region coded as NB_670 was created to size the transition region between the spoke and the wheel. This region, which contains many PCOMP cards, has been chosen by assuming that the plies coming from the spoke and wheel directly stick on top of each other.

Wheel area is divided into 2 different zones. In the region wheel zone 1 coded as NB_710, it is a region reserved for determining the layup transition and sequence after

the spoke transition. The wheel zone 2, coded as NB_740, is the zone of the rim reserved for carrying the main loads.

6.1.2 Selection of orientation variation

Prepreg composites in plain wave fabric structure show similar strength properties in the axis perpendicular to the main direction. In fabric structures, a ply laid in the 0 direction can also provide the strength in the 90 degree direction. Therefore, all angular variations between 0 and 90 degrees cover other orientation possibilities.

In many different industrial sectors, prepreg material orientations are evaluated to produce different products. Generally; 0, 45 and 90 degree directions are taken into account when designing with fabric prepreg materials. These are the orientations that are frequently used, especially in the aviation industry.

Minor changes in the orientation angle are challenging and unrealistic in terms of production. It is assumed that the orientation can be changed in 45-degree steps during the production phase. In the optimization study, the ply orientation was changed at 45 degree intervals to cover the 0 to 135 degree directions. In the Table 6.1, input parameter definition is shown.

Table 6.1 : Orientation variation definition.

Variable	Upper Bound	Lower Bound	Base	Step
Orientation	135	0	4	45

6.1.3 Selection of layup variation

In the optimization study, the maximum material layup configuration was studied in order to apply the symmetrical boundary condition in laminate plates. The basis of this idea is the behavior of a continuous ply that will follow the whole structure. In the case of maximum material, the red region shown in Figure 6.2 can be thought of as a combination of two yellow regions. In the case of maximum material, the laminate $[P0/P1/P2/P3/P4/P5/P6/P7/P8/P9]_S$ consisting of a total of 20 ply shown in yellow and the yellow laminate $[P0/P1/P2/P3/P4/P5/P6/P7/P8/P9]_S$ on the wheel combine to form the laminate structure $[P0/P1/P2/P3/P4/P5/P6/P7/P8/P9]_{2S}$ shown in red.



Figure 6.2 : Input parameters for layup.

Thus, the whole structure will be revealed by specifying only 10 ply orientations. At the same time, it will be ensured that the laminate layer can remain in a symmetrical state.

Considering the reference orientation system, it is known that it will vary depending on whether the structure is on the body or on the wheel, as mentioned before. For example, when we consider the P0 ply, it is understood that Ply 0 rotates 90 degrees as it passes from the yellow region to the red region. For this reason, an orientation modifier of 90 degrees should be defined in addition to the PCOMP patches in the structure.

6.1.4 Parametrization of ply numbers

By obtaining the orientation parameters for 10 different plies, the structure that will provide the strength of the entire rim will be obtained. However, another parameter is the variability associated with increasing and decreasing the ply numbers per PCOMP laminate.

It is ensured that there are different ply numbers for 6 different zones determined in the structure. Thus, the minimum amount of material required is obtained. The mentioned regions are shown in the Figure 6.2.

Variations can be obtained in the [P0/P1/P2/P3/P4/P5/P6/P7/P8/P9] sequence, with each ply thickness being 0 (absent) or 1 (present). A ply's presence or absence value is an independent choice for each zone. However, since the continuity and symmetry of the ply are controlled by the rules in maximum material definition, the continuity of the structure and its production logical results are ensured.

The optimization parameter is defined when the ZO parameter, which is in the PCOMP material property and mentioned in the material modeling section in 3.3.2, takes a value very close to 0 or a CPT (Cure Ply Thickness) value.

6.2 Analysis of Maximum Material Design

6.2.1 Laminate property definition

Before the optimization study, analyzes were made under the determined maximum material and load conditions. For this purpose, a laminate is defined as 40 ply in the rim region shown in red and 20 ply in the yellow region in Figure 6.2.

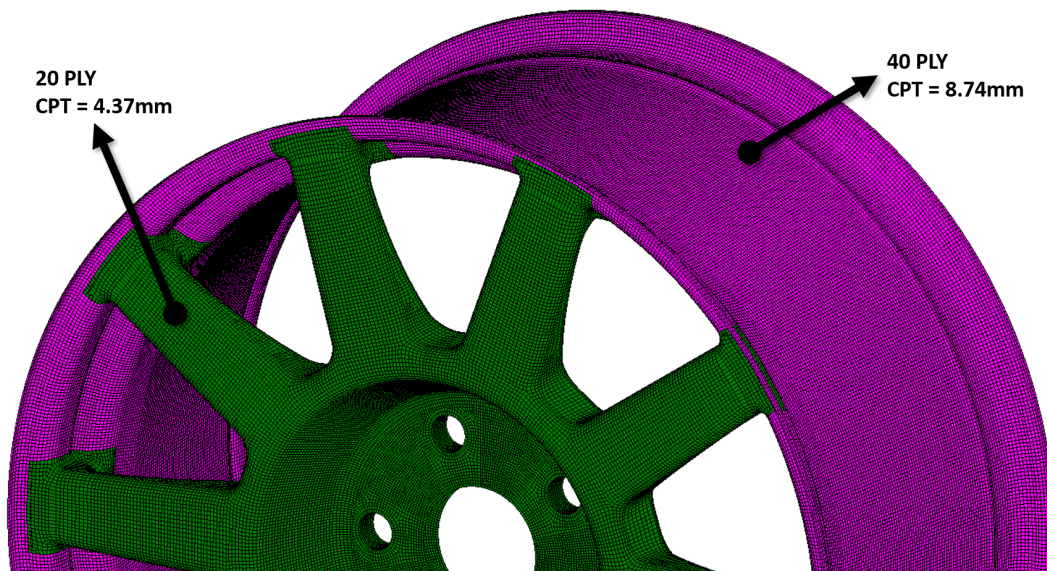


Figure 6.3 : Maximum material condition laminate thicknesses.

Each ply has a 0.218 mm cure ply thickness. There are two different laminate thicknesses available, shown in the Figure 6.3 in green and purple. The hub and spoke parts of the rim, which have a hollow design, can take a thickness of 4.37 mm in the case of maximum material and are painted green in the Figure 6.3. In the purple region, the laminates coming from the spokes unite in the case of maximum material. This region has 40 ply and a maximum thickness of 8.74 mm.

	Material Name	Thickness	Orientation
1	TORAY_T700SC-12-50C	2.184400E-1	9.000000E+1
2	TORAY_T700SC-12-50C	2.184400E-1	4.500000E+1
3	TORAY_T700SC-12-50C	2.184400E-1	9.000000E+1
4	TORAY_T700SC-12-50C	2.184400E-1	4.500000E+1
5	TORAY_T700SC-12-50C	2.184400E-1	9.000000E+1
6	TORAY_T700SC-12-50C	2.184400E-1	0.000000E+0
7	TORAY_T700SC-12-50C	2.184400E-1	4.500000E+1
8	TORAY_T700SC-12-50C	2.184400E-1	4.500000E+1
9	TORAY_T700SC-12-50C	2.184400E-1	0.000000E+0
10	TORAY_T700SC-12-50C	2.184400E-1	9.000000E+1
11	TORAY_T700SC-12-50C	2.184400E-1	9.000000E+1
12	TORAY_T700SC-12-50C	2.184400E-1	0.000000E+0
13	TORAY_T700SC-12-50C	2.184400E-1	4.500000E+1
14	TORAY_T700SC-12-50C	2.184400E-1	4.500000E+1
15	TORAY_T700SC-12-50C	2.184400E-1	0.000000E+0
16	TORAY_T700SC-12-50C	2.184400E-1	9.000000E+1
17	TORAY_T700SC-12-50C	2.184400E-1	4.500000E+1
18	TORAY_T700SC-12-50C	2.184400E-1	9.000000E+1
19	TORAY_T700SC-12-50C	2.184400E-1	4.500000E+1
20	TORAY_T700SC-12-50C	2.184400E-1	9.000000E+1

Set Thickness = for ALL Layers of "TORAY_T700SC-12-50C"
Total Thickness in Stacking Sequence = 4.3688006 Plies in Stacking Sequence = 20

Figure 6.4 : Laminate definition for 20 ply region.

A laminate definition made on MSC Patran can be seen in the Figure 6.4. In the maximum material condition parameterized as $[P0/P1/P2/P3/P4/P5/P6/P7/P8/P9]_S$, all plies are present and have an orientation. In the maximum material run, the orientation given to the input parameters is $[90/45/90/45/90/0/45/45/0/90]_S$. Similarly, in the thick purple region, a ply orientation array in the form of $[90/45/90/45/90/0/45/45/0/90]_{2S}$ was performed.

6.2.2 Failure criteria

Tsai-Wu criterion is used as a failure criterion. According to this criterion, the Tsai-Wu failure index value is expected to have a value less than 1. The equation of Tsai-Wu failure criteria is given in equation 6.1. Failure criteria were defined with allowable

values of TORAY T700SC-12-50C using MSC Patran software. Figure 6.5 shows the patran material definition interface and the criteria definition section.

$$\begin{aligned}
 &F_1\sigma_{11} + F_2\sigma_{22} + F_3\sigma_{33} + F_4\tau_{23} + F_5\tau_{31} + F_6\tau_{12} + F_{11}\sigma_{11}^2 + F_{22}\sigma_{22}^2 \\
 &+ F_{33}\sigma_{33}^2 + F_{44}\tau_{23}^2 + F_{55}\tau_{31}^2 + F_{66}\tau_{12}^2 \\
 &+ 2F_{12}\sigma_{11}\sigma_{22} + 2F_{13}\sigma_{11}\sigma_{33} + 2F_{23}\sigma_{22}\sigma_{33} \leq 1
 \end{aligned} \tag{6.1}$$

Property Name	Value
Tension Stress Limit 11 =	979.
Tension Stress Limit 22 =	781.
Compress Stress Limit 11 =	404.
Compress Stress Limit 22 =	430.
Shear Stress Limit =	70.
Interaction Term =	
Bonding Shear Stress Limit =	55.

Temperature Dep/Model Variable Fields:

Current Constitutive Models:

Linear Elastic - [,,,] - [Active]
 Failure - [Stress,Tsai-Wu,,,] - [Active]

Figure 6.5 : Allowable definition for Tsai-Wu failure criterio on MSC Patran.

6.2.3 Composite analysis results

Maximum material design was obtained with the models specified in Chapter 5 and analysis results were obtained. Displacement and stress results were requested as output requests to be used in the optimization study. In composite analyzes, results were requested with PARAM, NOCOMPS, 0 parameter, thus ply-based results were obtained. Likewise, with the Tsai-Wu failure criterion definition specified in the Figure 6.5, the failure index result was requested.

In the model to be used during the optimization study, there are differences in the solution time depending on the number of elements desired. In addition, as the number of desired elements increases, the size of the op2 file, which is the result file, also

increases. Since thousands of results are planned during the optimization, the size of the model output file and the information it contains are expected to be optimally efficient. For this reason, it would be a logical decision to take the 1/10 rim portion, which is known to have the worst results in all load cases. In the Figure 6.6, a 1/10 rim portion is seen with its coloring, which also expresses the thickness change in case of maximum material.

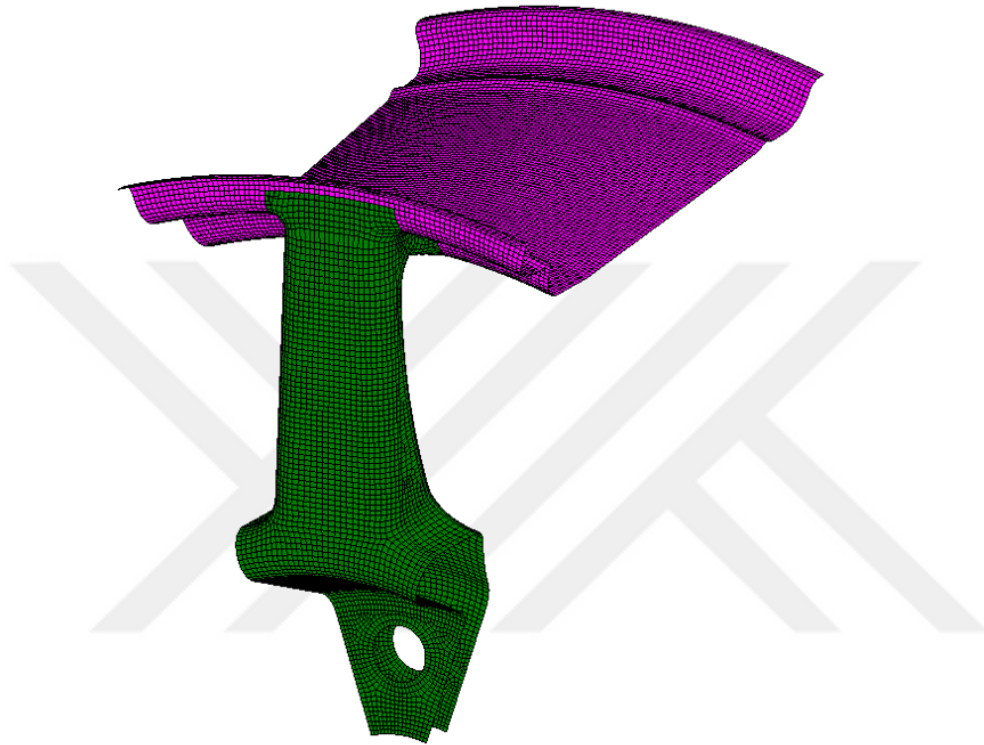


Figure 6.6 : 1/10 portion of composite rim different thickness regions.

6.2.3.1 Radial loading results

Under radial loading, ply failure indice results were obtained as in Figure 6.7 when maximum ply number was applied. Also, the maximum displacement results are given in the Figure 6.8.

When the results were examined, as expected, maximum failure indice and displacement were observed at the tip of the wheel under radial load. A displacement of 1,565 mm was observed at the maximum ply condition at the free end where the hub part of the wheel was not attached. In the same region, the maximum ply failure index value of 0.15 was obtained.

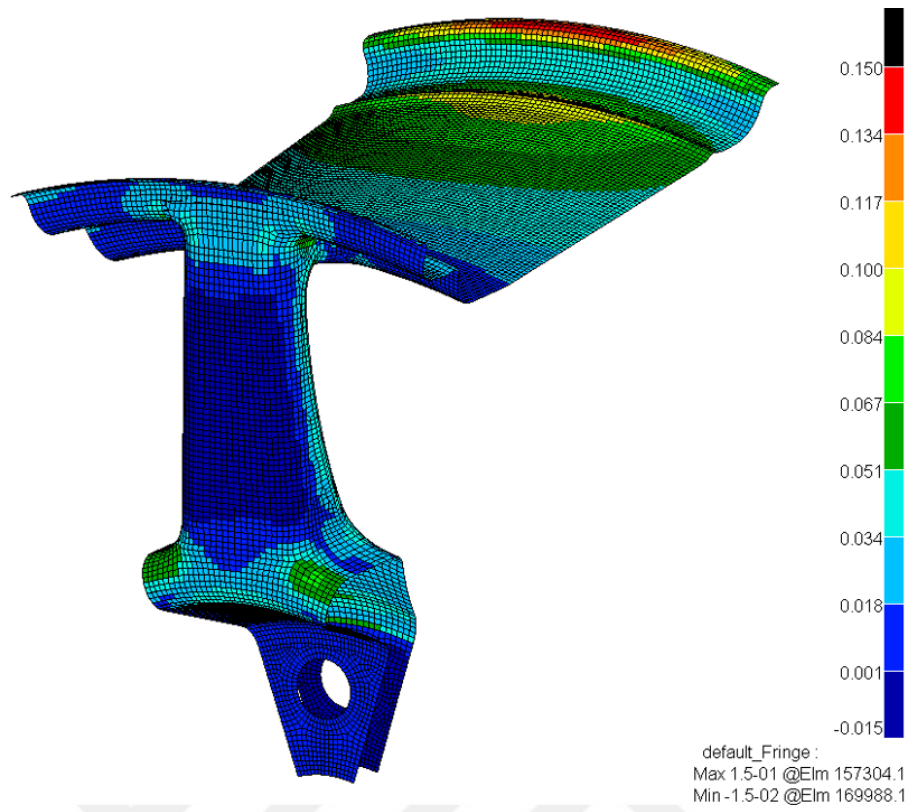


Figure 6.7 : Maximum ply failure indice in radial loading.

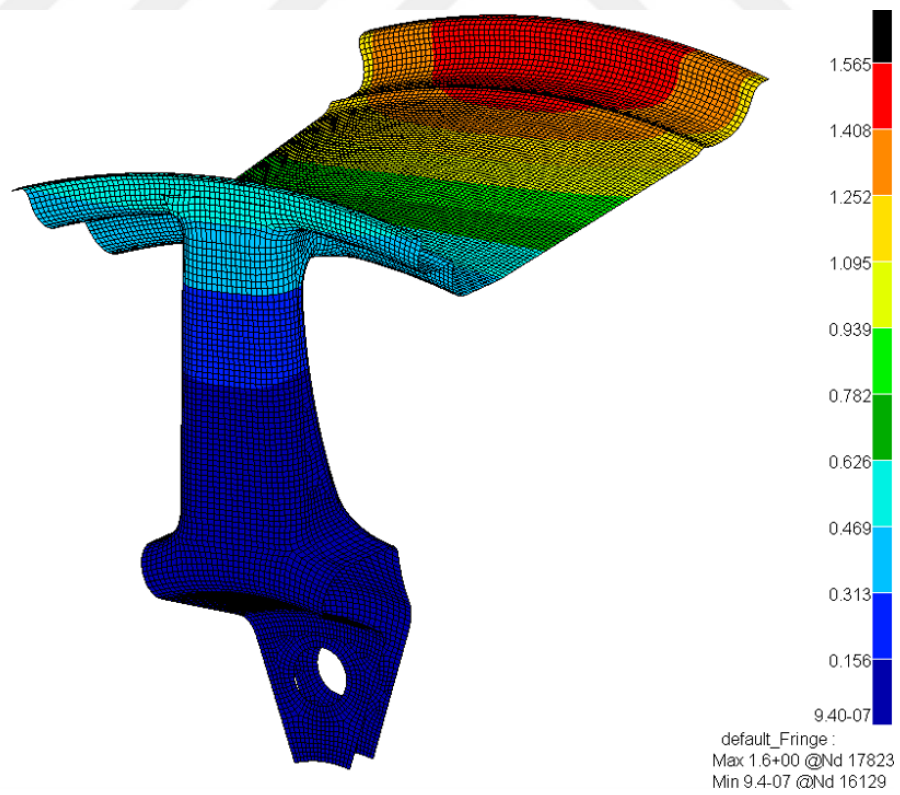


Figure 6.8 : Maximum displacement in radial loading.

6.2.3.2 Cornering loading results

Under cornering loading, ply failure indice results were obtained as in Figure 6.9 when maximum ply number was applied. Also, the maximum displacement results are given in the Figure 6.10.

When the results were examined under the cornering loading, higher failure indice values were obtained at the connector edge under the effect of the load applied from the hub region. Due to the high bending deformation in the hub region, the maximum displacement appeared in this region. A maximum displacement value of 0.266 mm was obtained and a failure indice value of 0.218 was found at the fastener edge.

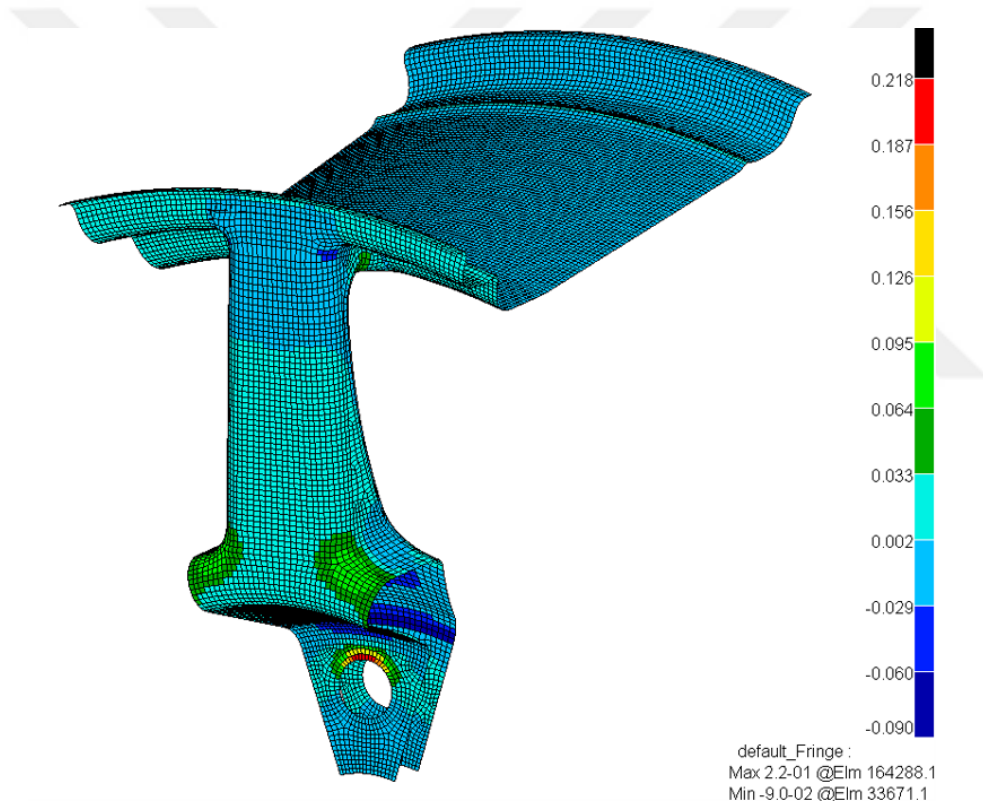


Figure 6.9 : Maximum ply failure indice in cornering loading.

6.2.3.3 Torsion loading results

Under torsion loading, ply failure indice results were obtained as in Figure 6.11 when maximum ply number was applied. Also, the maximum displacement results are given in the Figure 6.12.

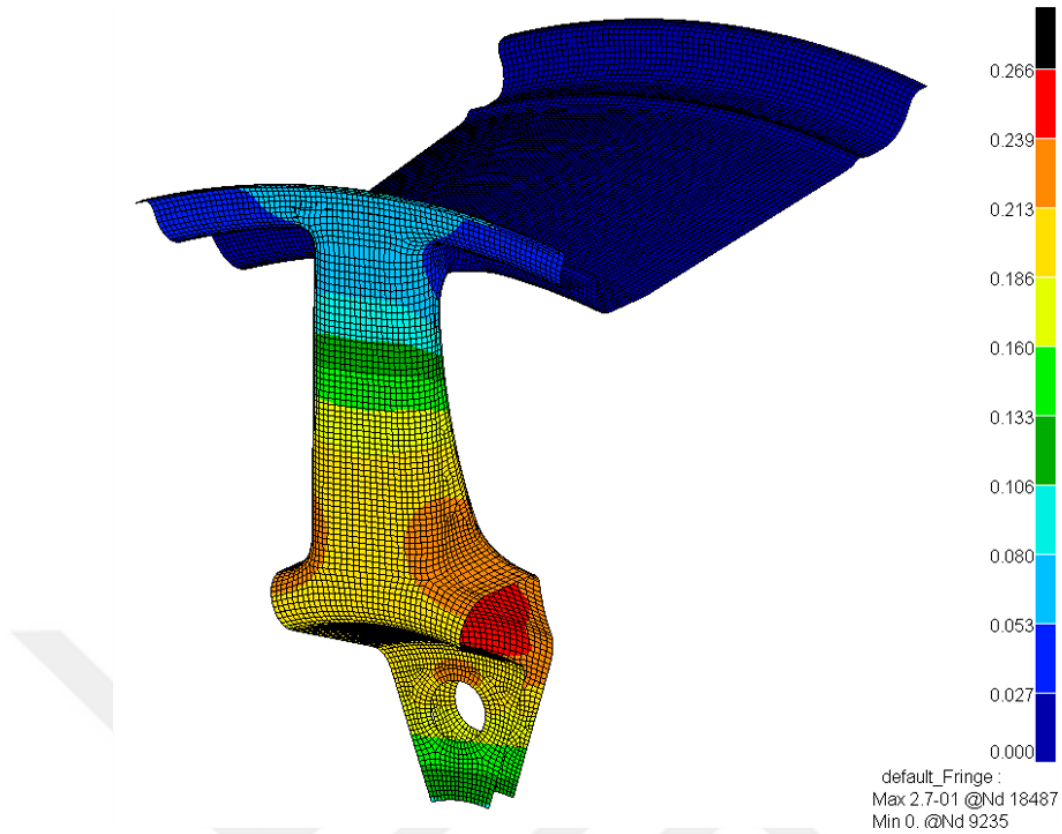


Figure 6.10 : Maximum displacement in cornering loading.

