

DESIGN OPTIMIZATION OF WHIFFLETREE SYSTEMS FOR WIND TURBINE  
BLADE TESTING

A THESIS SUBMITTED TO  
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES  
OF  
MIDDLE EAST TECHNICAL UNIVERSITY

BY

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IN PARTIAL FULLFILLMENT OF THE REQUIREMENTS  
FOR  
THE DEGREE OF MASTER OF SCIENCE  
IN  
AEROSPACE ENGINEERING

JANUARY 2014



Approval of the thesis:

**DESIGN OPTIMIZATION OF WHIFFLETREE SYSTEMS FOR WIND  
TURBINE BLADE TESTING**

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## **ABSTRACT**

### **DESIGN OPTIMIZATION OF WHIFFLETREE SYSTEMS FOR WIND TURBINE BLADE TESTING**

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January 2014, 123 pages

In this thesis, the design optimization of a whiffletree system, which is used to simulate the loads for a selected design load case by applying discrete test loads on a wind turbine blade, is performed. Firstly, distributed design loads are calculated for the selected load case by using Microsoft (MS) EXCEL. Then, the test load optimization is performed with the Solver Add-In of the MS EXCEL to find the optimum locations of the load saddles which give the best moment distribution along the blade span according to the design loads. To simplify and generalize the test load optimization process, a tool with Graphical User Interface (GUI) is prepared with MATLAB which has built-in optimization algorithms. Genetic algorithm and gradient based optimization algorithms of MATLAB are used in hybrid form to determine the saddle locations and associated force values for test load optimization. To demonstrate the winch loading method option, which is different from the whiffletree system, and to apply developed optimization tool in a much longer blade, design loads for the NREL offshore 5-MW baseline wind turbine blade is calculated and test load optimization is performed. Finally, the whiffletree is designed to

connect the primary load introduction apparatus with the saddles according to the saddle locations obtained by optimization. Results show that the developed optimization tool which makes use of the built-in optimization algorithms in MATLAB successfully determines the optimum load introduction points and associated force values both for the Whiffletree system and winch loading case.

Keywords: Whiffletree design, wind turbine blade, test load optimization