As expected under torsion loading, the ply failure index was higher in the spoke root region. Spoke roots are counter loaded by the effect of torsion. As expected, the maximum displacement was seen in the root part close to the central hub, and a displacement of 0.088 mm was calculated. The maximum ply failure indice value was calculated as 0.047 at the spoke root.

6.3 Optimization Process

ModeFrontier interface and capabilities are used to realize the optimization process. The workflow can be divided into three main sections. These are input parameters, process control and output parameters. The diagram created on the software and the three main sections specified are shown in Figure 6.13.

The input parameter is the section that contains the independent variables in the optimization. It is also the section where symmetrical arrangements and orientation modifications are made.

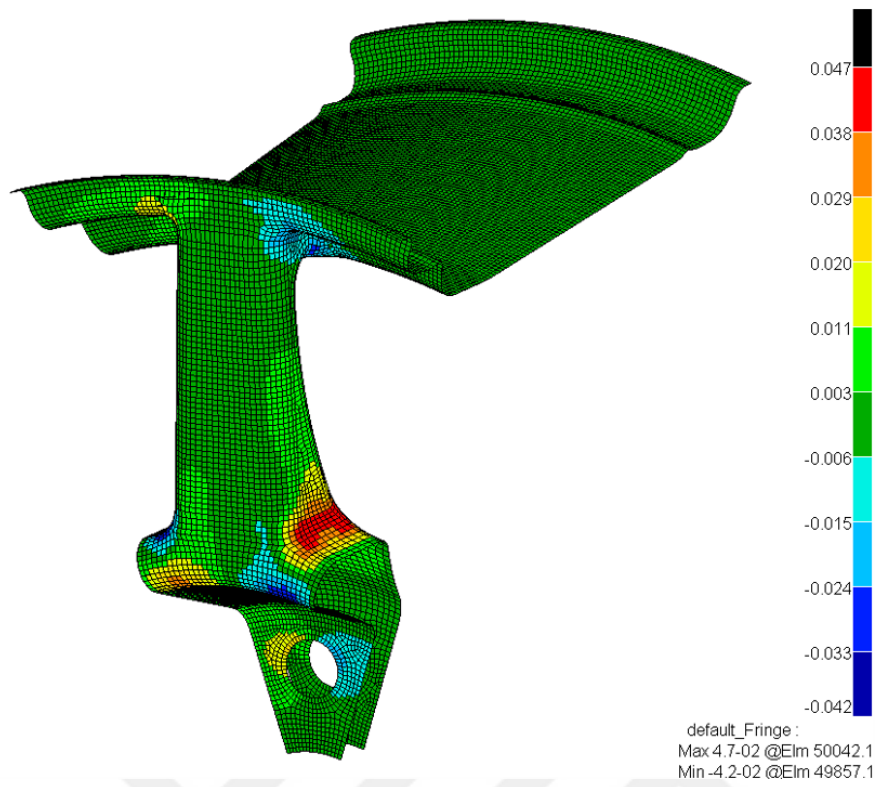


Figure 6.11 : Maximum ply failure indice in torsion loading.

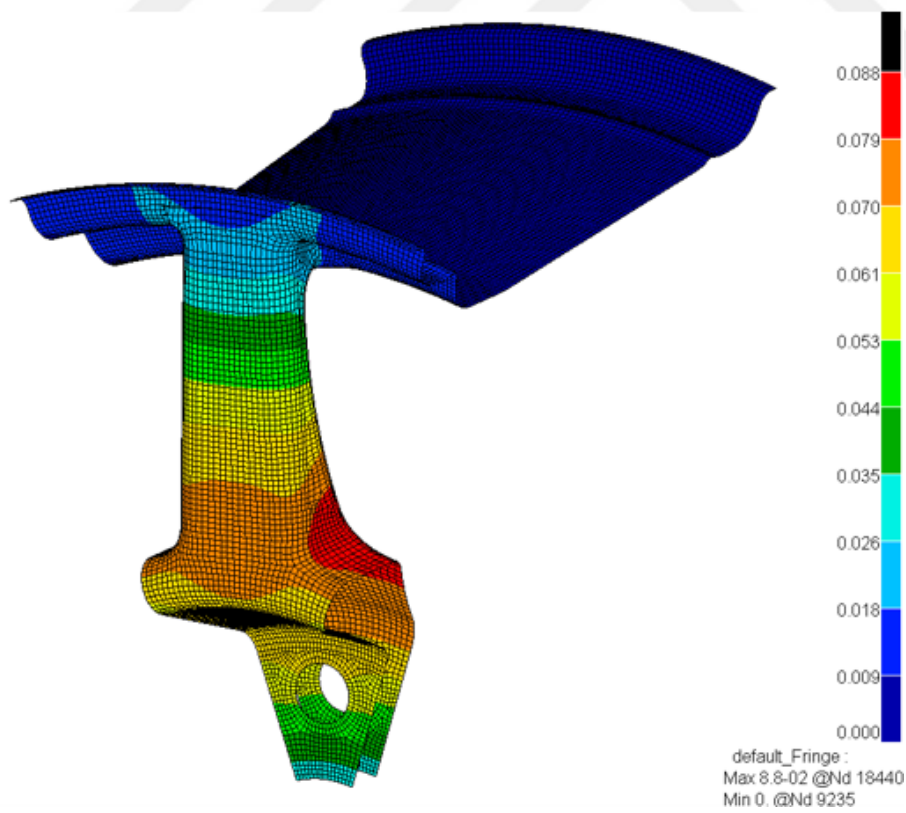


Figure 6.12 : Maximum displacement in torsion loading.

The process control section is the section that controls the optimization process. It ensures that the filing system is set up properly. Data transfer between files is performed. Patran and Nastran software are run here.

Output parameters are collected after each analysis in the output parameters section and processed according to the objective function.

6.3.1 Input parameters

Variable parameters are defined in the input parameters section. This region can be basically divided into two parts. These are the regions that provide the orientation diversity and the variability of whether the continuous ply will be in the relevant region.

In the region containing the orientation input parameters shown in the blue area in the Figure 6.14; there is an orientation modifier for the wheel part of the rim.

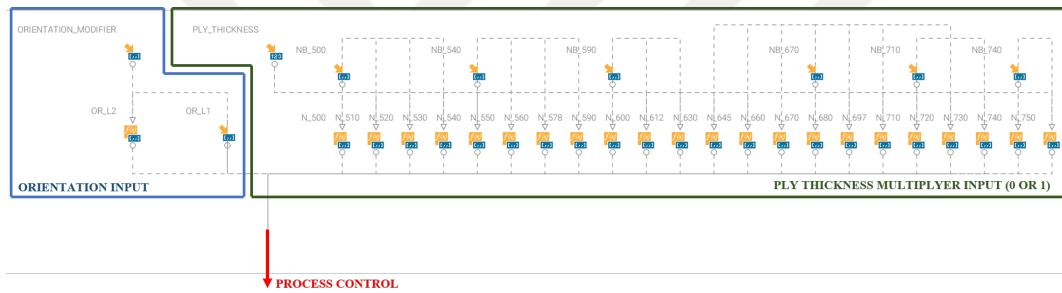


Figure 6.14 : Input parameters in optimization process.

The parameters called OR_L1 and OR_L2 are the two main parts manipulated with this modifier. OR_L1 defines the center part of the rim, while OR_L2 is the component that defines the wheel part of the rim. The details of the region are given in the Figure 6.15.

OR_L1 and OR_L2 are vectors. They contain one component for each ply. Vectors contain ten components, since there can be ten plies that will allow us to obtain the whole structure. The variable components in the OR_L1 vector and their values are given in the Table 6.2.

In the Ply thickness multiplier section, there are 7 main regions consisting of NB_500, NB_540, NB_590, NB_670, NB_710 and NB_740. The regions are shown in the Figure 6.1. Ply thickness is given as a constant value. However, the important thing here is to evaluate the presence or absence of this thickness value. The value of 1 or

0 is multiplied by the ply thickness value and defined for the relevant patches in the model. The scheme of this process is shown in the Figure 6.16.

The variable parameters of the six main variable laminate zones are the same. There are presence or absence parameters for each of the ten plies. Since it is not possible for the thickness value to be 0 in the PCOMP material card, a very small number value was entered. The parameterization of the components of the variable vector of one of the six different regions is given in the Table 6.3.

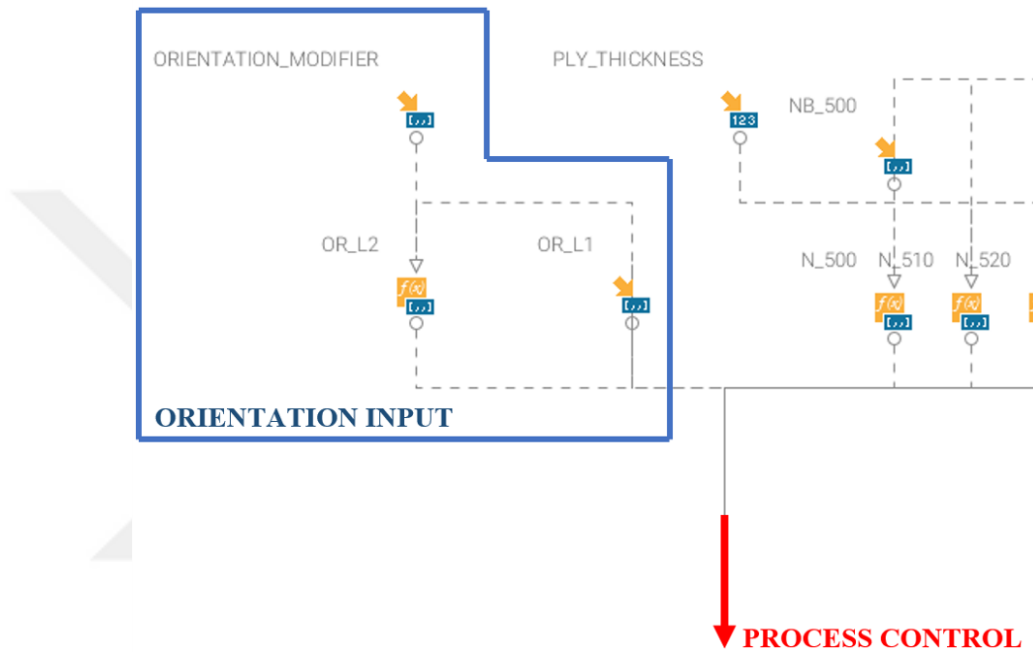


Figure 6.15 : Orientation input parameters in optimization process.

Table 6.2 : Layup orientation input parameters.

No	Type	Lower Bound	Upper Bound	Base	Step
0	Discrete Unordered	0	90	7	15
1	Discrete Unordered	0	90	7	15
2	Discrete Unordered	0	90	7	15
3	Discrete Unordered	0	90	7	15
4	Discrete Unordered	0	90	7	15
5	Discrete Unordered	0	90	7	15
6	Discrete Unordered	0	90	7	15
7	Discrete Unordered	0	90	7	15
8	Discrete Unordered	0	90	7	15
9	Discrete Unordered	0	90	7	15

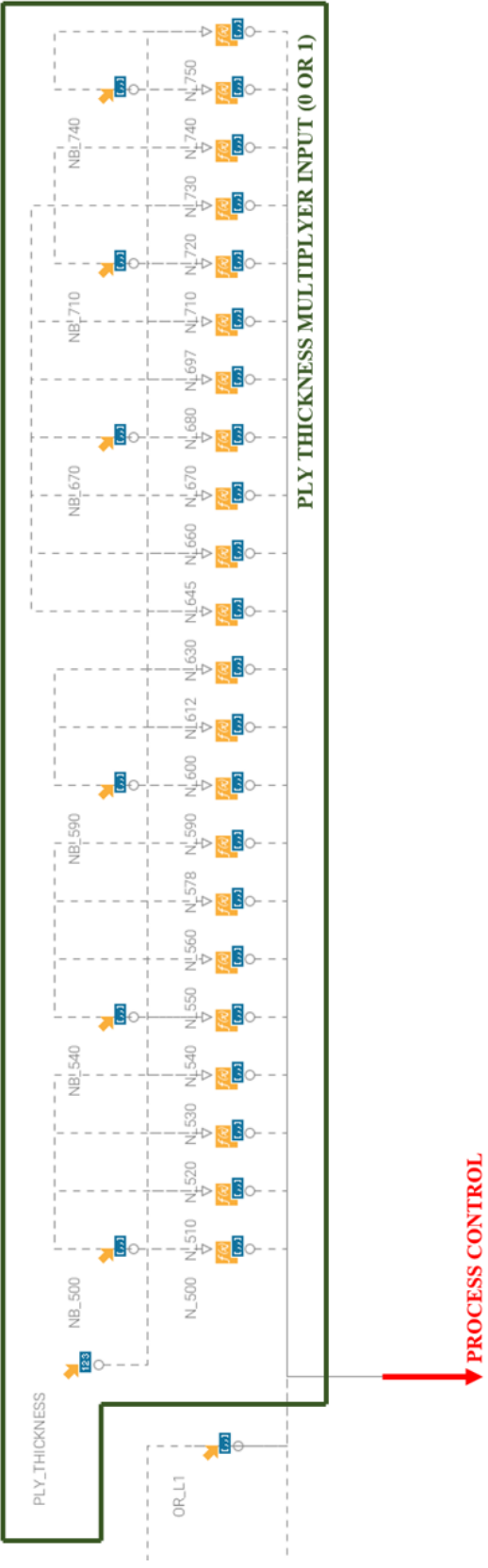


Figure 6.16 : Input parameters of ply occurrence in optimization process.

Table 6.3 : Input parameter definition of ply occurrence.

No	Type	Lower Bound	Upper Bound	Base	Step
0	Discrete Unordered	0.000001	1	2	0.999999
1	Discrete Unordered	0.000001	1	2	0.999999
2	Discrete Unordered	0.000001	1	2	0.999999
3	Discrete Unordered	0.000001	1	2	0.999999
4	Discrete Unordered	0.000001	1	2	0.999999
5	Discrete Unordered	0.000001	1	2	0.999999
6	Discrete Unordered	0.000001	1	2	0.999999
7	Discrete Unordered	0.000001	1	2	0.999999
8	Discrete Unordered	0.000001	1	2	0.999999
9	Discrete Unordered	0.000001	1	2	0.999999

Input parameters are written into a session file that will edit the Patran FE model for each solution. The parameters set in the input zone are ready to pass into the process control zone.

6.3.2 Process control

After defining each design solution trial, this information is transferred to the process control area. This region is also the section where the optimization process is managed. The folder management in the optimization process is done in this region.

The process control area can be divided into three main components. One of these is "preprocessing" in which the defined design parameters will be edited to create the Nastran input file. "Run", which is the region where the solution will be taken using Nastran, will take the most time. Finally, in the "postprocessing" section, necessary data is generated from the OP2 output files. The process control zone flow chart is given in Figure 6.17.

MSC Patran is a software that can be encoded with session extension files. In the preprocessing area, the parameters coming from the input parameters section are collected in a file named Laminate Session. In addition to this session file, there is a file named material session. The material session file contains the prepreg mechanical properties to be defined in the PCOMP material card.

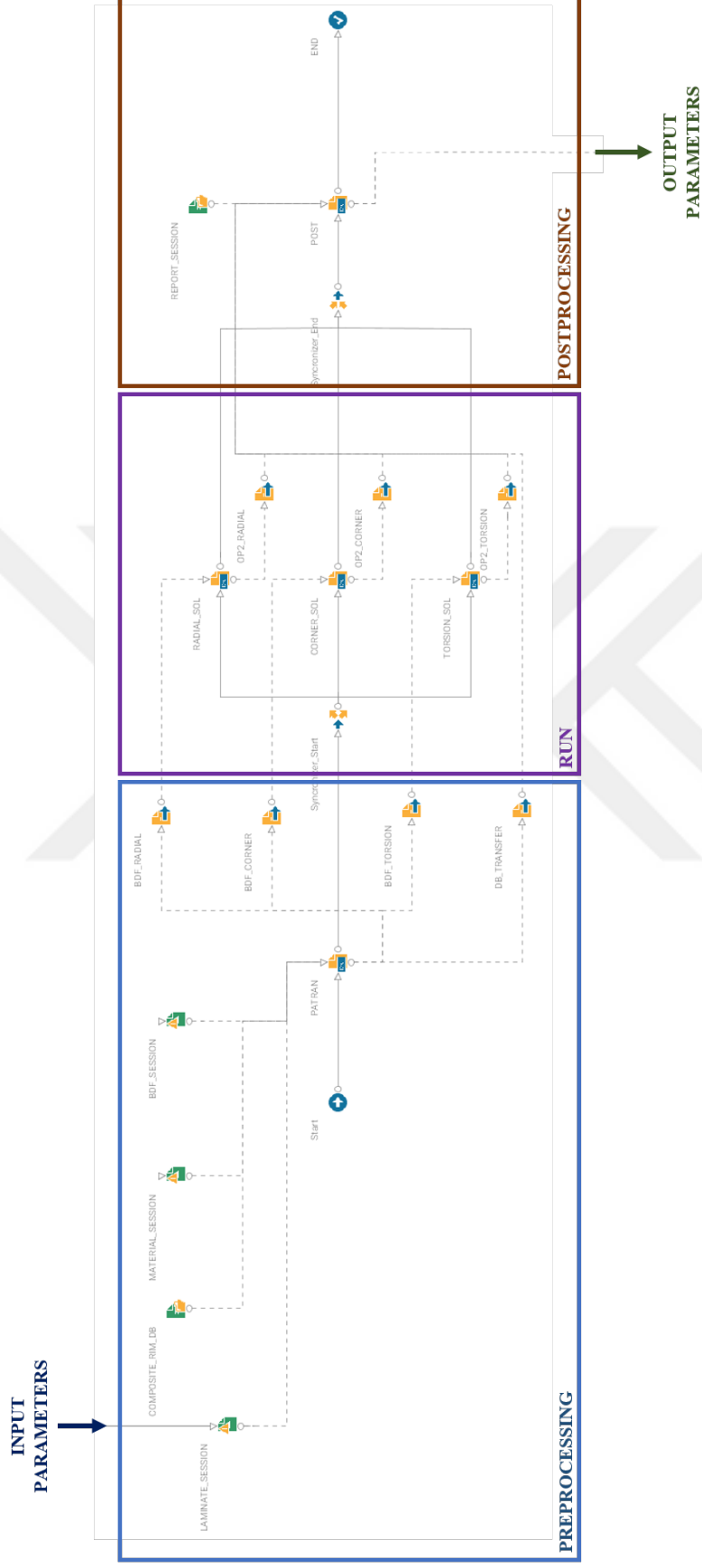


Figure 6.17 : Process control section of optimization process.

The MSC Patran software has provided the FE model for all load conditions and is opened with the database file named "composite rim db" and the material session and laminate session files are read, respectively. Finally, analysis input files for three separate load cases are provided with the BDF session file and MSC Patran software. The preprocessing section is shown in Figure 6.18 below.

Three nastran input files are obtained from this region, together with radial loading, cornering loading, and torsion loading. Each step has a folder area in the project folder of the ModeFrontier software. For this reason, the files that will occupy the excess data used in the analysis should be deleted or transferred to a different stage for later use. Therefore, the Patran database file has been transferred to be used in the postprocessing section.

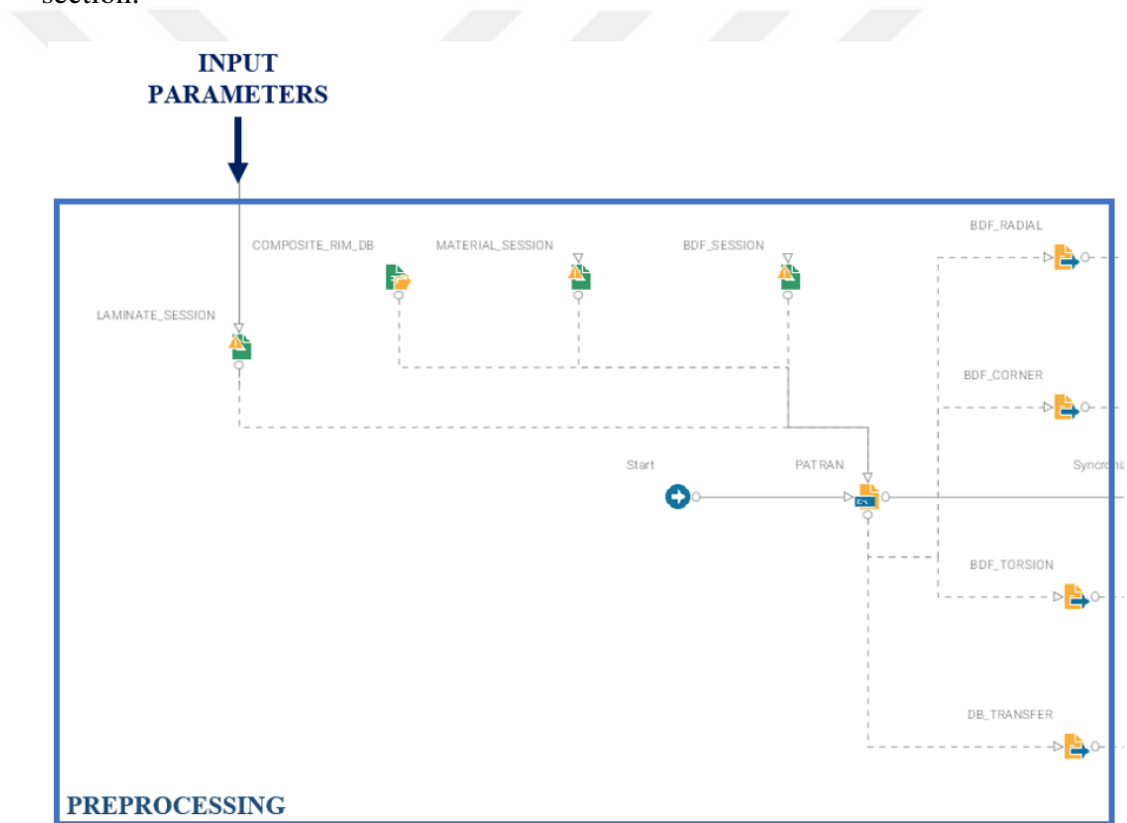


Figure 6.18 : Preprocessing in process control.

Input files of radial, cornering, and torsion loadings prepared in the run area of process control are resolved in a synchronized manner. It is aimed to shorten the optimization time by solving three different cases at the same time. The op2 output files created after the solution are combined into a single pool and transferred to the postprocessing

part. Unnecessary files will be deleted. The scheme of the run operation is given in the Figure 6.19.



Figure 6.19 : Run in process control.

Postprocess is the part where all the results are processed. Result files are uploaded to the Patran database. It is provided to obtain the results related to the report session file. The relevant data is sent to the output parameters section. This completes the cycle of a design solution. The relevant scheme is given in the Figure 6.20.

6.3.3 Output parameters

Output parameters are the last part of the optimization process. Data is collected under these components. After the postprocessing in the process control area, seven different output parameters are obtained. These are the maximum Tsai-Wu indices, maximum displacements, and the composite mass. Tsai-Wu indices and displacements are obtained separately for three different load cases. All optimization work is done

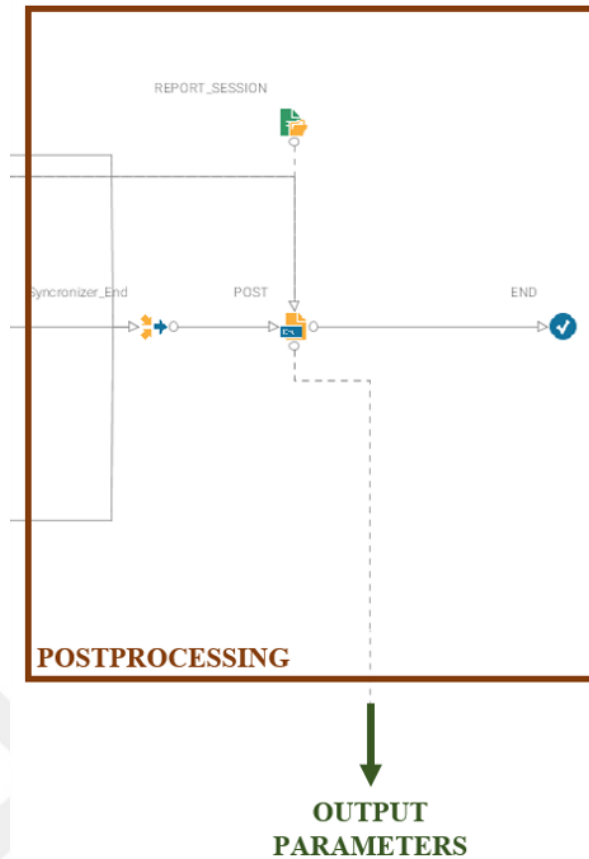


Figure 6.20 : Postprocessing in process control.

with these seven output parameters. The Figure 6.21 shows the output parameters area on the ModeFrontier interface.

6.4 Optimization Plan

The optimization planner enables the parameters in the optimization scheme designed in the workflow to be defined for the optimization run and the optimization parameters to be determined. The main things to be defined in this section are input domain, output domain, objectives, constraints, DOE algorithm, and optimization algorithm.

6.4.1 Input domain

Input parameters of the input domain, which were previously specified in the Chapter 6.3.1 are defined as variables. The input domain defined from the ModeFrontier interface is given in Figure 6.22.

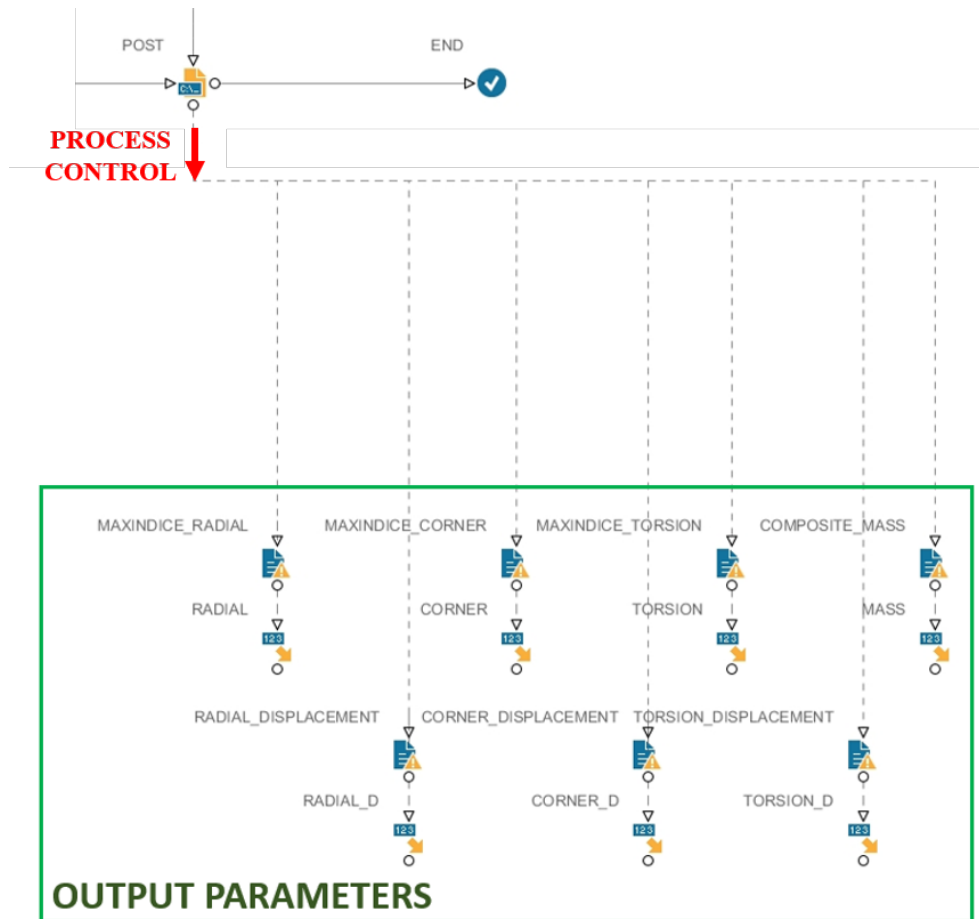


Figure 6.21 : Output parameters section in optimization process.

6.4.2 Output domain

Output parameters of the output domain, which were previously specified in the Chapter 6.3.3 are defined as variables. The output domain defined from the ModeFrontier interface is given in Figure 6.23.

6.4.3 Objectives

Two objective functions are used in the optimization study. One of these is minimizing the deformation of the rim, while the other is minimizing its mass.

As can be seen in the analyzes made in the case of maximum material, the highest deformation was observed in the central hub in torsion and cornering loading, while in radial loading, the maximum deformation was observed at the edge of the wheel part that is not connected to the hub. In automotive, we expect the rim to be light as

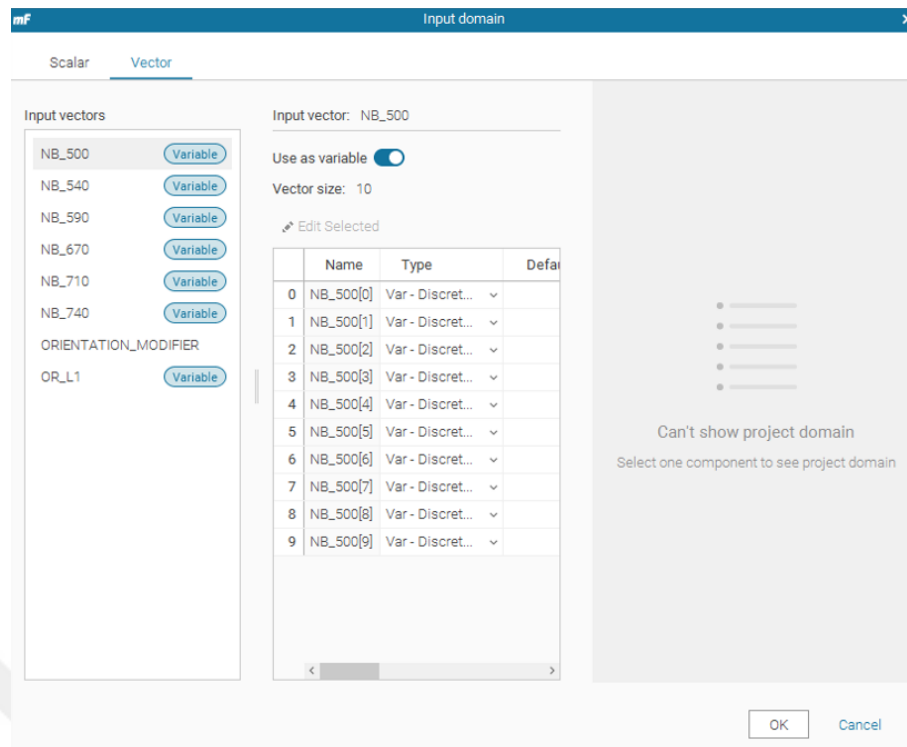


Figure 6.22 : Input domain definition on ModeFrontier user interface.

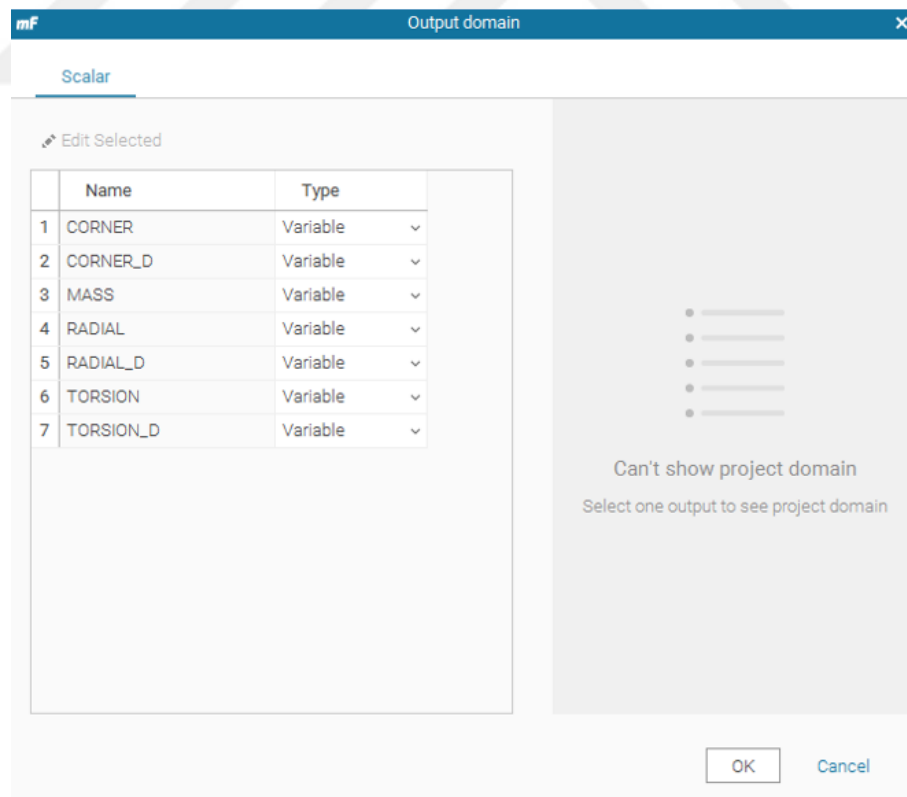


Figure 6.23 : Output domain definition on ModeFrontier user interface.

well as rigid. Rigidity will also be an indirect indicator of strength among feasible solutions. Therefore, minimizing the maximum displacement between three different loads is given as an objective function.

In automotive, mass is one of the main determining factors in vehicle performance. In particular, a rotating mass is one of the determining factors of performance and fuel consumption. Therefore, minimizing the mass is an essential objective in the optimization of the composite rim.

Objective parameters are defined with the functions specified over the ModeFrontier program, as seen in Figure 6.24.

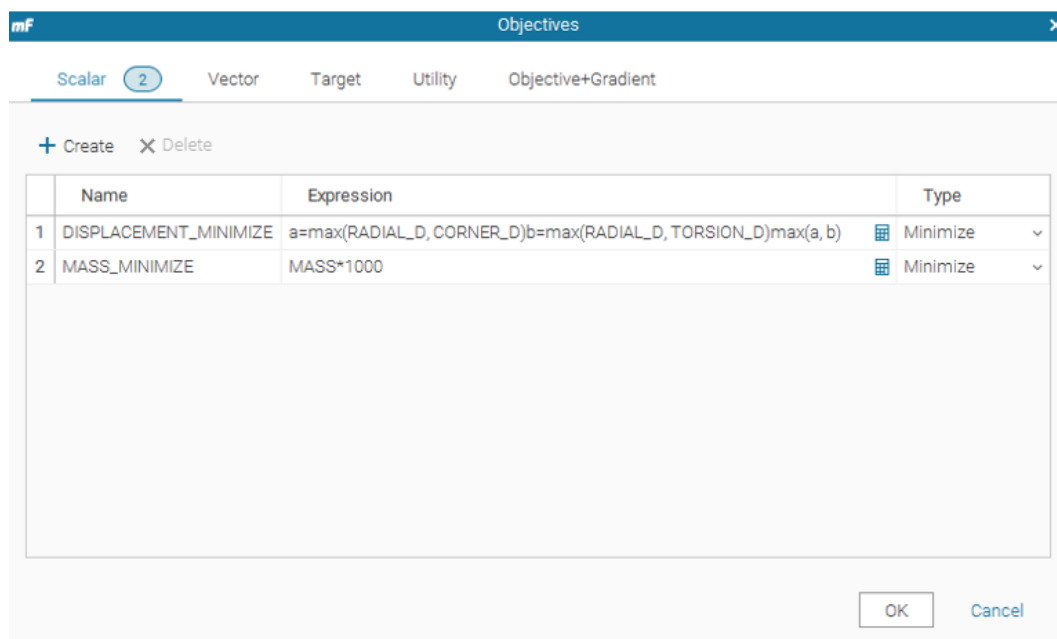


Figure 6.24 : Objective definition on ModeFrontier user interface.

6.4.4 Constraints

In the optimization study, Tsai-Wu failure criteria were defined over the model in order to evaluate whether the designs were feasible or unfeasible. By taking the results of the analysis, the maximum failure index value, which includes the bond failure index and ply failure index, is obtained. This value is obtained from the analyzes under radial, cornering, and torsion loadings run for each design.

As stated in Chapter 2.3.2.3, if the failure index number is below 1, it means that no failure has occurred. For this reason, the constraint of max failure indice value below 1

was defined for all three different analyzes. The Figure 6.25 shows the definition made on the ModeFrontier interface.

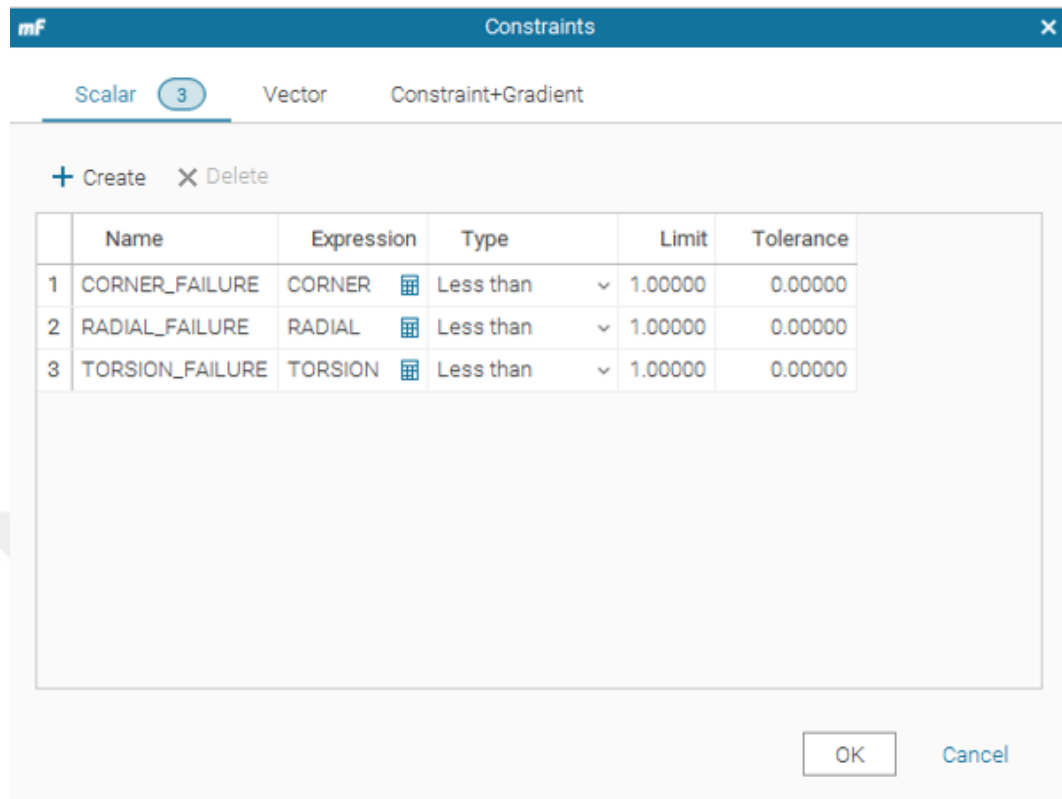


Figure 6.25 : Constraint definition on ModeFrontier user interface.

6.4.5 DOE algorithm

As for the DOE algorithm, the ModeFrontier software offers many options. Among the presented DOE algorithms, there are some that can work well with genetic optimization algorithms.

Space filler DOE algorithms work more harmoniously with genetic algorithms. For the purpose, it is sufficient to fill the design space. Uniform Latin hypercube, random, and sobol DOE algorithms can be given as examples of space filler DOE algorithms.

The Sobol algorithm was used in the composite rim optimization study. The Sobol algorithm is mentioned in Chapter 3.6.1.2. This algorithm prevents clustering in the design space compared to the random algorithm. The ModeFrontier interface where the DOE algorithm is defined is shown in Figure 6.26. In the design space, the number

of designs has been determined as 100. The designs included in the Sobol DOE set are given in Appendix A.

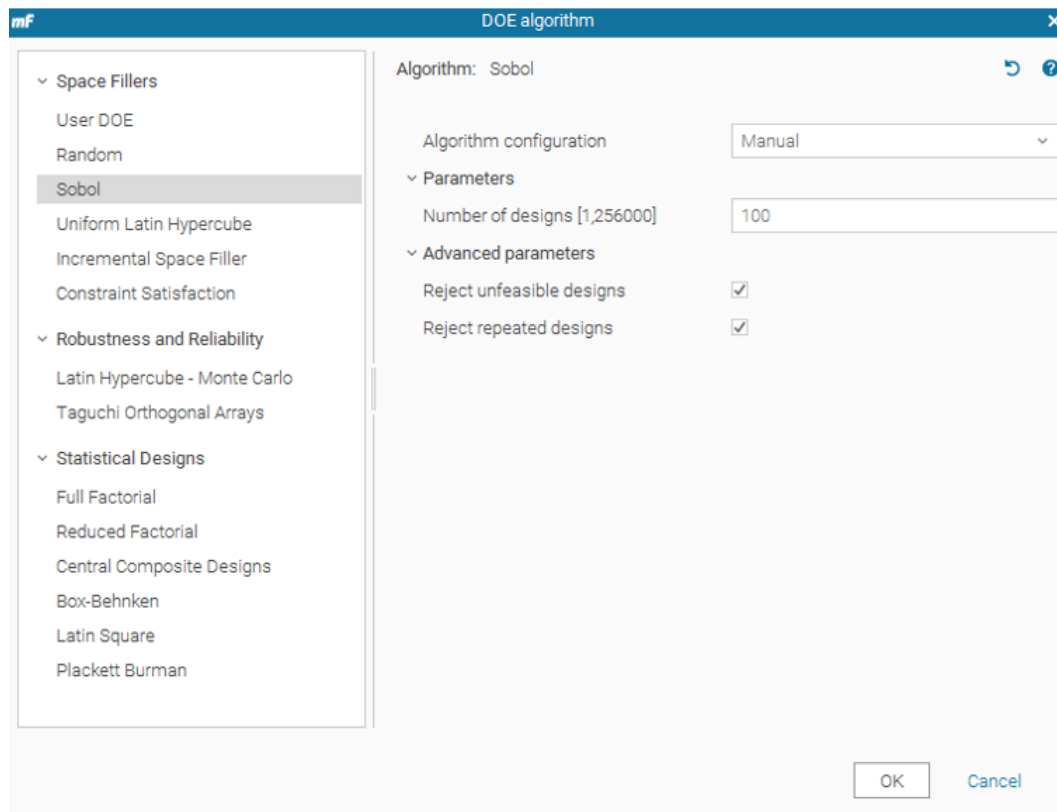


Figure 6.26 : DOE algorithm definition on ModeFrontier user interface.

6.4.6 Optimization algorithm

In the optimization study, the multi-objective design algorithm II (MOGAI) mentioned in Chapter 3.5 will be used.

With the optimization parameters, how the generations will be derived and how the optimization will be done are defined. The number of generations is defined as 60. After the 60th generation is run, the analysis will be finished.

Generational evolution is selected as the algorithm type. With this selection, after a generation is fully run, the next generation will be produced. By selecting elitism as enabled, elite sets will be created from non-dominated designs.

Probability values are assigned to directional crossover, selection, mutation, and classical crossover parameters, which are genetic algorithm operators. This assignment was carried out as suggested by the software. Probability of directional crossover was

selected as 0.5, while probability of selection was set as 0.05. probability of mutation is entered as 0.1. In this case, the probability of a classical crossover is 0.35. The DNA string mutation rate was defined as 0.05. Thus, the mutated bits will be %5. The definition of the optimization algorithm is made on the ModeFrontier interface and shown in Figure 6.27.

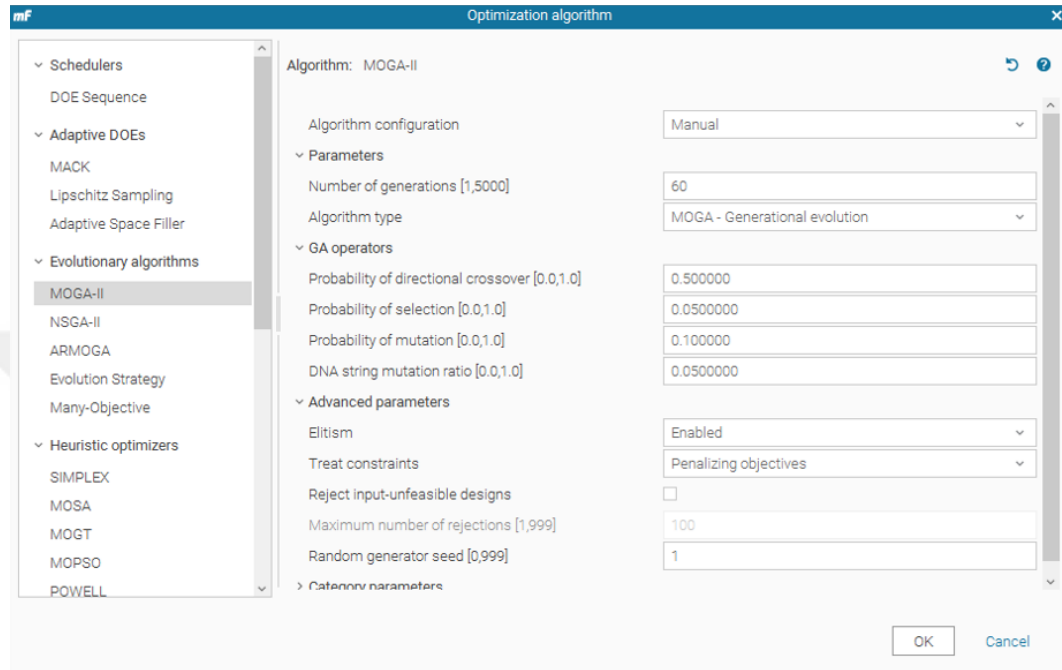


Figure 6.27 : Optimization algorithm definition on ModeFrontier user interface.

6.5 Optimization Results

MOGAII Optimization was run using ModeFrontier software and solutions were obtained for a total of 6000 different designs. There are 60 generations together with the initial generation created by DOE designs. There are 100 designs in each generation. In the optimization study, it took a total of 210 hours, 43 minutes, and 16 seconds to obtain the 60 generation. While the number of feasible designs was quite low in the first generations of the 9-day analysis, the incidence of feasible designs increased as generations were produced.

56.70% of the designs created in the study were unfeasible due to constraints; In 43.05%, no failure was observed according to the Tsai-Wu failure criterion and it was considered feasible. 0.25% of the designs gave an error because the designs created

were too bad to give analysis results. Values are shown in the pie chart in the Figure 6.28.

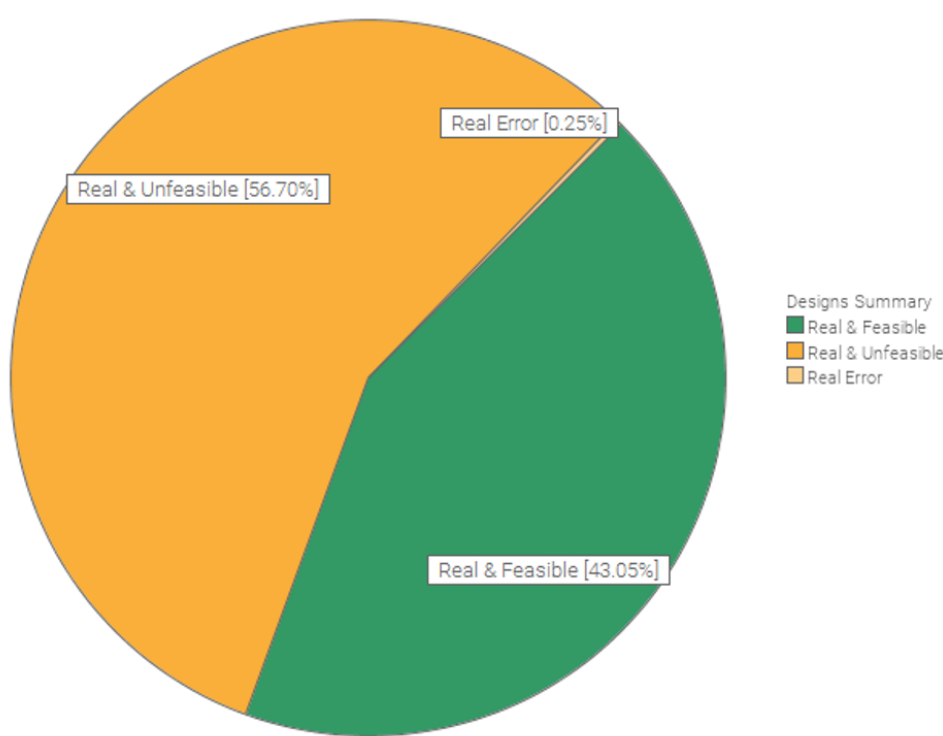


Figure 6.28 : Feasible, unfeasible and error distribution.

When it was investigated under which loads the designs with broken constraint occurred, it was seen that 72.68% of the designs caused failure under radial loading, 26.64% of them caused failure under cornering loading, and 0.67% of them caused failure under torsion loading. The results are shown in the Figure 6.29.

According to the data obtained, it is clear that radial loading is the most decisive and dominant loading among the loads. The distribution of the designs obtained in the optimization study, where displacement minimization and mass minimization are defined as objectives, in terms of displacement and mass, shows whether a pareto set is formed. 6000 designs are shown in the Figure 6.30 as unfeasible in orange and feasible in green.

When the distribution is examined, it is seen that the designs with a mass of more than 4.5 kg are not considered feasible. In addition, the values of approximately 8 kg, where we approach the maximum material, are among the other limiting areas. The scatter chart with only feasible designs is shown in the Figure 6.31.

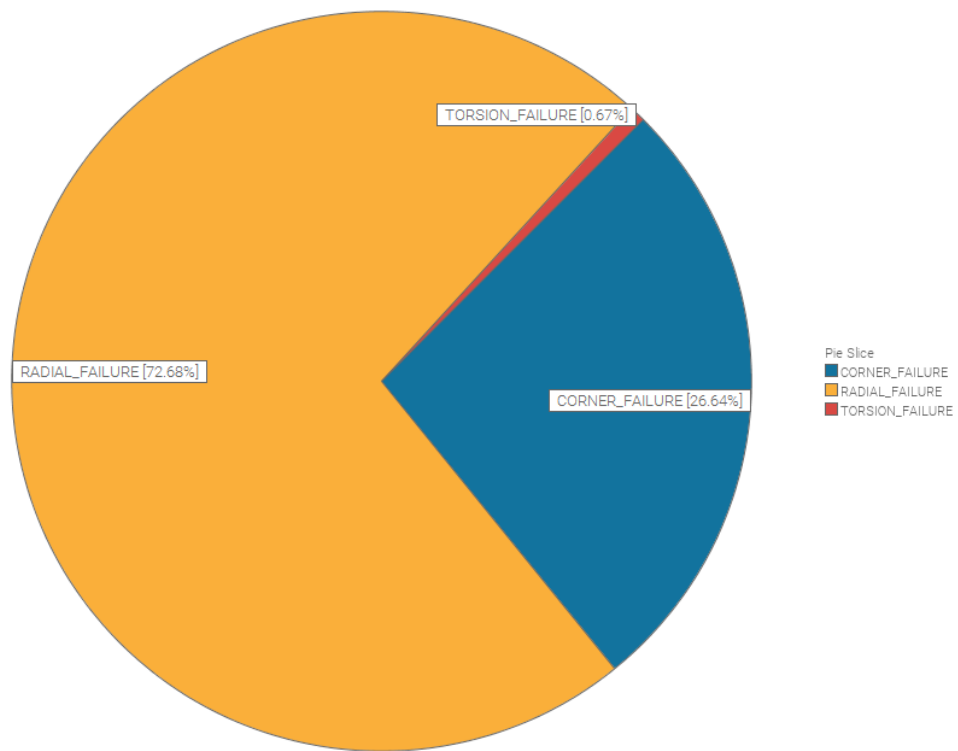


Figure 6.29 : Broken constraints distribution.

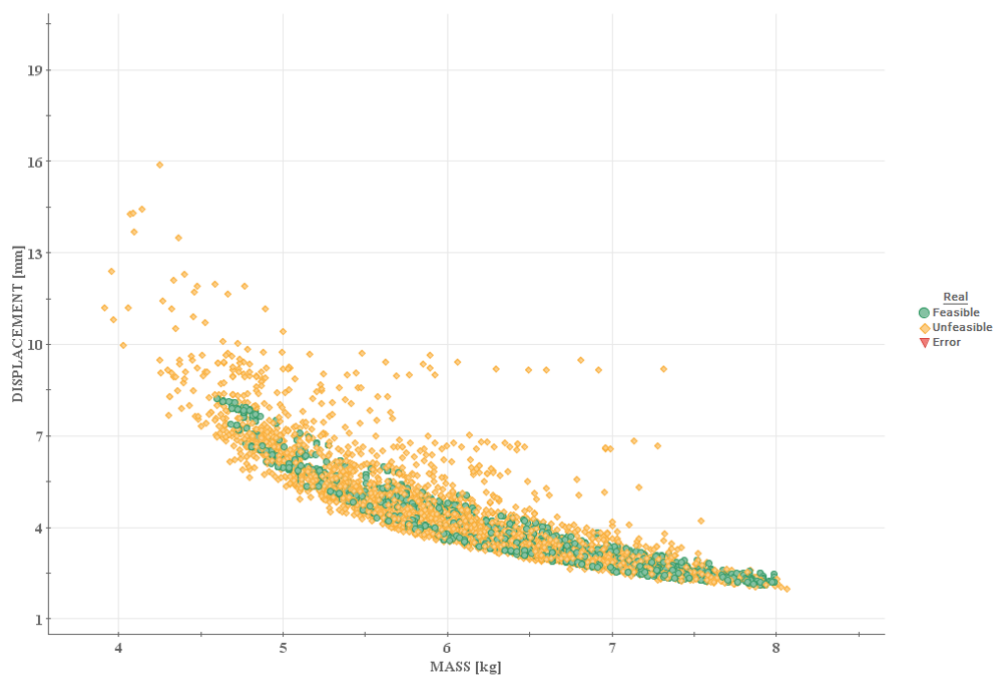


Figure 6.30 : Distribution of design points.

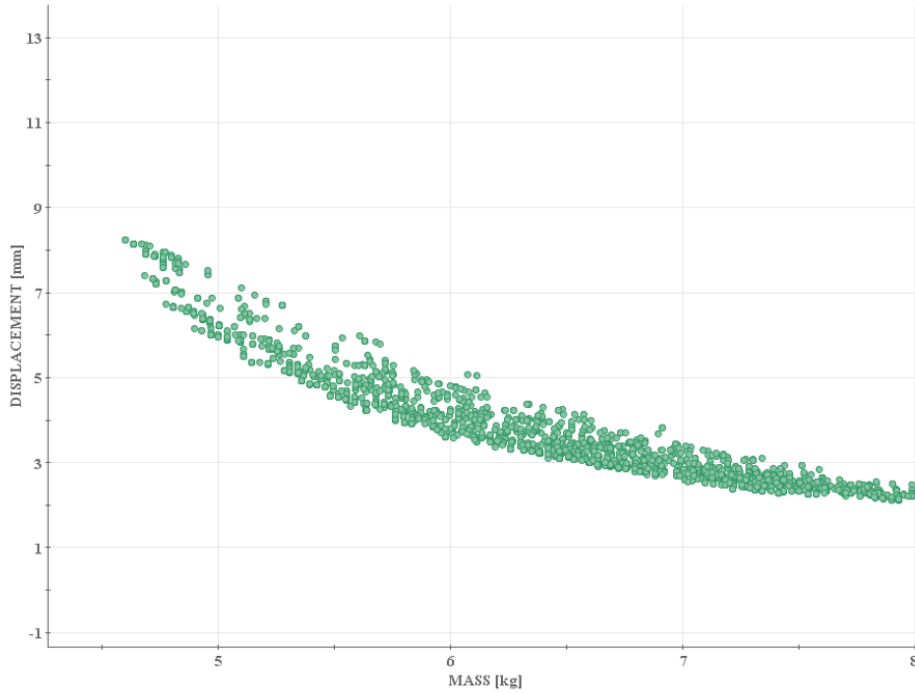


Figure 6.31 : Distribution of feasible design points.

6.5.1 Pareto front results

The Pareto Front set was created from the feasible designs. Scatter chart is given in Figure 6.32. At the same time, the generation numbers of the designs in the Pareto set are also indicated. The 59th generation is the last generation, and it is noteworthy that most of the designs in the pareto are from the last generation. The designs in the Pareto set are given in Appendix B.

There are 230 designs in the resulting Pareto set. While 145 of these designs were obtained in the last 10 generations, 60 designs were obtained from the 50th to 40th generation range. The majority of the remaining 25 designs are from the 30th to 20th generation range.

6.5.2 Multi criteria decision making

Multi criteria decision making (MCDM) techniques were used in order to select and use the appropriate Pareto design. In order to make the selection, two objectives in

the optimization study were weighted and subjected to various techniques. There are many decision making techniques within the ModeFrontier software. Among these techniques, linear MCDM and genetic algorithm (GA) MCDM techniques were examined.

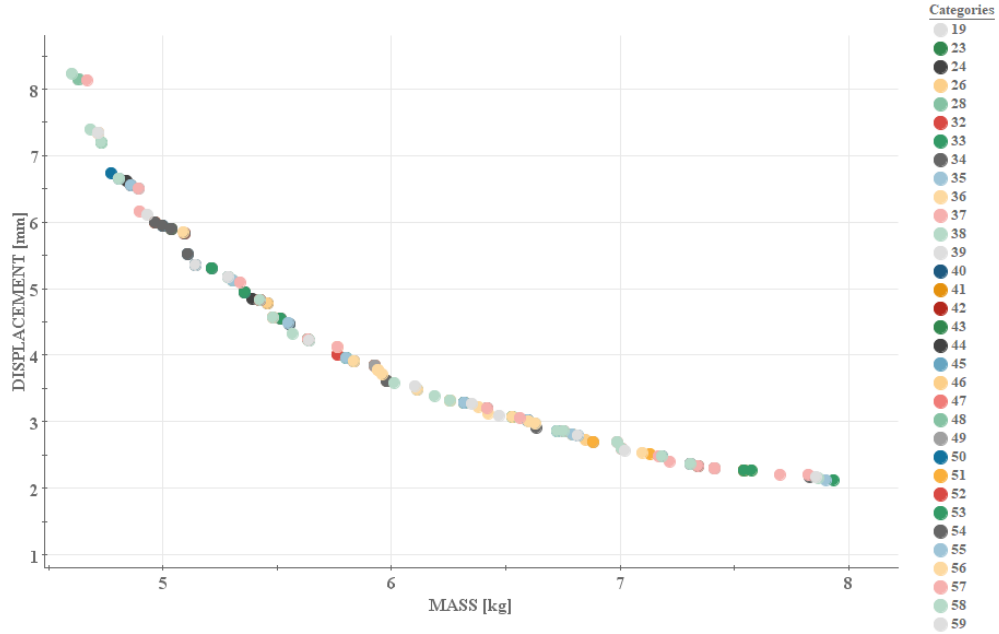


Figure 6.32 : Pareto front designs with generation numbers.

6.5.2.1 Linear MCDM

The utility function is calculated in the linear MCDM algorithm. Ranking is done with the utility function. In the utility function, weight and alpha values are assigned to the criteria. These values are assigned in the ModeFrontier interface. Weight takes a value between 0 and 1. The weight of one of the two criteria, which are the maximum displacement and mass criteria, also determines the other. By specifying the alpha value, linear or nonlinear features are reflected to the function.

Alpha value can be defined between 0.1 and 10. Defining a value of 1 makes a linear function. The alpha and weight values entered in the ModeFrontier software interface for the Linear MCDM application are shown in Figure 6.33. Weight values were set to 0.5 and evenly distributed. The alpha value was evaluated as 1. Thus, the nonlinear effect was not taken into account.

As a result of the Linear MCDM application, the designs in the Pareto set were scored and ranked. Ranking results are given in Figure 6.34 and in Table 6.4 with the objective output values and design IDs.

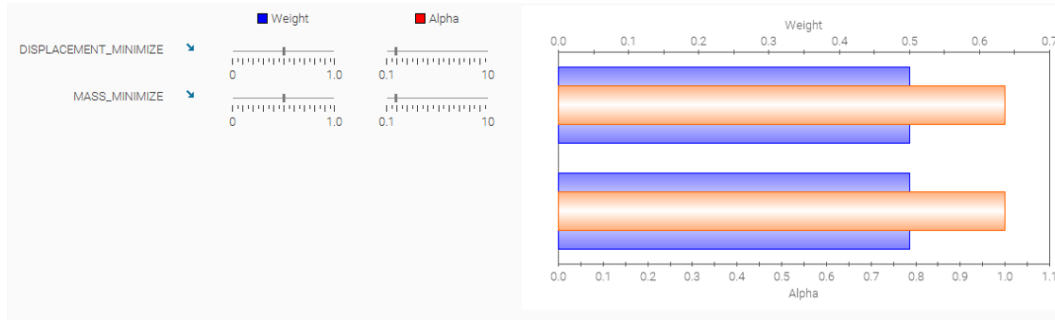


Figure 6.33 : Linear MCDM weight and alpha parameters.

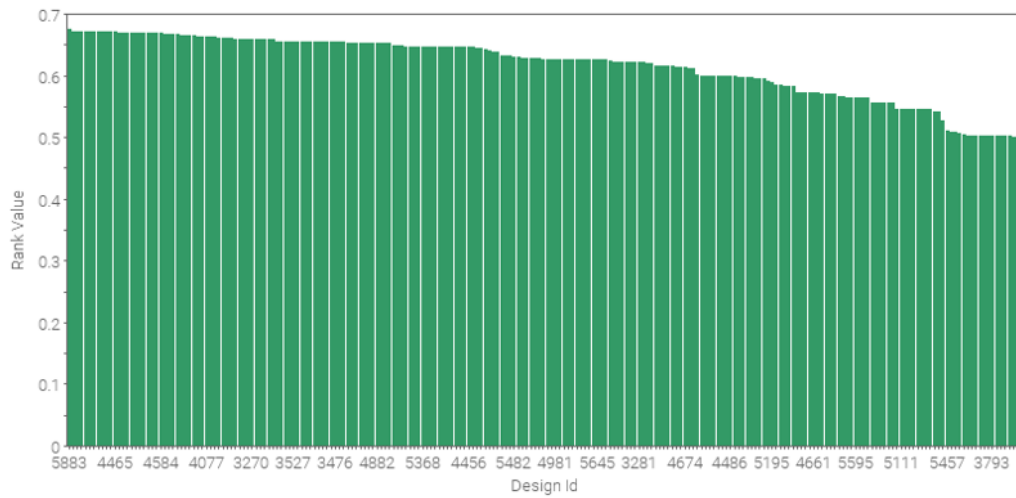


Figure 6.34 : Linear MCDM ranking bar chart.

When the top 10 designs are examined according to the linear MCDM ranking, it is observed that the designs numbered 5883, 5989 and 5397 come to the fore.

6.5.2.2 Genetic algorithm MCDM

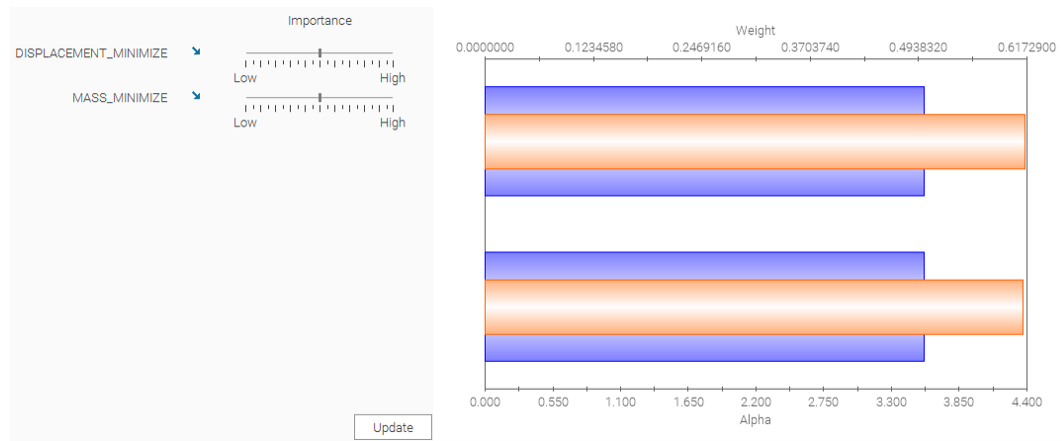
In the GA MCDM method, the utility function is calculated by genetic algorithm. As in Linear MCDM, the utility function depends on the weight and alpha values. However, in the GA MCDM method, these weight and alpha values are calculated by the algorithm. In order to run this algorithm, some parameters need to be defined. These are training cycles and random generator seed values.

Table 6.4 : Linear MCDM ranking table.

No	ID	Displacement [mm]	Mass [kg]	Rank Value
1	5883	4.33	5.57	0.67471
2	5989	4.23	5.64	0.67161
3	5397	4.23	5.64	0.67161
4	5217	4.01	5.76	0.67158
5	4753	4.01	5.76	0.67158
6	5780	4.25	5.63	0.67100
7	5387	4.25	5.63	0.67100
8	4817	4.25	5.63	0.67100
9	5494	3.63	5.98	0.67055
10	5478	3.63	5.98	0.67055

The training cycle is the maximum number of iterations that the algorithm will perform. It can be selected between 1 and 1024. Selecting 1024 gives the most accurate result. Random generator seed provides sequence repeatability. Two different analyzes using the same value will give the same result.

The Pareto set was entered as 1024 iterations and the seed value was 1, and analyzed with GA MCDM. As can be seen in Figure 6.35, the 0.5 weight ratios in the linear MCDM technique were used in the same way in the GA MCDM solution. After iterations, alpha values were calculated as 4.38 for displacement minimization and 4.37 for mass minimization.

**Figure 6.35 : GA MCDM weight and alpha parameters.**

As a result of the GA MCDM application, the designs in the Pareto set were scored and ranked. Ranking results are given in Figure 6.36 and in the Table 6.5 with the objective output values and design IDs.

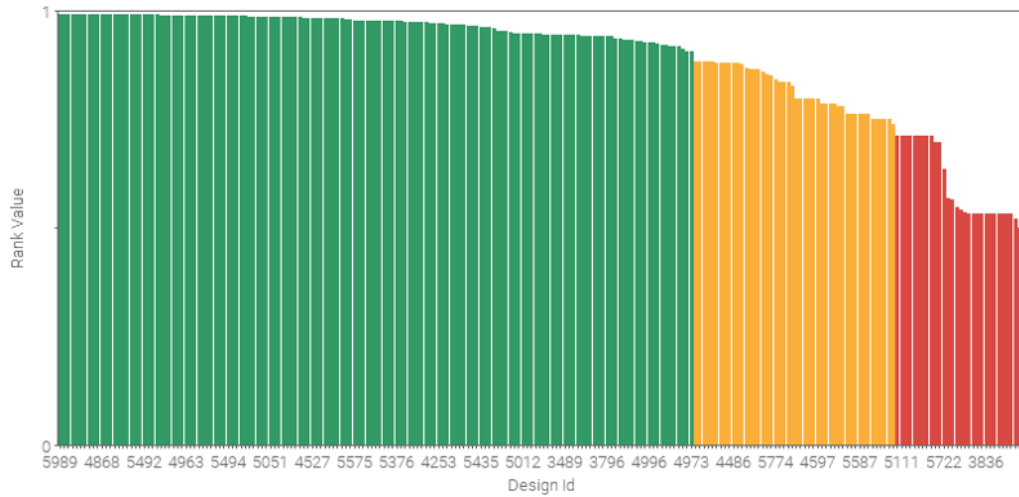


Figure 6.36 : GA MCDM ranking bar chart.

According to the data obtained by the GA MCDM method, designs numbered 5989, 5397 and 5780 take the first three places. When the results obtained in Linear MCDM are examined, it is seen that the designs numbered 5989 and 5397 are common options. The alpha values found by GA have added nonlinearity to the selection criteria and highlighted the designs numbered 5989 and 5397.

Table 6.5 : GA MCDM ranking table.

No	ID	Displacement [mm]	Mass [kg]	Rank Value
1	5989	4.23	5.64	0.992226
2	5397	4.23	5.64	0.992226
3	5780	4.25	5.63	0.992126
4	5387	4.25	5.63	0.992126
5	4817	4.25	5.63	0.992126
6	5217	4.01	5.76	0.992120
7	4753	4.01	5.76	0.992120
8	5883	4.33	5.57	0.992076
9	5563	3.96	5.80	0.991673
10	5361	3.96	5.80	0.991673

6.5.3 Detail results of optimum design

According to the GA MCDM and Linear MCDM results, design number 5989 was selected. The ply sequences of the design are shown in Figure 6.37.

As can be seen in Figure 6.37, the part of the wheel that has the interface of the rim with the tire constitutes the thickest region. While 28 ply numbers are seen in the

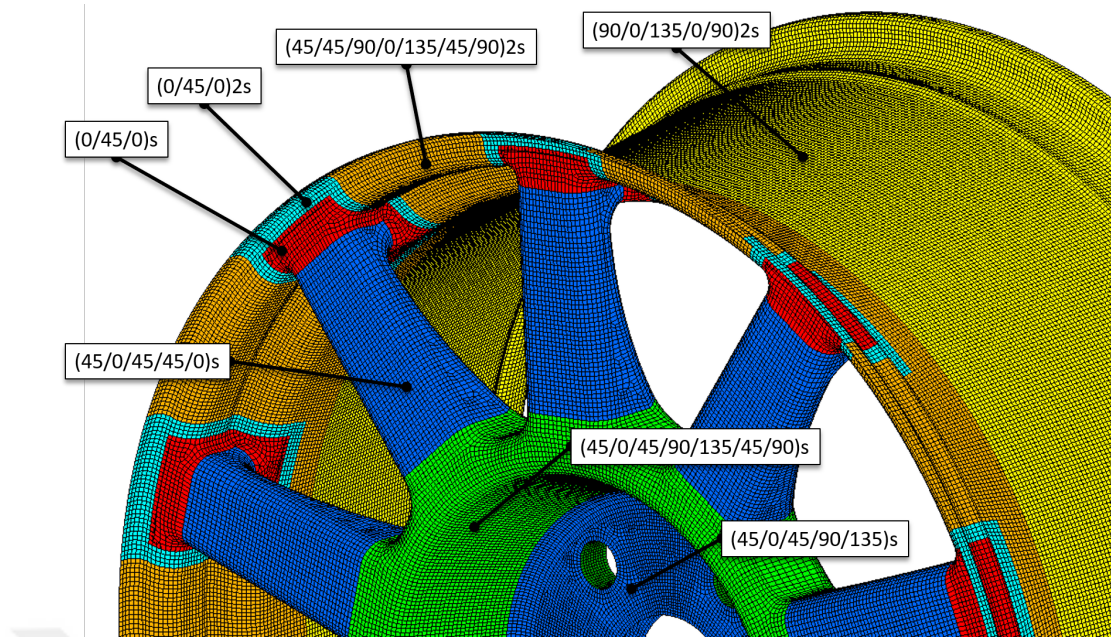


Figure 6.37 : Design number 5989 layup for different regions.

orange region, there are 20 ply numbers in the yellow region. With the hollow design in the hub area and spoke area, there are fewer ply numbers on the surface compared to the wheel part.

The optimum design number 5989 has a total composite weight of 5.64 kg, and a maximum displacement of 4.23 mm occurs on the rim under radial loading.

6.5.3.1 Radial load case results

Analysis of design 5989 was run with MSC Nastran to show the results under radial loading. The same values were obtained as the results obtained in the optimization process. Maximum displacement results are given in the Figure 6.38 in mm.

As expected, the maximum displacement occurred in the outer wheel region where the loading is located. The maximum displacement that occurs is the highest displacement value compared to other loadings.

The maximum Tsai-Wu failure value for the radial load case obtained during the optimization process includes the maximum of the inter-laminar bond indices and ply indices. The inter-laminar bond indices in radial loading are given in the Figure 6.39, while the ply indices are given in the Figure 6.40.

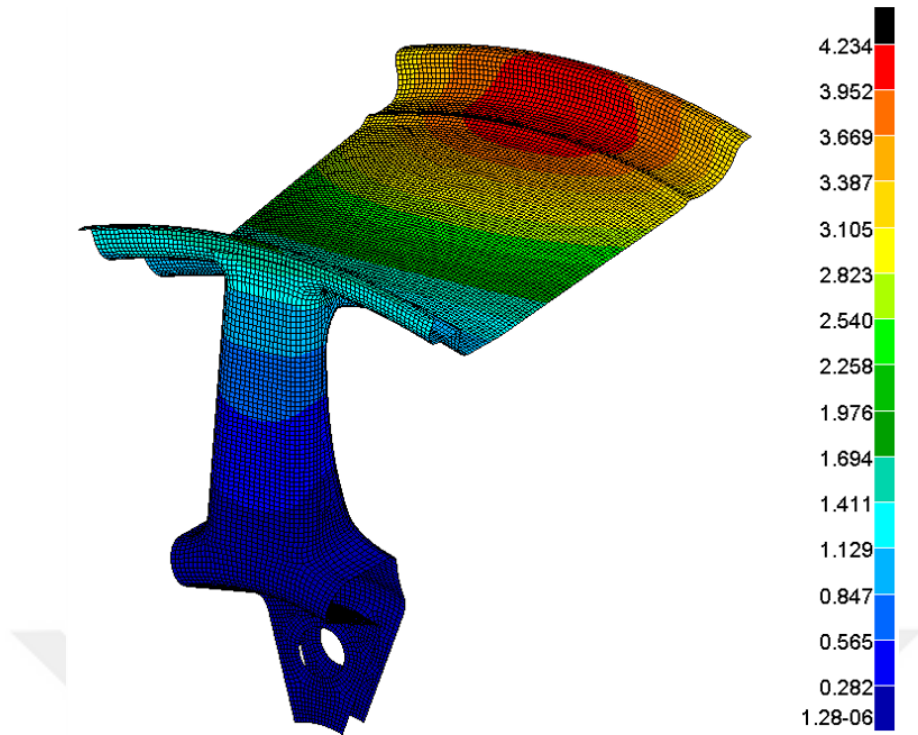


Figure 6.38 : Maximum displacement result of design number 5989 under radial loading.

In the study, the maximum Tsai-Wu bond indice region was observed in the outer wheel part and the spoke-wheel connection, while the maximum Tsai-Wu ply indice value was formed in the part corresponding to the spoke gap of the arm due to the applied normal loads.

6.5.3.2 Cornering load case results

Analysis of design 5989 was run with MSC Nastran to show the results under cornering loading. The same values were obtained as the results obtained in the optimization process. Maximum displacement results are given in the Figure 6.41 in mm.

As expected, maximum deformation occurred in the spoke root region with the bending moment created in the center.

The maximum Tsai-Wu failure value for the cornering load case obtained during the optimization process includes the maximum of the inter-laminar bond indices and ply indices. The inter-laminar bond indices in cornering loading are given in the Figure 6.42, while the ply indices are given in the Figure 6.43.

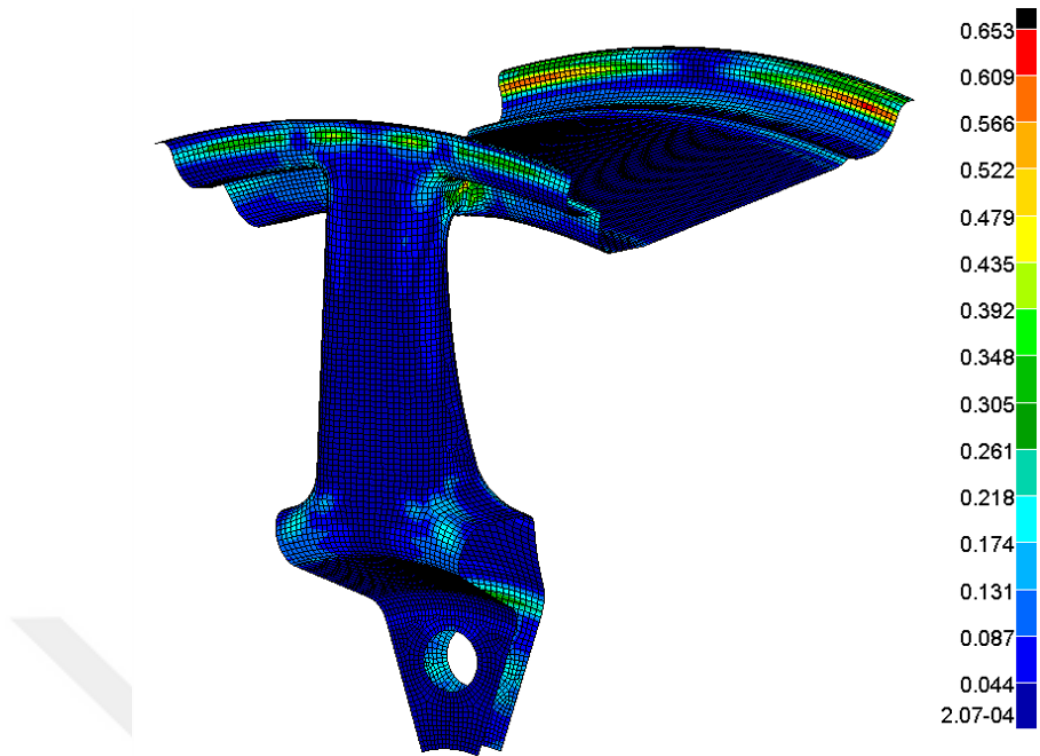


Figure 6.39 : Maximum Tsai Wu bond indice result of design number 5989 under radial loading.

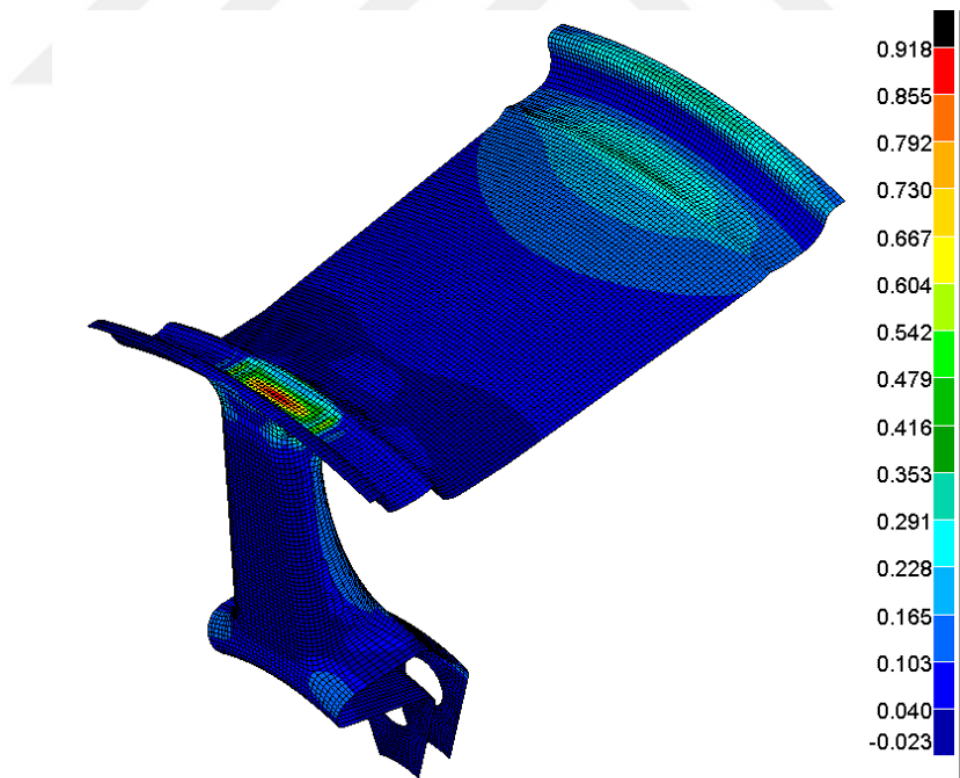


Figure 6.40 : Maximum Tsai Wu ply indice result of design number 5989 under radial loading.

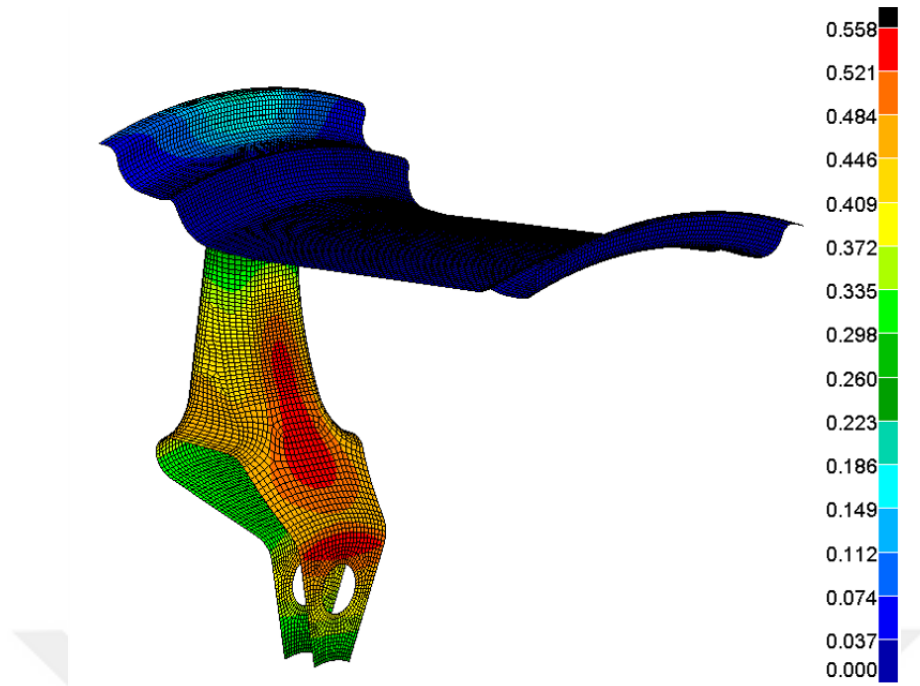


Figure 6.41 : Maximum displacement result of design number 5989 under cornering loading.

The bond indice results were examined under the cornering load and the critical region was observed in the radius between the hub and the spoke root due to the moment applied from the hub. By looking at the ply indice values, the region in the nodes where the load is applied and the load is transferred from the fastener is critical.

6.5.3.3 Torsion load case results

Analysis of design 5989 was run with MSC Nastran to show the results under torsion loading. The same values were obtained as the results obtained in the optimization process. Maximum displacement results are given in the Figure 6.44 in mm. Under the torsion load, bending occurred on the spoke lateral surface and maximum deformation occurred in the root region. The maximum Tsai-Wu failure value for the torsion load case obtained during the optimization process includes the maximum of the inter-laminar bond indices and ply indices. The inter-laminar bond indices in cornering loading are given in the Figure 6.45, while the ply indices are given in the Figure 6.46. According to the results obtained in torsion loading, tsai-wu bond indice critical regions were seen in the spoke root. The maximum ply indice was formed in the region of maximum deformation.

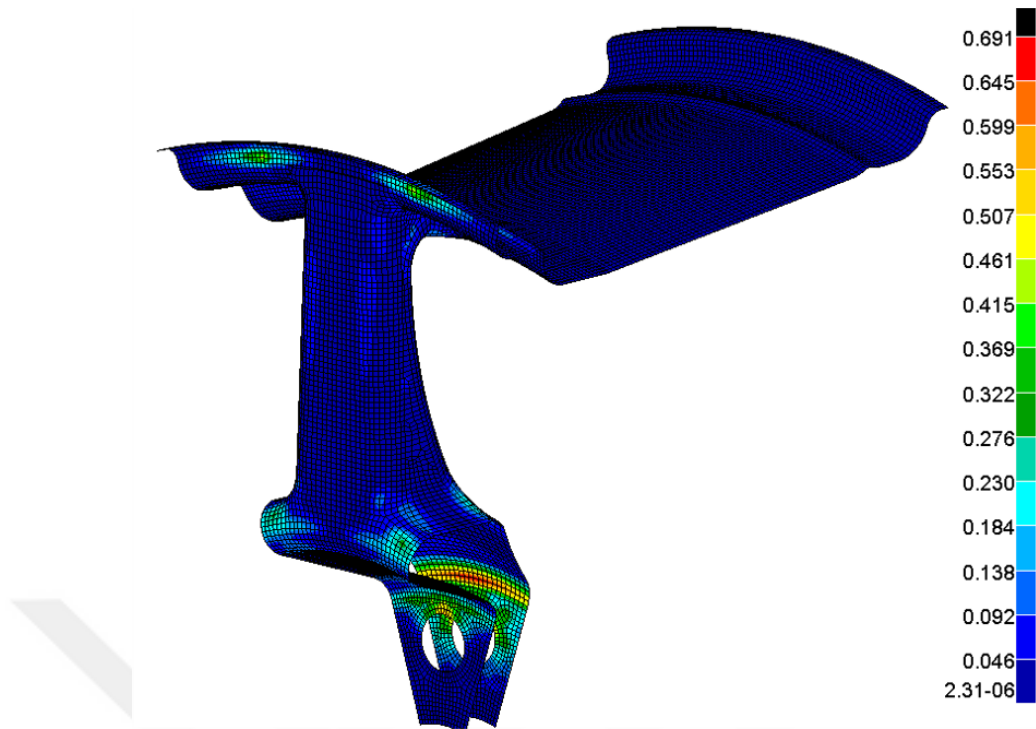


Figure 6.42 : Maximum Tsai Wu bond indice result of design number 5989 under cornering loading.

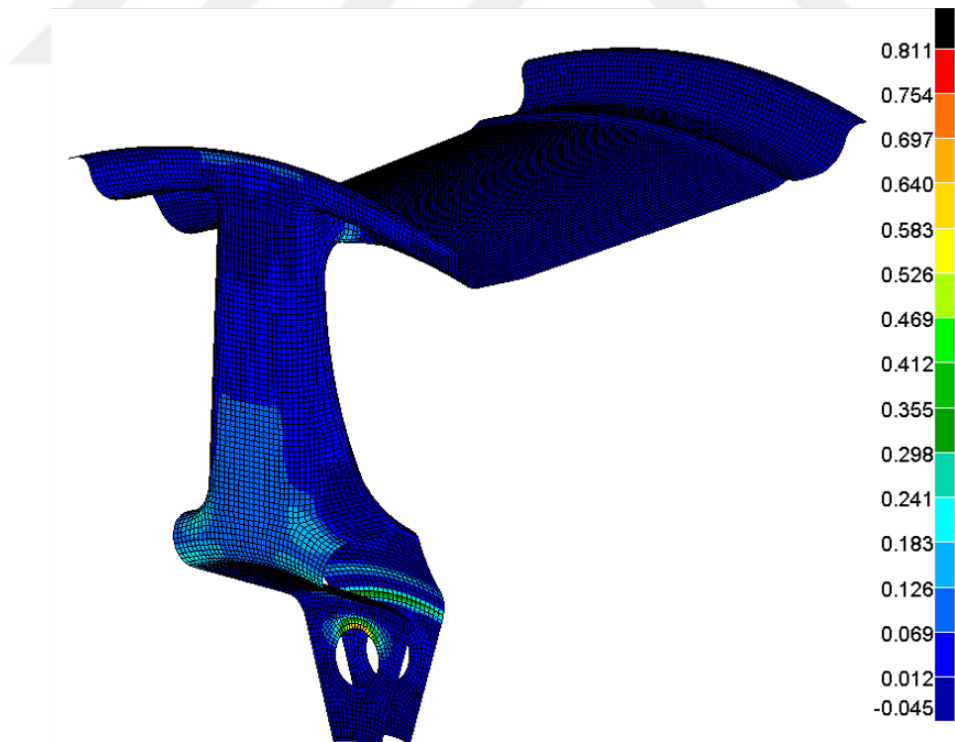


Figure 6.43 : Maximum Tsai Wu ply indice result of design number 5989 under cornering loading.

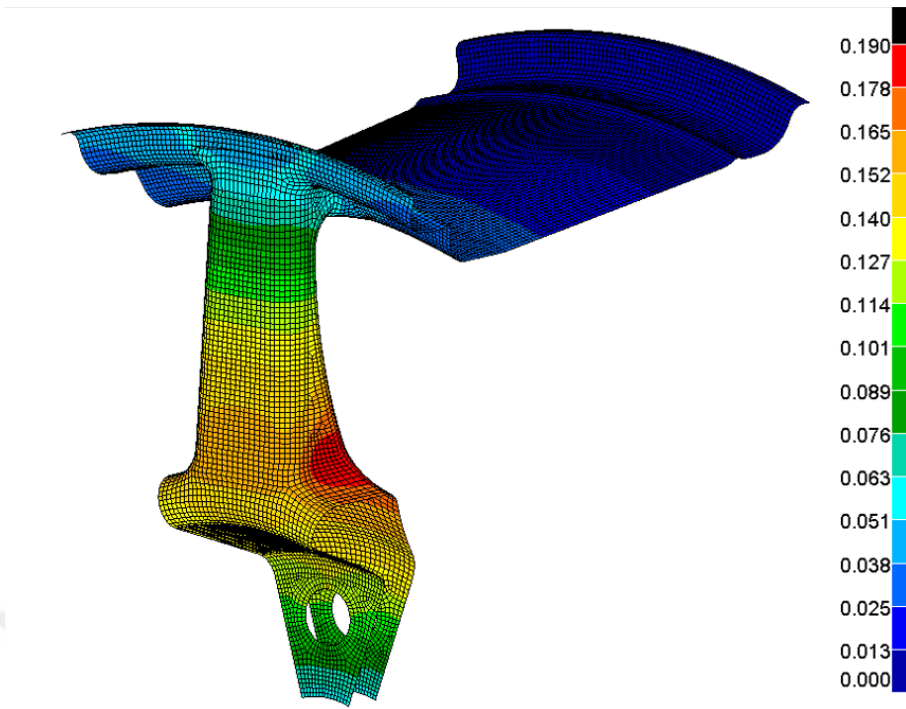


Figure 6.44 : Maximum displacement result of design number 5989 under torsion loading.

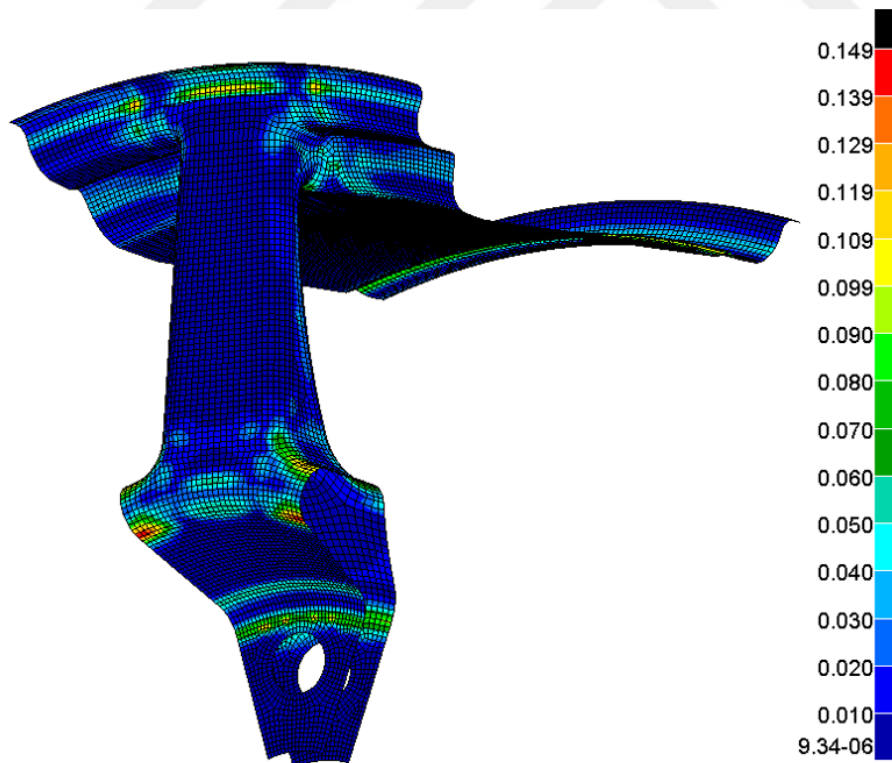


Figure 6.45 : Maximum Tsai Wu bond indice result of design number 5989 under torsion loading.

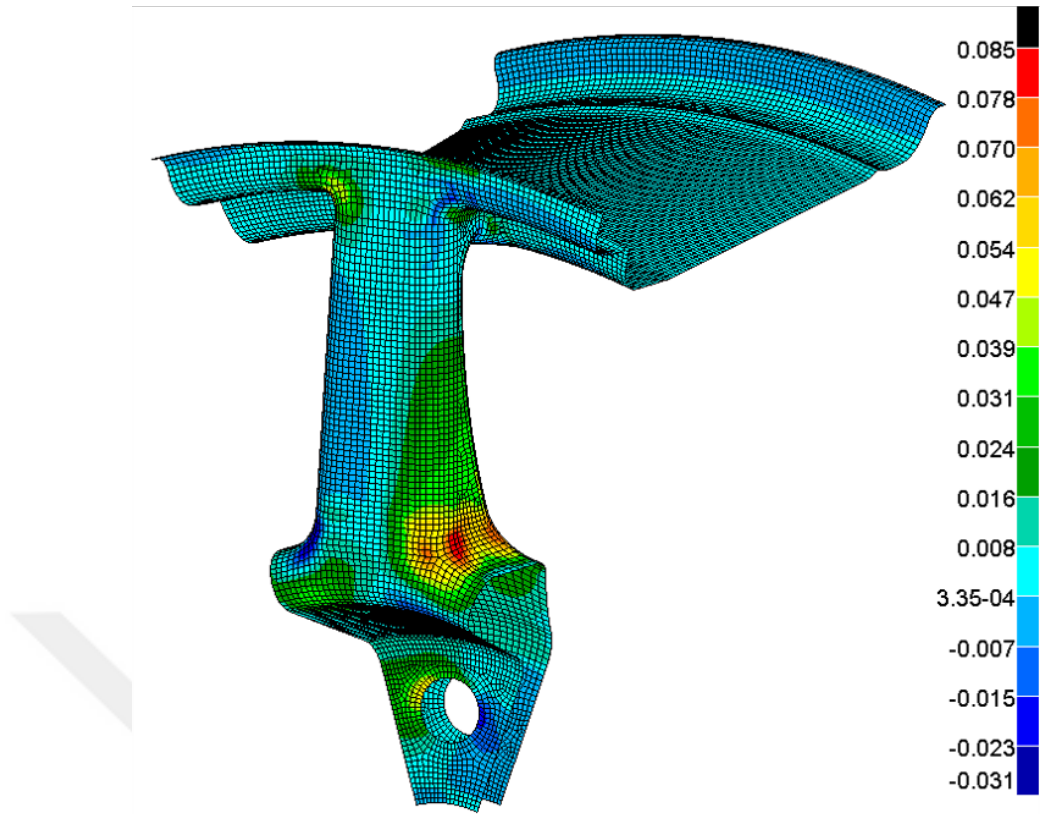


Figure 6.46 : Maximum Tsai Wu ply indice result of design number 5989 under torsion loading.



7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusion

This thesis is part of the composite wheel development project initiated by the Carre Wheel Design company. In the study, a rim design with 10 spokes was developed using plainweave fabric prepreg material. In order to create a symmetrical and balanced design, the input variables were determined by considering the design boundaries.

The rim that is aimed to be developed in the thesis study is designed according to ETRTO standards. The design was developed using CATIA v5 software. The resulting reference wheel design was modeled using Hypermesh software and made ready for use in the optimization cycle. Load scenarios are selected according to the ISO 3006:2015(E) standard. A total of three loading conditions, cornering, radial and torsion loading, were created on the model. Patran session files and various command files were created to be used in optimization, and an optimization process plan was designed using ModeFrontier software.

In this study, optimization was made using multi objective genetic algorithm II (MOGAI) with elitism. The sobol random algorithm provided by the ModeFrontier software was used as the design of experiment method. An initial population of 100 designs was obtained using the Sobol algorithm. A total of 60 generations were obtained using the MOGAI algorithm. There are 100 designs in each generation, and these designs are created with classical crossover, directional crossover, mutation, and selection.

In order to avoid failure under radial, cornering, and torsion loading conditions, Tsai-Wu failure criterion was used as a constraint in the optimization study. A Pareto optimum set was created in the 60-generation MOGAI optimization obtained with minimum deformation and minimum mass objective functions. The optimum

design selection was made with the Linear and GA MCDM methods performed on the obtained Pareto set.

The resulting rim was design number 5989, which was created with a directional crossover in the 60th generation. The bond and ply failure indices and deformations of the resulting rim design are detailed under radial, cornering, and torsion loading. In the case where the mass and deformation objectives are of equal importance, the most optimal design without failure under load conditions is obtained.

7.2 Recommendations

A wheel geometry that will be used in automotive and has aesthetic expectations creates challenging conditions for the use and production of composite materials. The use of very small features, especially in the spoke and wheel connection region, causes the production quality to decrease and the out of plane loads to be seen on the plate. The risk of interlaminar failure increases in regions with complex geometries.

Since geometric features have an important place, especially in bonding strength, adding geometric parameters to the optimization cycle can result in a more robust design solution. The participation of geometric parameters in the optimization requires the model to be updated for each design.

The degree of freedom of the model used in composite wheel optimization largely determines the optimization speed. In workstations with low system specifications, the difficulty will increase as the model grows. For this reason, it would be beneficial to determine the dominant load case for each region in the rim geometry and try to run a few analyzes.

The model used in this study is the full rim model. Especially since cornering and radial loads are not symmetrical, the symmetrical model was not used. However, if a loading situation is created that will reduce the model dimensions and can be used cyclic symmetrically, the result can be reached faster.

REFERENCES

- [1] **Peters, B.** (2019). Carbon Fibre Composite Wheel Design and Prototype for a FSAE Race Car, *The UNSW Canberra at ADFA Journal of Undergraduate Engineering Research*, 12(2).
- [2] **Bhagwat, P.G.G. et al.** (2017). *Design and Analysis of a 10" Carbon Fiber Wheel for a Formula SAE Racecar*, The University of Texas at Arlington.
- [3] **Walther, H.W.** (2016). *Development of a Lightweight Laminated Composite Wheel for Formula SAE Race Vehicles*, University of Kansas.
- [4] **Dhage, B., Shah, S., Barche, Y., Shiledar, N. and Gore, S.** (2020). Development of Carbon Fibre Wheel Rims for Formula Student Racing Car, *International Journal of Future Generation Communication and Networking*, 13(2s), 1083–1089.
- [5] **Hong, J.H., Yoo, S.H. and Chang, S.H.** (2013). Design and performance evaluation of carbon fiber/epoxy composite-aluminum hybrid wheel for passenger cars, *Composites Research*, 26(6), 386–391.
- [6] **Rohan, C.D.** (2015). Design and analysis of a composite wheel rim, *J. Mat. Sci. Mechanical Eng*, 2(6), 50–56.
- [7] **Schweizer, N., Giessl, A., Schwarzhaupt, O. and Büter, A.** (2012). Development of a composite wheel with integrated hub motor, *15th European Conference On Composite Materials (ECCM15), Venice, Italy (24–28 June 2012)*.
- [8] **Chandrashekhar, E. and Rishi, J.** (2015). Modeling and analysis of automotive wheel rim using FEM, *International Journal of Innovative Research in Technology (IJIRT)*, 3(4), 24–32.
- [9] **Xiaoyin, W., Xiandong, L., Yingchun, S., Xiaofei, W., Wanghao, L. and Yue, P.** (2016). Lightweight design of automotive wheel made of long glass fiber reinforced thermoplastic, *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 230(10), 1634–1643.
- [10] **König, O. and Wintermantel, M.** (2004). CAD-based evolutionary design optimization with CATIA V5, *Proceedings of 1st Weimar Optimization and Stochastic Days WOST, Weimar*, 1–30.

- [11] **Giger, M. and Ermanni, P.** (2005). Development of CFRP racing motorcycle rims using a heuristic evolutionary algorithm approach, *Structural and Multidisciplinary Optimization*, 30(1), 54–65.
- [12] **Lei, F., Qiu, R., Bai, Y. and Yuan, C.** (2018). An integrated optimization for laminate design and manufacturing of a CFRP wheel hub based on structural performance, *Structural and Multidisciplinary Optimization*, 57(6), 2309–2321.
- [13] **Wang, D., Xu, W., Wang, Y. and Gao, J.** (2021). Design and optimization of tapered carbon-fiber-reinforced polymer rim for carbon/aluminum assembled wheel, *Polymer Composites*, 42(1), 253–270.
- [14] **Porsche.com.** *Porsche 911 Turbo Carbon wheel and tyre set - Porsche AG*, Retrieved from <https://www.porsche.com/international/accessoriesandservice/tequipment/specials/summer-tyres/carbon/>.
- [15] **Kaw, A.K.** (2005). *Mechanics of composite materials*, CRC press.
- [16] **Jones, R.M.** (2018). *Mechanics of composite materials*, CRC press.
- [17] **Friedrich, K. and Almajid, A.A.** (2013). Manufacturing aspects of advanced polymer composites for automotive applications, *Applied Composite Materials*, 20(2), 107–128.
- [18] **Şahin, Y.** (2000). *Kompozit malzemelere giriş*, Gazi kitabevi.
- [19] **Singh, K.K. and Shinde, M.,** (2022). Low Velocity Impact on Fibre Reinforced Polymer Composite Laminates, Impact Behavior of Fibre Reinforced Laminates, Springer, pp.83–105.
- [20] **Korkut, S.** (2017). Statik ve dinamik yükler altında kompozit plakaların hasar durumlarına karşı davranışlarının incelenmesi, *Fen Bilimleri Enstitüsü, Makine Mühendisliği Anabilim Dalı, Konstrüksiyon Bilim Dalı, İstanbul*.
- [21] **Hexcel** (2013). *Hexply Prepreg Technology*.
- [22] **Datoo, M.H.** (2012). *Mechanics of fibrous composites*, Springer Science & Business Media.
- [23] **Hill, R.** (1950). The mathematical theory of plasticity. Oxford Univ, Press, London.
- [24] **Gol'denblat, I. and Kopnov, V.** (1965). Strength of glass-reinforced plastics in the complex stress state, *Polymer Mechanics*, 1(2), 54–59.
- [25] **Tsai, S.W. and Wu, E.M.** (1971). A general theory of strength for anisotropic materials, *Journal of composite materials*, 5(1), 58–80.
- [26] **Hoffman, O.** (1967). The brittle strength of orthotropic materials, *Journal of Composite Materials*, 1(2), 200–206.

- [27] **Hashin, Z. and Rotem, A.** (1973). A fatigue failure criterion for fiber reinforced materials, *Journal of composite materials*, 7(4), 448–464.
- [28] **Hashin, Z.** (1980). Failure Criteria for Unidirectional Fiber Composites, *Journal of Applied Mechanics*, 47(2), 329–334.
- [29] **Puck, A. and Schneider, W.** (1969). On failure mechanisms and failure criteria of filament-wound glass-fibre/resin composites, *Plastics and Polymers*, 37(127), 33–43.
- [30] **Puck, A.** (1992). Fracture criteria for highly stressed fibre'plastic composites which meet requirements of design practice, *Kunststoffe# German Plastics*, 82, 34–38.
- [31] **Puck, A.** (1996). *Festigkeitsanalyse von Faser-Matrix-Laminaten: Modelle für die Praxis*, Hanser.
- [32] **Puck, A., Kopp, J. and Knops, M.** (2002). Guidelines for the determination of the parameters in Puck's action plane strength criterion, *Composites Science and Technology*, 62(3), 371–378.
- [33] **Chang, F.K. and Chang, K.Y.** (1987). Post-failure analysis of bolted composite joints in tension or shear-out mode failure, *Journal of Composite Materials*, 21(9), 809–833.
- [34] **Chang, F.K. and Chang, K.Y.** (1987). A progressive damage model for laminated composites containing stress concentrations, *Journal of composite materials*, 21(9), 834–855.
- [35] **Christensen, P.W. and Klarbring, A.** (2008). *An introduction to structural optimization*, volume 153, Springer Science & Business Media.
- [36] **Yaşartekin, M.**, (2012). Bir akrobasi uçağının yatay dengeleyicisinin yapısal tasarımı, Master's thesis, Fen Bilimleri Enstitüsü.
- [37] **Çakır, M.K.**, (2008). Structural optimization of a trainer aircraft wing by using genetic algorithm, Master's thesis, Middle East Technical University.
- [38] **Şen, Z.** (2004). *Genetik algoritmalar ve en iyileme yöntemleri*, Su Vakfı.
- [39] **Guide, M.A.** (2020). Multi-Objective Genetic Algorithm II, *ModeFrontier Algorithm Guide*.
- [40] **Guide, M.A.** (2020). *Algorithm Guide, DOE Algorithms*.
- [41] **Chen, V.C., Tsui, K.L., Barton, R.R. and Allen, J.K.** (2002). A review of design and modeling in computer experiments, *Handbook in Statistics: Statistics in Industry*.
- [42] **Tyre, E. and Organisation, R.T.** (2003). *ETRTO: Standards Manual*, ETRTO.

- [43] **ISO/3006:2015(E)** (2015). Road vehicles — Passenger car wheels for road use — Test methods, **Standard ISO 3006:2015(E)**, International Organization for Standardization, Geneva, CH.
- [44] **VkBI** (1998). *Alternating Torsion Test. Guidelines for the testing and inspection of custom wheels for motor vehicles and their trailers.*
- [45] **Tomblin, J., Sherraden, J. and Seneviratne** (2002). *A-basis and B-basis design allowables for epoxy-based prepreg Toray T700SC-12K-50C/2510 plain weave fabric.*
- [46] **Corporation, M.S.** (2020). *MSC. Nastran 2020: Quick Reference Guide*, MSC Software Corporation.



APPENDICES

APPENDIX A : Design of Experiment Points in Optimization

APPENDIX B : Pareto Front Designs





APPENDIX A : Sobol Design of Experiment Data



Table A.1 : Sobol design of experiment data.

ID	NB500	NB540	NB590	NB670	NB710	NB740	(P0/P1/P2/P3/P4/P5/P6/P7/P8/P9)
0	[0000000000]	[0000000000]	[0000000000]	[0000000000]	[0000000000]	[0000000000]	[0/0/0/0/0/0/0/0/0/0]
1	[0111001000]	[0011010101]	[1011101010]	[1110001111]	[1011011100]	[1101101000]	[135/45/45/45/45/45/45/45/135/45]
2	[1000110111]	[1100101010]	[0100010101]	[0001110000]	[0100100011]	[0010010111]	[45/135/135/135/135/135/135/135/45/135]
3	[1100111000]	[0110101001]	[1110001011]	[1100000010]	[0010010111]	[1011010100]	[90/135/45/90/135/0/45/0/135/90]
4	[0011000111]	[1001010110]	[0001110100]	[0011111101]	[1101101000]	[0100101011]	[0/45/135/0/45/90/135/90/45/0]
5	[0100001111]	[1010000011]	[1010011110]	[1101110010]	[0110110100]	[1001000011]	[135/0/90/45/0/135/90/135/90/45]
6	[1011110000]	[0101111100]	[0101100001]	[0010001101]	[1001001011]	[0110111100]	[45/90/0/135/90/45/0/45/0/135]
7	[1101011001]	[0100000001]	[1010110100]	[1010011010]	[0101111111]	[0110011011]	[0/90/135/0/0/135/45/90/0/0]
8	[0010100110]	[1011111110]	[0101001011]	[0101100101]	[1010000000]	[1001100100]	[90/0/45/90/90/45/135/0/90/90]
9	[0101101110]	[1000101011]	[1110100001]	[1011101010]	[0001011100]	[0100001100]	[45/45/0/135/135/0/90/45/45/135]
10	[1010010001]	[0111101010]	[0001011110]	[0100010101]	[1110100011]	[1011110011]	[135/135/90/45/45/90/0/135/135/45]
11	[1110011110]	[1101010111]	[1011000000]	[1001100111]	[1000010111]	[0010110000]	[0/135/0/0/45/45/90/0/45/0]
12	[0001100001]	[0010101000]	[0100111111]	[0110011000]	[0111101000]	[1101001111]	[90/45/90/90/135/135/0/90/135/90]
13	[0110101001]	[0001111101]	[1111010101]	[1000010111]	[1100110100]	[0000100111]	[45/0/135/135/90/90/45/135/0/135]
14	[1001010110]	[1110000010]	[0000101010]	[0111101000]	[0011001011]	[1111011000]	[135/90/45/45/0/0/135/45/90/45]
15	[1110100011]	[1100110001]	[0000011011]	[1110101110]	[1100101010]	[0010000001]	[0/0/90/90/90/45/45/135/135/90]
16	[0001011100]	[0011001110]	[1111100100]	[0001010001]	[0011010101]	[1101111110]	[90/90/0/0/0/135/135/45/45/0]
17	[0110010100]	[0000011011]	[0100001110]	[1111011110]	[1000001001]	[0000010110]	[45/135/45/45/45/90/90/0/90/45]
18	[1001101011]	[1111100100]	[1011110001]	[0000100001]	[0111110110]	[1111101001]	[135/45/135/135/135/0/0/90/0/135]
19	[1101100100]	[0101100111]	[0001101111]	[1101010011]	[0001000010]	[0110101010]	[0/45/45/90/135/135/90/45/90/90]
20	[0010011011]	[1010011000]	[1110010000]	[0010101100]	[1110111101]	[1001010101]	[90/135/135/0/45/45/0/135/0/0]
21	[0101010011]	[1001001101]	[0101111010]	[1100100011]	[0101100001]	[0100111101]	[45/90/90/45/0/0/45/90/135/45]
22	[1010101100]	[0110110010]	[1010000101]	[0011011100]	[1010011110]	[1011000010]	[135/0/0/135/90/90/135/0/45/135]
23	[1100000101]	[0111001111]	[0101010000]	[1011001011]	[0110101010]	[1011100101]	[90/0/135/0/0/0/90/135/45/0]
24	[0011111010]	[1000110000]	[1010101111]	[0100110100]	[1001010101]	[0100011010]	[0/90/45/90/90/90/0/45/135/90]

Table A.1 (continued) : Sobol design of experiment data.

ID	NB500	NB540	NB590	NB670	NB710	NB740	(P0/P1/P2/P3/P4/P5/P6/P7/P8/P9)
25	[0100110010]	[1011100101]	[0001000101]	[1010111011]	[0010001001]	[1001110010]	[135/135/0/135/135/135/45/0/0/135]
26	[1011001101]	[0100011010]	[1110111010]	[0101000100]	[1101110110]	[0110001101]	[45/45/90/45/45/45/135/90/90/45]
27	[1111000010]	[1110011001]	[0100100100]	[1000110110]	[1011000010]	[1111001110]	[90/45/0/0/45/90/45/45/0/0]
28	[0000111101]	[0001100110]	[1011011011]	[0111001001]	[0100111101]	[0000110001]	[0/135/90/90/135/0/135/135/90/90]
29	[0111110101]	[0010110011]	[0000110001]	[1001000110]	[1111100001]	[1101011001]	[135/90/135/135/90/45/90/90/45/135]
30	[1000001010]	[11101001100]	[1111001110]	[0110111001]	[0000011110]	[0010100110]	[45/0/45/45/0/135/0/0/135/45]
31	[1100100001]	[1010011110]	[1010111110]	[0001000011]	[1000010111]	[0100110111]	[0/0/45/135/135/135/0/0/45/45]
32	[0011011110]	[0101100001]	[0101000001]	[1110111100]	[0111110100]	[1011001000]	[90/90/135/45/45/45/90/90/135/135]
33	[0100010110]	[0110110100]	[1110101011]	[0000110011]	[1100101000]	[0110100000]	[45/135/90/0/0/0/135/135/0/90]
34	[1011101001]	[1001001011]	[0001010100]	[1111001100]	[0011010111]	[1001011111]	[135/45/0/90/90/90/45/45/90/0]
35	[1111100110]	[0011001000]	[1011001010]	[0010111110]	[0101100011]	[0000011100]	[0/45/90/135/90/45/135/90/0/45]
36	[0000011001]	[1100110111]	[0100110101]	[1101000001]	[1010011100]	[1111100011]	[90/135/0/45/0/135/45/0/90/135]
37	[0111010001]	[1111100010]	[1111011111]	[0011001110]	[0001000000]	[0010001011]	[45/90/45/0/45/90/0/45/45/90]
38	[1000101110]	[0000011101]	[0000100000]	[1100110001]	[1110111111]	[1101110100]	[135/0/135/90/135/0/90/135/135/0]
39	[1110000111]	[0001100000]	[1111110101]	[0100100110]	[0010001011]	[1101010011]	[90/0/0/45/45/90/135/0/135/135]
40	[0001111000]	[1110011111]	[0000001010]	[1011011001]	[1101110100]	[0010101100]	[0/90/90/135/135/0/45/90/45/45]
41	[0110110000]	[1101001010]	[1011100000]	[0101010110]	[0110101000]	[1111000100]	[135/135/135/90/90/45/0/135/90/0]
42	[1001001111]	[0010110101]	[0100011111]	[1010101001]	[1001010111]	[0000111011]	[45/45/45/0/0/135/90/45/0/90]
43	[1101000000]	[1000110110]	[1110000001]	[0111011011]	[1111100011]	[1001111000]	[90/45/135/45/0/0/0/90/90/135]
44	[0010111111]	[0111001001]	[0001111110]	[1000100100]	[0000011100]	[0110000111]	[0/135/45/135/90/90/90/0/0/45]
45	[0101110111]	[0100011100]	[1010010100]	[0110101011]	[1011000000]	[1011101111]	[135/90/0/90/135/135/135/45/135/0]
46	[1010001000]	[1011100011]	[0101101011]	[1001010100]	[0100111111]	[0100010000]	[45/0/90/0/45/45/45/135/45/90]
47	[1101111101]	[1001010000]	[0101011010]	[0000010010]	[1011011110]	[1001001001]	[90/90/45/135/135/0/135/45/0/45]
48	[0010000010]	[0110101111]	[1010100101]	[1111110110]	[0100100001]	[0110110110]	[0/0/135/45/45/90/45/135/90/135]
49	[0101001010]	[0101111010]	[0001001111]	[0001100010]	[1111111101]	[1011011110]	[135/45/90/0/0/135/0/90/45/90]

Table A.1 (continued) : Sobol design of experiment data.

ID	NB500	NB540	NB590	NB670	NB710	NB740	(P0/P1/P2/P3/P4/P5/P6/P7/P8/P9)
50	[1010110101]	[1010000101]	[1110110000]	[1110011101]	[0000000010]	[0100100001]	[45/135/0/90/90/45/90/0/135/0]
51	[1110111010]	[0000000110]	[0100101110]	[0011101111]	[0110110110]	[1101100010]	[90/135/90/135/90/90/0/135/45/45]
52	[0001000101]	[1111111001]	[1011010001]	[1100010000]	[1001001001]	[0010011101]	[0/45/0/45/0/0/90/45/135/135]
53	[0110001101]	[1100101100]	[0000111011]	[0010011111]	[0010010101]	[1111111010]	[135/0/45/0/45/45/135/0/0/90]
54	[1001110010]	[0011010011]	[1111000100]	[1101100000]	[1101101010]	[0000001010]	[45/90/135/90/135/135/45/90/90/0]
55	[1111011011]	[0010101110]	[0000010001]	[0101110111]	[0001011110]	[0000010110]	[0/90/0/45/45/45/0/45/90/135]
56	[0000100100]	[1101010001]	[1111110110]	[1010001000]	[1110100001]	[11111010010]	[90/0/90/135/135/135/90/135/0/45]
57	[0111101100]	[1110000100]	[0100000100]	[0100000111]	[0101111101]	[00101111010]	[45/45/135/90/90/90/135/90/135/0]
58	[1000010011]	[0001111011]	[1011111011]	[1011111000]	[1010000010]	[1101000101]	[135/135/45/0/0/45/0/45/90]
59	[1100011100]	[1011111000]	[0001100101]	[0110001010]	[1100110110]	[0100000110]	[0/135/135/45/0/135/135/135/135/135]
60	[0011100011]	[0100000111]	[11100011010]	[1001110101]	[0011001001]	[10111110001]	[90/45/45/135/90/45/45/45/45/45]
61	[0100101011]	[0111010010]	[01011110000]	[0111111010]	[1000010101]	[01100100001]	[45/0/0/90/135/0/0/90/0]
62	[1011010100]	[1000101101]	[1010001111]	[1000000101]	[0111101010]	[1001101110]	[135/90/90/0/45/90/90/90/0/90]
63	[1100010101]	[0110000110]	[0011000111]	[1010100100]	[1001110100]	[1101001100]	[45/45/135/45/90/135/0/0/0/90]
64	[0011101010]	[1001111001]	[1100111000]	[0101011011]	[0110001011]	[0010110011]	[135/135/45/135/0/45/90/90/90/0]
65	[0100100010]	[1010101100]	[0111010010]	[1011010100]	[1101010111]	[11111011011]	[0/90/0/90/45/0/135/135/45/45]
66	[1011011101]	[0101010011]	[1000101101]	[0100101011]	[0010101000]	[0000100100]	[90/0/90/0/135/90/45/45/135/135]
67	[1111010010]	[1111010000]	[0010110011]	[1001011001]	[0100011100]	[1001100111]	[45/0/0/45/135/45/135/90/45/90]
68	[0000101101]	[0000101111]	[1101001100]	[0110100110]	[1011100011]	[0110011000]	[135/90/90/135/45/135/45/0/135/0]
69	[0111100101]	[0011111010]	[0110100110]	[1000101001]	[0000111111]	[1011110000]	[0/135/135/90/0/90/0/45/0/45]
70	[1000011010]	[1100000101]	[1001011001]	[0111010110]	[1111000000]	[0100001111]	[90/45/45/0/90/0/90/135/90/135]
71	[1111010011]	[1101111000]	[0110001100]	[1111000001]	[0011110100]	[0100101000]	[135/45/90/135/0/90/135/0/90/0]
72	[0001001100]	[0010000111]	[1001110011]	[0000111110]	[1100001011]	[1011010111]	[45/135/0/45/90/0/45/90/0/90]
73	[0110000100]	[0001010010]	[0010011001]	[1110110001]	[0111010111]	[0110111111]	[90/90/45/0/135/45/0/135/135/135]
74	[1001111011]	[1110101101]	[11101100110]	[0001001110]	[1000101000]	[1001000000]	[0/0/135/90/45/135/90/45/45/45]

Table A.1 (continued) : Sobol design of experiment data.

ID	NB500	NB540	NB590	NB670	NB710	NB740	(P0/P1/P2/P3/P4/P5/P6/P7/P8/P9)
75	[1101110100]	[0100101110]	[011111110000]	[11001111100]	[11100111100]	[0000000011]	[135/0/45/135/45/0/0/90/135/0]
76	[0010001011]	[1011010001]	[1000000111]	[0011000011]	[0001100011]	[1111111100]	[45/90/135/45/135/90/90/0/45/90]
77	[0101000011]	[1000000100]	[0011101101]	[1101001100]	[1010111111]	[0010010100]	[90/135/90/0/90/135/135/45/90/135]
78	[1010111100]	[0111111011]	[1100010010]	[0010110011]	[0101000000]	[1101101011]	[0/45/0/90/0/45/45/135/0/45]
79	[1101001001]	[0101001000]	[1100100011]	[1011110101]	[1010100001]	[0000110010]	[135/135/135/45/90/0/135/45/45/90]
80	[0010110110]	[1010110111]	[0011011100]	[0100001010]	[0101011110]	[1111001101]	[45/45/45/135/0/90/45/135/135/0]
81	[0101111110]	[1001100010]	[1000110110]	[1010000101]	[1110000010]	[0010100101]	[90/0/0/90/45/135/0/90/0/45]
82	[1010000001]	[0110011101]	[0111001001]	[0101111010]	[0001111101]	[1101011010]	[0/90/90/0/135/45/90/0/90/135]
83	[1110001110]	[1100011110]	[1101010111]	[1000001000]	[0111001001]	[0100011001]	[135/90/0/45/135/90/0/135/0/90]
84	[0001110001]	[0011100001]	[0010101000]	[0111110111]	[1000110110]	[1011100110]	[45/0/90/135/45/0/90/45/90/0]
85	[0110111001]	[0000110100]	[1001000010]	[1001111000]	[0011101010]	[0110001110]	[90/45/135/90/0/45/135/0/45/45]
86	[1001000110]	[1111001011]	[0110111101]	[0110000111]	[1100010101]	[1001110001]	[0/135/45/0/90/135/45/90/135/135]
87	[1111101111]	[1110110110]	[1001101000]	[1110010000]	[0000100001]	[1001010110]	[45/135/90/135/0/45/0/45/135/0]
88	[0000010000]	[0001001001]	[0110010111]	[0001101111]	[1111011110]	[0110101001]	[135/45/0/45/90/135/90/135/45/90]
89	[0111011000]	[0010011100]	[1101111101]	[1111110000]	[0100000010]	[1011000001]	[0/0/45/0/135/90/135/90/90/135]
90	[1000100111]	[1101100011]	[0010000010]	[0000011111]	[1011111101]	[0100111110]	[90/90/135/90/45/0/45/0/0/45]
91	[1100101000]	[0111100000]	[1000011100]	[1101101101]	[1101001001]	[1101111101]	[45/90/45/135/45/135/135/135/90/0]
92	[0011010111]	[1000011111]	[0111100011]	[0010010010]	[0010110110]	[0010000010]	[135/0/135/45/135/45/45/45/0/90]
93	[0100011111]	[1011001010]	[1100001001]	[1100011101]	[1001101010]	[1111101010]	[0/45/90/0/90/0/0/0/135/135]
94	[1011100000]	[0100110101]	[0011110110]	[0011100010]	[0110010101]	[0000010101]	[90/135/0/90/0/90/90/90/45/45]
95	[1111001011]	[0011100111]	[0110000110]	[0100011000]	[1110000000]	[0110000100]	[135/135/0/0/135/90/90/90/135/45]
96	[0000110100]	[1100011000]	[10011111001]	[1011100111]	[0001111111]	[1001111011]	[45/45/90/90/45/0/0/45/135]
97	[0111111100]	[1111001101]	[0010010011]	[0101101000]	[1010100011]	[0100010011]	[90/0/135/135/0/45/45/45/90/90]
98	[1000000011]	[0000110010]	[1101101100]	[1010010111]	[0101011100]	[1011101100]	[0/90/45/45/90/135/135/135/0/0]
99	[1100001100]	[1010110001]	[0111110010]	[0111100101]	[0011101000]	[0010101111]	[135/90/135/0/90/0/45/0/90/45]



APPENDIX B : Pareto Front Designs



Table B.1 : Pareto front designs.

ID	NB500	NB540	NB590	NB670	NB710	NB740	(P0/P1/P2/P3/P4/P5/P6/P7/P8/P9)
1992	[1011110000]	[1111100101]	[10100000110]	[0100000110]	[10110110111]	[1100101110]	(0/0/90/45/45/90/45/0/45/0)
2335	[1111110000]	[1111100101]	[1010100110]	[0100000110]	[1011101111]	[0000011110]	(0/90/90/45/90/45/0/0/45/0)
2436	[1000110110]	[1110100111]	[01000000010]	[0000010110]	[1011001111]	[0000011010]	(0/90/45/135/45/45/0/45/45/0)
2489	[1011110000]	[1111100101]	[1010000110]	[0100000110]	[1011011011]	[1100101110]	(0/0/90/45/45/90/45/0/45/0)
2688	[1111110000]	[1111100101]	[1010100110]	[0100000110]	[1011101111]	[0000011110]	(0/90/90/45/90/45/0/0/45/0)
2896	[1011100000]	[1110100111]	[1010100110]	[0100000110]	[1011101111]	[0000011110]	(0/90/90/45/90/45/0/0/135/90)
3270	[1011110000]	[1111100101]	[10100000110]	[0100000110]	[1011011011]	[1100101110]	(0/0/90/45/45/90/45/0/45/0)
3281	[1011100010]	[0110111101]	[11000000010]	[1010010000]	[1011001111]	[0000011110]	(0/45/135/0/90/45/45/0/90/0)
3389	[1011100000]	[1110100111]	[1010100110]	[0100000110]	[1011101111]	[0000011110]	(0/90/90/45/90/45/0/0/135/90)
3419	[1011100010]	[0110111111]	[01001000010]	[1010010000]	[1011001101]	[0000011110]	(0/45/135/0/90/45/45/0/90/0)
3476	[1111110000]	[1111100101]	[1010100110]	[0100000110]	[1011101111]	[0000011110]	(0/90/90/45/90/45/0/0/45/0)
3489	[1011100010]	[0110111101]	[11000000010]	[1010010000]	[1011001111]	[0000011110]	(0/45/135/0/90/45/45/0/90/0)
3527	[1011100000]	[1110100111]	[1010100110]	[0100000110]	[1011101111]	[0000011110]	(0/90/90/45/90/45/0/0/135/90)
3553	[1000110110]	[1110100111]	[01000000010]	[0000010110]	[1011001111]	[0000011010]	(0/90/45/135/45/45/0/45/45/0)
3555	[1001111000]	[1111100101]	[10100000110]	[0100000110]	[1010011011]	[1100101110]	(0/0/90/45/135/0/45/0/135/0)
3637	[1000110110]	[1110100111]	[01000000010]	[0000010110]	[1011001111]	[0000011010]	(0/90/45/135/45/45/0/45/45/0)
3641	[1011010011]	[0111110101]	[11100000110]	[0000010110]	[1011101110]	[1111111111]	(1/45/90/90/0/45/0/0/45/0)
3658	[1111110000]	[1111100101]	[1010100110]	[0100000110]	[1011101111]	[0000011110]	(0/90/90/45/90/45/0/0/45/0)
3689	[1111101010]	[1111100101]	[11100000110]	[0000010110]	[1011101110]	[1111111111]	(1/45/90/0/90/45/90/90/45/0)
3698	[1011100010]	[0111100101]	[11100000110]	[0000010110]	[1011101110]	[1011111010]	(0/90/45/45/0/45/0/90/45/0)
3731	[1011010011]	[0111110101]	[11100000110]	[0000010110]	[1011101110]	[1111111111]	(1/45/90/90/0/45/0/0/45/0)
3760	[1011100010]	[0110111101]	[11000000010]	[1010010000]	[1011001111]	[0000011110]	(0/45/135/0/90/45/45/0/90/0)
3762	[1000110110]	[1110100111]	[01000000010]	[0000010110]	[1011001111]	[0000011010]	(0/90/45/135/45/45/0/45/45/0)
3793	[1000110110]	[1110100111]	[01000000010]	[0000010110]	[1011001111]	[0000011010]	(0/90/45/135/45/45/0/45/45/0)
3796	[1011100010]	[0110111111]	[01001000010]	[1010010000]	[1011001101]	[0000011110]	(0/45/135/0/90/45/45/0/90/0)

Table B.1 (continued) : Pareto front designs.

ID	NB500	NB540	NB590	NB670	NB710	NB740	(P0/P1/P2/P3/P4/P5/P6/P7/P8/P9)
3819	[1000110110]	[1110100111]	[0100000010]	[0000010110]	[1011001111]	[0000011010]	(0/90/45/135/45/45/0/45/45/0)
3836	[1000110110]	[1110100111]	[0100000010]	[0000010110]	[1011001111]	[00000011010]	(0/90/45/135/45/45/0/45/45/0)
3843	[1000110110]	[1110100111]	[0100000010]	[0000010110]	[1011001111]	[00000011010]	(0/90/45/135/45/45/0/45/45/0)
3869	[1000110110]	[1110100111]	[0100000010]	[0000010110]	[1011001111]	[00000011010]	(0/90/45/135/45/45/0/45/45/0)
3907	[1000110110]	[1110100011]	[0100100110]	[0000010110]	[1011111101]	[00000010110]	(0/90/135/135/0/45/0/45/45/0)
3972	[1000110110]	[1110100111]	[0100000010]	[0000010110]	[1011001111]	[00000011010]	(0/90/45/135/45/45/0/45/45/0)
3990	[1011100010]	[0110111101]	[1110000010]	[1010010000]	[1011001111]	[00000011110]	(0/45/135/0/90/45/45/0/90/0)
4077	[1011111000]	[0110110110]	[0100100110]	[0100000110]	[1011011011]	[0010011011]	(1/45/90/90/135/45/0/90/45/0)
4092	[1011010011]	[0111110101]	[1110000110]	[0000010110]	[1011101110]	[1111111111]	(1/45/90/90/0/45/0/0/45/0)
4127	[1011100000]	[1110100111]	[1010100110]	[0100000110]	[1011101111]	[00000011110]	(0/90/90/45/90/45/0/0/135/90)
4151	[1111110000]	[1111100101]	[1010100110]	[0100000110]	[1011101111]	[00000011110]	(0/90/90/45/90/45/0/0/45/0)
4189	[1011100010]	[0111100101]	[1110000110]	[0000010110]	[1011101110]	[1011111010]	(0/90/45/45/0/45/0/90/45/0)
4237	[1000110110]	[1110100011]	[1100000100]	[1010010000]	[1001011010]	[11000011010]	(0/90/45/135/45/45/0/45/45/0)
4244	[1011010011]	[0111110101]	[1110000110]	[0000010110]	[1011101110]	[1111111111]	(1/45/90/90/0/45/0/0/45/0)
4247	[1011100110]	[0111100011]	[1100000111]	[0010011000]	[1001011110]	[1101011111]	(1/45/0/90/90/90/90/45/90/0)
4253	[1111100010]	[1111101100]	[1010000110]	[0100000110]	[1011011011]	[0010010011]	(1/45/90/90/135/45/0/90/135/0)
4347	[1011100010]	[0110111111]	[10100100010]	[1010010000]	[1011001101]	[00000011110]	(0/45/135/0/90/45/45/0/90/0)
4352	[1011100010]	[0111100101]	[1110000110]	[0000010110]	[1011101110]	[1011111010]	(0/90/45/45/0/45/0/90/45/0)
4371	[1011110000]	[1111100101]	[1010000110]	[0100000110]	[1011011011]	[1100101110]	(0/0/90/45/45/90/45/0/45/0)
4378	[1011100010]	[0111100101]	[1110000110]	[0000010110]	[1011101110]	[1011111010]	(0/90/45/45/0/45/0/90/45/0)
4456	[1000101110]	[0110010111]	[10110000110]	[0000010110]	[1011101101]	[00001011010]	(0/90/45/90/90/45/0/45/45/0)
4465	[1011110000]	[1111100100]	[1010000110]	[0100000110]	[0011010011]	[1110101110]	(0/0/90/45/0/90/0/0/45/0)
4467	[1111110100]	[1110110110]	[1010100110]	[0100000110]	[1011101111]	[00000011110]	(0/90/90/45/90/45/0/0/45/0)
4468	[1111100000]	[1110100111]	[1010100110]	[0100000110]	[1011101111]	[00000011110]	(0/90/90/45/45/45/0/0/135/90)
4473	[1001101110]	[0110110111]	[10110000110]	[0000010110]	[1011011101]	[00000011010]	(0/90/45/135/45/45/0/45/45/0)

Table B.1 (continued) : Pareto front designs.

ID	NB500	NB540	NB590	NB670	NB710	NB740	(P0/P1/P2/P3/P4/P5/P6/P7/P8/P9)
4486	[1000110110]	[1110100011]	[0100100110]	[0000010110]	[1011111101]	[00000010110]	(0/90/135/135/0/45/0/45/45/0)
4527	[1111110001]	[1111100101]	[1010000110]	[0110010000]	[1001011010]	[1110101110]	(0/0/90/45/45/90/0/90/45/0)
4534	[1111100010]	[1111101100]	[1010000110]	[0100000110]	[1011011011]	[00100100111]	(1/45/90/90/135/45/0/90/135/0)
4571	[1000101110]	[0110010111]	[0110000110]	[0000010110]	[1011101101]	[0001011010]	(0/90/45/90/90/45/0/45/45/0)
4581	[1011100010]	[0111100101]	[1110000110]	[0000010110]	[1011101110]	[1011111010]	(0/90/45/45/0/45/0/90/45/0)
4584	[1011111000]	[1111100101]	[1010000110]	[0100000110]	[1010011011]	[1100101110]	(0/0/90/45/90/0/45/0/135/0)
4597	[1011100010]	[0111100101]	[1100100110]	[0000011100]	[1001101110]	[1111111111]	(1/90/90/135/90/45/0/0/45/0)
4600	[1011100010]	[0111100101]	[1110000110]	[0000010110]	[1010111101]	[1111011000]	(0/90/45/45/0/45/0/90/45/0)
4613	[1000110110]	[1110110111]	[1001000100]	[1010010000]	[1001011010]	[1100011010]	(0/90/45/135/45/45/0/45/45/0)
4639	[1111110100]	[1110110110]	[1010100110]	[0100000110]	[1011101111]	[0000001110]	(0/90/90/45/90/45/0/0/45/0)
4661	[1011100010]	[0111100101]	[1100100110]	[0000011100]	[1001101110]	[1111111111]	(1/90/90/135/90/45/0/0/45/0)
4663	[1011110000]	[1111100101]	[1010000110]	[0100000110]	[1011011011]	[1100101110]	(0/0/90/45/45/90/45/0/45/0)
4668	[1011100010]	[0110111101]	[1100000010]	[1010010000]	[1011001111]	[0000001110]	(0/45/135/0/90/45/45/0/90/0)
4672	[1011111000]	[1111100101]	[1010000110]	[0100000110]	[1010011011]	[1100101110]	(0/0/90/45/90/0/45/0/135/0)
4674	[1011110000]	[1111100101]	[1110100110]	[0100000011]	[1010111101]	[1011111110]	(0/45/135/0/90/45/0/0/90/0)
4678	[1011100010]	[0110110111]	[0110000110]	[0000010110]	[1011101111]	[0000001110]	(0/90/0/135/45/45/0/90/45/0)
4694	[1011110000]	[1111100100]	[1010000110]	[0100000110]	[0011010011]	[1110101110]	(0/0/90/45/0/90/0/0/45/0)
4732	[1110110110]	[1110100011]	[1100000100]	[1010010000]	[1011011011]	[0010010010]	(0/90/45/45/0/45/0/90/135/0)
4740	[1011110000]	[1111100101]	[1010000110]	[0100000110]	[1011011011]	[1100101110]	(0/0/90/45/45/90/45/0/45/0)
4745	[1011111000]	[1111100101]	[1010000110]	[0100000110]	[1010011011]	[1100101110]	(0/0/90/45/90/0/45/0/135/0)
4753	[1011111000]	[0110110101]	[1010000110]	[0100000110]	[1010011011]	[1100101110]	(0/0/90/45/135/0/45/90/45/0)
4765	[1011100000]	[1110100111]	[1010100110]	[0100000110]	[1011101111]	[0000001110]	(0/90/90/45/90/45/0/0/135/90)
4769	[1001111010]	[0111100101]	[1110100110]	[0100000011]	[1010111101]	[1111111110]	(0/45/135/0/90/45/0/0/90/0)
4770	[0111110101]	[1101100101]	[1100100110]	[0000010110]	[1011101110]	[1111011110]	(0/90/90/45/90/45/0/0/45/0)
4778	[1011111000]	[0110110110]	[0100100110]	[0100000110]	[1011011011]	[0010011011]	(1/45/90/90/135/45/0/90/45/0)

Table B.1 (continued) : Pareto front designs.

ID	NB500	NB540	NB590	NB670	NB710	NB740	(P0/P1/P2/P3/P4/P5/P6/P7/P8/P9)
4781	[1011111000]	[1111100101]	[1010000110]	[0100000110]	[1010011011]	[1100101110]	(0/0/90/45/90/0/45/0/135/0)
4805	[1111000010]	[0111100101]	[1100011110]	[0000010110]	[1011101111]	[0101011111]	(1/135/90/135/90/45/0/45/45/0)
4807	[1011100010]	[0110110111]	[0110000110]	[0000010110]	[1011101111]	[0000001110]	(0/90/0/135/45/45/0/90/45/0)
4817	[1111100011]	[0111100101]	[1110000110]	[0000010110]	[1011011101]	[0001011011]	(1/45/0/45/90/135/0/135/45/0)
4847	[1011111000]	[1111100101]	[1010000110]	[0100000110]	[1010011011]	[1100101110]	(0/0/90/45/90/0/45/0/135/0)
4861	[1000110110]	[1110100111]	[0100000010]	[0000010110]	[1011001111]	[00000011010]	(0/90/45/135/45/45/0/45/45/0)
4868	[1001111000]	[1111100101]	[1010000110]	[0100000110]	[1010011011]	[1100101110]	(0/0/90/45/135/0/45/0/135/0)
4869	[1011010011]	[0111110101]	[1110000110]	[0000010110]	[1011101110]	[1111111111]	(1/45/90/90/0/45/0/0/45/0)
4879	[1111001100]	[0111110100]	[0100000111]	[0000010110]	[1011101111]	[0000010110]	(0/90/135/135/90/45/90/0/135/0)
4882	[1000110110]	[1110100011]	[1100000100]	[1010010000]	[1001011010]	[11000011010]	(0/90/45/135/45/45/0/45/45/0)
4945	[1011010011]	[0111110101]	[1110000110]	[0000010110]	[1011101110]	[1111111111]	(1/45/90/90/0/45/0/0/45/0)
4955	[1111101000]	[1111100101]	[1100100110]	[000001100]	[1001101110]	[1111111111]	(1/90/90/135/90/45/0/0/45/0)
4963	[1011110000]	[1111100101]	[1010000110]	[0100000110]	[1011011011]	[1100101110]	(0/0/90/45/45/90/45/0/45/0)
4973	[1011110010]	[0110110111]	[11110100110]	[0100000011]	[1010111101]	[0111111110]	(0/45/135/0/90/45/0/0/90/0)
4981	[1011100110]	[0111100011]	[1100000111]	[0010011000]	[1001011110]	[1101011111]	(1/45/0/90/90/90/90/45/90/0)
4982	[1011010011]	[0111110101]	[1110000110]	[0000010110]	[1011101110]	[1111111111]	(1/45/90/90/0/45/0/0/45/0)
4986	[1111110000]	[1111100101]	[1010100110]	[0100000110]	[1011101111]	[00000011110]	(0/90/90/45/90/45/0/45/0)
4996	[01111110101]	[1101100101]	[1100100110]	[0000010110]	[1011101110]	[1111011110]	(0/90/90/45/90/45/0/45/0)
4999	[1111100000]	[0111110101]	[1001000110]	[0000010110]	[1011011101]	[00001011011]	(1/45/0/45/90/135/0/135/45/0)
5011	[1011100010]	[0111100101]	[1100100110]	[000001100]	[1001101110]	[1111111111]	(1/90/90/135/90/45/0/0/45/0)
5012	[1011100110]	[0111100011]	[1100000111]	[0010011000]	[1001011110]	[1101011111]	(1/45/0/90/90/90/90/45/90/0)
5035	[1111100000]	[0111110101]	[1001000110]	[0000010110]	[1011011101]	[00001011011]	(1/45/0/45/90/135/0/135/45/0)
5044	[1011110010]	[0110110101]	[1100100110]	[0100000011]	[1010111101]	[0111111110]	(0/45/135/0/90/45/0/0/90/0)
5050	[1011100110]	[0111100011]	[1100000111]	[0010011000]	[1001011110]	[1101011111]	(1/45/0/90/90/90/90/45/90/0)
5051	[1111110000]	[1111100101]	[1010100110]	[0100000110]	[1011101111]	[00000011110]	(0/90/90/45/90/45/0/0/45/0)

Table B.1 (continued) : Pareto front designs.

ID	NB500	NB540	NB590	NB670	NB710	NB740	(P0/P1/P2/P3/P4/P5/P6/P7/P8/P9)
5062	[1000101010]	[0110110111]	[0110000110]	[0000010110]	[1011011101]	[00000011010]	(0/90/45/135/45/45/0/45/45/0)
5075	[1111100010]	[1111101100]	[1000100010]	[0000010110]	[1011001011]	[0010010011]	(1/45/90/90/135/45/0/90/135/0)
5079	[1000110110]	[1110100011]	[1100000100]	[1010010000]	[1001011010]	[11000011010]	(0/90/45/135/45/45/0/45/45/0)
5089	[1011100000]	[1111100101]	[1110100110]	[0100000011]	[1010111101]	[10111111110]	(0/45/135/0/90/45/0/0/90/0)
5093	[1001111010]	[0111100101]	[1110100110]	[0100000011]	[1010111101]	[11111111110]	(0/45/135/0/90/45/0/0/90/0)
5097	[1011100000]	[1110100111]	[1010100110]	[0100000110]	[1011101111]	[00000011110]	(0/90/90/45/90/45/0/0/135/90)
5111	[1011010011]	[0111110101]	[1110000110]	[0000010110]	[1011101110]	[11111111111]	(1/45/90/90/0/45/0/0/45/0)
5121	[1111100000]	[0111100101]	[1001000110]	[0000010110]	[1011011101]	[0001011011]	(1/45/0/45/90/135/0/135/45/0)
5128	[0011110011]	[0111110101]	[1100100110]	[0100000011]	[1010111101]	[01111111110]	(0/45/135/0/90/45/0/0/90/0)
5156	[1110110110]	[1110100011]	[1100000100]	[1010010000]	[1011011011]	[0010010010]	(0/90/45/45/0/45/0/90/135/0)
5161	[1011110010]	[0110110111]	[1110100110]	[0100000011]	[1010111101]	[01111111110]	(0/45/135/0/90/45/0/0/90/0)
5166	[1011100010]	[0110111101]	[0100100010]	[1010010000]	[1011001101]	[00000011110]	(0/45/135/0/90/45/45/0/90/0)
5171	[1111101000]	[1110100101]	[1100100110]	[0000011100]	[1001101110]	[11111111111]	(1/90/90/135/90/45/0/0/45/0)
5184	[1111101010]	[0111100011]	[1100100110]	[0000010110]	[1001011110]	[01010111111]	(1/135/90/45/90/45/0/90/45/0)
5194	[1111100001]	[1111100101]	[1100100110]	[0000011100]	[1001101110]	[11111111111]	(1/90/90/135/90/45/0/0/45/0)
5195	[1011111000]	[0110110101]	[1000000111]	[0000010110]	[1000111100]	[11111111111]	(1/90/90/90/135/45/0/90/45/0)
5211	[1011100010]	[0111100101]	[1100100110]	[0000011100]	[1001101110]	[11111111111]	(1/90/90/135/90/45/0/0/45/0)
5215	[1111110000]	[1111100101]	[1010100110]	[0100000110]	[1011101111]	[00000011110]	(0/90/90/45/90/45/0/0/45/0)
5217	[1011111000]	[0110110101]	[1010000110]	[0100000110]	[1010011011]	[11001011110]	(0/0/90/45/135/0/45/90/45/0)
5239	[1011100010]	[0110111101]	[0100100010]	[1010010000]	[1011001101]	[00000011110]	(0/45/135/0/90/45/45/0/90/0)
5252	[1011100010]	[0110110111]	[0110100110]	[0100000011]	[1010101101]	[11111111110]	(0/45/135/0/90/45/0/0/90/0)
5264	[1111110000]	[1111100101]	[1010100110]	[0100000110]	[1011101111]	[00000011110]	(0/90/90/45/90/45/0/0/45/0)
5270	[1011100010]	[0110111111]	[0100100010]	[1010010000]	[1011001101]	[00000011110]	(0/45/135/0/90/45/45/0/90/0)
5285	[1011100010]	[0110111101]	[1100000010]	[1010010000]	[1011001111]	[00000011110]	(0/45/135/0/90/45/45/0/90/0)
5332	[1111101010]	[1111100101]	[1110000110]	[0000010110]	[1011101110]	[11111111111]	(1/45/90/0/90/45/90/90/45/0)

Table B.1 (continued) : Pareto front designs.

ID	NB500	NB540	NB590	NB670	NB710	NB740	(P0/P1/P2/P3/P4/P5/P6/P7/P8/P9)
5339	[1011010010]	[0110111111]	[0100100010]	[1010010000]	[1011001101]	[0000011110]	(0/45/135/0/90/45/45/0/90/0)
5343	[1111100110]	[0111110111]	[0100100010]	[0000010110]	[1011001101]	[1000001010]	(0/90/45/90/45/45/0/45/45/90)
5357	[1011100000]	[1110100111]	[1010100110]	[0100000110]	[1011101111]	[0000011110]	(0/90/90/45/90/45/0/0/135/90)
5361	[1001111000]	[1111100101]	[1010000110]	[0100000110]	[1010011011]	[1100101110]	(0/0/90/45/135/0/45/0/135/0)
5362	[1011010011]	[0111110101]	[1110000110]	[0000010110]	[1011101110]	[1111111111]	(1/45/90/90/0/45/0/0/45/0)
5368	[1111100010]	[1111101100]	[1010000110]	[0100000110]	[1011011011]	[0010010011]	(1/45/90/90/135/45/0/90/135/0)
5369	[1011110000]	[0110110110]	[0100100110]	[0100000110]	[1011011011]	[0010011011]	(1/45/90/90/135/45/0/90/45/0)
5376	[1000110110]	[1110110111]	[1001000100]	[1010010000]	[1001011010]	[1100011010]	(0/90/45/135/45/45/0/45/45/0)
5382	[1111110110]	[1111100101]	[1100100110]	[0000010111]	[1011111111]	[1111111111]	(1/45/90/0/90/45/90/0/45/0)
5387	[1111100011]	[0111100101]	[1110000110]	[0000010110]	[1011011101]	[0001011011]	(1/45/0/45/90/135/0/135/45/0)
5395	[1111000010]	[0111100101]	[1100011110]	[0000010110]	[1011101111]	[0101011111]	(1/135/90/135/90/45/0/45/45/0)
5397	[1111100000]	[1111100101]	[1110000110]	[0000010110]	[1011011101]	[0001011011]	(1/45/0/45/90/135/0/135/45/0)
5421	[1011010010]	[0110111111]	[0100100010]	[1010010000]	[1011001101]	[0000011110]	(0/45/135/0/90/45/45/0/90/0)
5428	[1011100010]	[0110111101]	[1100000010]	[1010010000]	[1011001111]	[0000001110]	(0/45/135/0/90/45/45/0/90/0)
5435	[1000101110]	[0110010111]	[0110000110]	[0000010110]	[1011101101]	[0001011010]	(0/90/45/90/90/45/0/45/45/0)
5451	[1111101000]	[1110100101]	[1100100110]	[0000011100]	[1001101110]	[1111111111]	(1/90/90/135/90/45/0/0/45/0)
5457	[1111110100]	[1111000101]	[1100100110]	[0000010111]	[1011111111]	[1111111111]	(1/45/0/0/90/45/90/0/45/0)
5472	[1111110000]	[1111100101]	[1110000110]	[0000010110]	[1011101110]	[1011111010]	(0/90/45/45/0/45/0/0/45/0)
5474	[1000110110]	[0110110111]	[0110000110]	[0000010110]	[1011011101]	[00000011010]	(0/90/45/135/45/45/0/45/45/0)
5478	[1011110000]	[1111100100]	[1010000110]	[0100000110]	[0011010011]	[1110101110]	(0/0/90/45/0/90/0/0/45/0)
5482	[1011100010]	[1111100101]	[1110100010]	[0000010110]	[1010111100]	[1110101111]	(1/135/90/135/90/45/0/90/45/0)
5490	[1111100010]	[1111101100]	[1000100010]	[0000010110]	[1011001011]	[0010010011]	(1/45/90/90/135/45/0/90/135/0)
5492	[1111100000]	[0111110101]	[1001000110]	[0000010110]	[1011011101]	[0001011011]	(1/45/0/45/90/135/0/135/45/0)
5494	[1011110000]	[1111100100]	[1010000110]	[0100000110]	[0011010011]	[1110101110]	(0/0/90/45/0/90/0/0/45/0)
5498	[1011100010]	[0110111101]	[0100100010]	[1010010000]	[1011001101]	[0000011110]	(0/45/135/0/90/45/45/0/90/0)

Table B.1 (continued) : Pareto front designs.

ID	NB500	NB540	NB590	NB670	NB710	NB740	(P0/P1/P2/P3/P4/P5/P6/P7/P8/P9)
5499	[1111101000]	[1110100101]	[1100100110]	[0000011100]	[1001101110]	[1111111111]	(1/90/90/135/90/45/0/0/45/0)
5518	[1111000010]	[0110110111]	[0110011110]	[0000010110]	[1011101111]	[0101011111]	(1/135/90/135/90/45/0/45/45/0)
5532	[1011100110]	[0111100011]	[1110000011]	[0010011000]	[1001011110]	[1101011111]	(1/45/0/90/90/90/90/45/90/0)
5559	[1011100010]	[0111100101]	[1100100110]	[0000011100]	[1001101110]	[1111111111]	(1/90/90/135/90/45/0/0/45/0)
5563	[1001111000]	[1111100101]	[1010000110]	[0100000110]	[1010011011]	[1100101110]	(0/0/90/45/135/0/45/0/135/0)
5565	[1011100010]	[0111100101]	[1110000110]	[0000010110]	[1011101110]	[1011111010]	(0/90/45/45/0/45/0/90/45/0)
5566	[1000110110]	[1110100011]	[0100100110]	[0000010110]	[1011111101]	[0000010110]	(0/90/135/135/0/45/0/45/45/0)
5571	[1111110001]	[1111100101]	[1100100110]	[0000010111]	[1011111111]	[1111111111]	(1/45/90/0/90/45/90/90/45/0)
5574	[1000110110]	[1110110111]	[1001000100]	[1010010000]	[1001011010]	[1100011010]	(0/90/45/135/45/45/0/45/45/0)
5575	[1011100010]	[0110110111]	[0110000110]	[0000010110]	[1011101111]	[0000011110]	(0/90/0/135/45/45/0/90/45/0)
5581	[0111110101]	[1101100101]	[1100100110]	[0000010110]	[1011001110]	[1111011110]	(0/90/45/45/90/90/0/0/45/0)
5582	[1111100110]	[1110100011]	[0100100110]	[0000010110]	[1011011101]	[0001011011]	(1/45/0/45/90/135/0/135/45/0)
5584	[1111001100]	[0111110100]	[0100000111]	[0000010110]	[1011101111]	[0000010110]	(0/90/135/135/90/45/90/0/135/0)
5587	[1111100001]	[1111100101]	[1100100110]	[0000011100]	[1001101110]	[1111111111]	(1/90/90/135/90/45/0/0/45/0)
5588	[1000110110]	[0110110111]	[0110000110]	[0000010110]	[1011011101]	[0000011010]	(0/90/45/135/45/45/0/45/45/0)
5593	[0011110011]	[0111110101]	[1100100110]	[0100000011]	[1010111101]	[0111111110]	(0/45/135/0/90/45/0/0/90/0)
5594	[1111101010]	[0111100011]	[1100100110]	[0000010110]	[1001011110]	[0101011111]	(1/135/90/45/90/45/0/90/45/0)
5595	[1111100001]	[1111100101]	[1100100110]	[0000011100]	[1001101110]	[1111111111]	(1/90/90/135/90/45/0/0/45/0)
5610	[1111000010]	[0110110111]	[0110011110]	[0000010110]	[1011101111]	[0101011111]	(1/135/90/135/90/45/0/45/45/0)
5616	[1111100000]	[0111110111]	[1000100111]	[0000010110]	[1011001101]	[1001011011]	(1/45/0/45/90/135/0/135/45/0)
5617	[1110110110]	[1110100011]	[1100000100]	[1010010000]	[1011011011]	[0010010010]	(0/90/45/45/0/45/0/90/135/0)
5624	[1011100010]	[0110110101]	[1000000111]	[0000010110]	[1000111100]	[1111111111]	(1/90/90/90/135/45/0/90/45/0)
5645	[0111110101]	[1101100101]	[1100100110]	[0000010110]	[1011001110]	[1111011110]	(0/90/45/45/90/90/0/0/45/0)
5648	[1111101010]	[0111100011]	[1100100110]	[0000010110]	[1001011110]	[0101011111]	(1/135/90/45/90/45/0/90/45/0)
5657	[1111101010]	[0111100011]	[1100100110]	[0000010110]	[1001011110]	[0101011111]	(1/135/90/45/90/45/0/90/45/0)

Table B.1 (continued) : Pareto front designs.

ID	NB500	NB540	NB590	NB670	NB710	NB740	(P0/P1/P2/P3/P4/P5/P6/P7/P8/P9)
5672	[1011110000]	[1111100101]	[1010000110]	[0100000110]	[0011010011]	[1110111110]	(0/0/90/45/0/90/0/0/45/0)
5675	[1111110001]	[1111100101]	[1010000110]	[0110010000]	[1001011010]	[1110101110]	(0/0/90/45/45/90/0/90/45/0)
5677	[1011111000]	[1111100101]	[1010000110]	[0100000110]	[1010011011]	[1100101110]	(0/0/90/45/90/0/45/0/135/0)
5678	[1011100010]	[0111100101]	[1110000110]	[0000010110]	[1010111101]	[1111011000]	(0/90/45/45/0/45/0/90/45/0)
5682	[0111110101]	[1101100101]	[1100100110]	[0000010110]	[1011101110]	[1101011110]	(0/45/90/45/90/45/0/0/45/0)
5683	[11111000010]	[0111100101]	[1100011110]	[0000010110]	[1011101111]	[0101011111]	(1/135/90/135/90/45/0/45/45/0)
5684	[1111100011]	[0111100101]	[1110000110]	[0000010110]	[1011111101]	[0001011011]	(1/45/0/45/90/90/0/90/45/0)
5697	[1110110110]	[1110100011]	[1100000100]	[1010010000]	[1011101110]	[1010010010]	(0/90/45/45/0/45/0/90/135/0)
5719	[1011100010]	[0111100011]	[1100000111]	[0010011000]	[1001011110]	[1101011111]	(1/45/0/90/90/90/90/45/90/0)
5722	[1111110100]	[1111000101]	[1100100110]	[0000010111]	[1011111101]	[1111111111]	(1/45/0/0/90/45/90/0/45/0)
5723	[1111110100]	[1110110101]	[1010000110]	[0100000011]	[1011001110]	[1111111110]	(0/135/90/45/90/45/0/0/90/0)
5751	[11111100011]	[0111100101]	[1110000110]	[0000010110]	[1011111101]	[0001011011]	(1/45/0/45/90/90/0/90/45/0)
5753	[11111100001]	[1111100101]	[1100100110]	[0000011100]	[1001101110]	[1111111111]	(1/90/90/135/90/45/0/0/45/0)
5756	[1111001100]	[0111110100]	[0100000111]	[0000010110]	[1011101111]	[0000010110]	(0/90/135/135/90/45/90/0/135/0)
5766	[1000110010]	[0110111111]	[0100000010]	[0000010110]	[1011001111]	[0000011010]	(0/90/45/135/45/45/0/45/45/0)
5772	[1011100110]	[0110110101]	[1100000111]	[0000010110]	[1000111100]	[1111111111]	(1/90/90/90/135/45/0/90/45/0)
5773	[11111100010]	[1111101100]	[1010000110]	[0000010110]	[1011111101]	[0000011011]	(1/45/90/90/135/45/0/90/135/0)
5774	[1011011000]	[1111100101]	[1100000110]	[0000010110]	[1000111100]	[1111111111]	(1/90/45/45/90/45/0/90/45/0)
5776	[11111101010]	[0110110111]	[1100100110]	[0000010110]	[1011111111]	[1111111111]	(1/0/135/90/90/45/90/45/45/0)
5780	[11111100011]	[0111100101]	[1110000110]	[0000010110]	[1011011101]	[0001011011]	(1/45/0/45/90/135/0/135/45/0)
5783	[11111100000]	[0111100101]	[1001000110]	[0000010110]	[1011011101]	[0001011011]	(1/45/0/45/90/135/0/135/45/0)
5786	[11111101000]	[1110100101]	[1100100110]	[0000011100]	[1001101110]	[1111111111]	(1/90/90/135/90/45/0/0/45/0)
5787	[11111100001]	[1111100101]	[1100100110]	[0000011100]	[1001101110]	[1111111111]	(1/90/90/135/90/45/0/0/45/0)
5789	[10111100010]	[0110110111]	[0110100110]	[0100000011]	[1010101101]	[1111111110]	(0/45/135/0/90/45/0/0/90/0)
5793	[11111110000]	[1111100101]	[1110000110]	[0000010110]	[1011101110]	[1011111010]	(0/90/45/45/0/45/0/0/45/0)

Table B.1 (continued) : Pareto front designs.

ID	NB500	NB540	NB590	NB670	NB710	NB740	(P0/P1/P2/P3/P4/P5/P6/P7/P8/P9)
5798	[1111100010]	[1111100100]	[1000100010]	[0100000110]	[1011001011]	[0010010011]	(1/45/90/90/90/45/0/90/135/0)
5824	[1111110000]	[1111100101]	[1010100110]	[0100000110]	[1011101111]	[0000011110]	(0/90/90/45/90/45/0/0/45/0)
5845	[1111110100]	[1110110101]	[1010000110]	[0100000011]	[1011001110]	[1111111110]	(0/135/90/45/90/45/0/0/90/0)
5849	[1111110000]	[0111100101]	[1001000110]	[0000010110]	[1011011101]	[0001011011]	(1/45/0/45/90/135/0/135/45/0)
5854	[1011100010]	[0110110111]	[10110100110]	[0100000011]	[1010101101]	[1111111110]	(0/45/135/0/90/45/0/0/90/0)
5860	[1000110100]	[1110100111]	[0100000010]	[0000010110]	[1011001111]	[0000011010]	(0/90/45/135/45/45/0/45/45/0)
5862	[1111101010]	[0111100011]	[1100100110]	[0000010110]	[1001011110]	[0101011111]	(1/135/90/45/90/45/0/90/45/0)
5866	[1011100010]	[0111100101]	[1110000110]	[0000010110]	[1011001110]	[1011111010]	(0/90/45/45/0/45/0/90/45/0)
5872	[1011110010]	[0110110101]	[1100100110]	[0100000011]	[1010111101]	[0111111110]	(0/45/135/0/90/45/0/0/90/0)
5874	[1011100010]	[0111100101]	[1100100110]	[0000011100]	[1001101110]	[1111111111]	(1/90/90/135/90/45/0/45/0/45/0)
5875	[1100110110]	[1110100011]	[1100000100]	[1010010000]	[1011011011]	[0010010010]	(0/90/45/45/0/45/0/90/135/0)
5880	[0111110101]	[1101100101]	[1100100110]	[0000010110]	[1011101110]	[1111011110]	(0/90/90/45/90/45/0/45/0/45/0)
5881	[1111101000]	[1111100101]	[1100100110]	[0000010111]	[1011111111]	[1111111111]	(1/45/90/0/90/45/0/0/45/0)
5883	[1111110000]	[0111100101]	[1110000110]	[0000010110]	[1011011101]	[0001011011]	(1/45/0/45/90/135/0/135/45/0)
5887	[1001111010]	[0111100101]	[1110100110]	[0100000011]	[1010111101]	[1111111110]	(0/45/135/0/90/45/0/0/90/0)
5889	[1111110010]	[0111110111]	[10100100010]	[0000010110]	[1011001101]	[1000001010]	(0/90/45/90/45/45/0/45/45/90)
5893	[1000110110]	[0110110111]	[10110000110]	[0000010110]	[1011011101]	[0000011010]	(0/90/45/135/45/45/0/45/45/0)
5898	[11111100010]	[0110110101]	[1000000111]	[0110010000]	[1001011010]	[1110101110]	(0/0/90/45/45/90/0/90/45/0)
5925	[1000110110]	[1110110111]	[1001000100]	[1010010000]	[1001011010]	[1100011010]	(0/90/45/135/45/45/0/45/45/0)
5929	[11111100010]	[1111000101]	[1110000110]	[0000010110]	[1011101110]	[1011111010]	(0/90/45/45/0/45/0/0/45/0)
5943	[1100110110]	[1110100011]	[1100000100]	[1010010000]	[1011011001]	[0010011010]	(0/90/45/45/0/45/0/90/135/0)
5946	[1011110110]	[1110100011]	[1110001110]	[0000010110]	[1011101110]	[1011111010]	(0/90/45/45/90/45/0/90/45/0)
5951	[1001101010]	[01111100101]	[1110100110]	[0100000011]	[1010111100]	[1111111110]	(0/45/135/0/90/45/0/0/90/0)
5958	[1110110110]	[1110100011]	[1100000100]	[1010010000]	[1011011011]	[0010010010]	(0/90/45/45/0/45/0/90/135/0)
5965	[1000110110]	[1110100011]	[1100000100]	[1010010000]	[1001011010]	[1100011010]	(0/90/45/135/45/45/0/45/45/0)

Table B.1 (continued) : Pareto front designs.

ID	NB500	NB540	NB590	NB670	NB710	NB740	(P0/P1/P2/P3/P4/P5/P6/P7/P8/P9)
5968	[1011110000]	[1111100100]	[1010000110]	[0100000110]	[0011010111]	[1110101110]	(0/0/90/45/0/90/45/0/45/0)
5976	[1110110110]	[1110100011]	[1100000100]	[1010010000]	[1011011011]	[0010010010]	(0/90/45/45/0/45/0/90/135/0)
5983	[1011100000]	[1111100101]	[1110100110]	[0100000011]	[1010111101]	[1011111110]	(0/45/135/0/90/45/0/0/90/0)
5988	[1111110110]	[1111100101]	[1100100110]	[0000010110]	[1011111111]	[1111111111]	(1/45/90/0/90/45/90/0/45/0)
5989	[1111110000]	[1111100101]	[1110000110]	[0000010110]	[1011011101]	[0001011011]	(1/45/0/45/90/135/0/135/45/0)



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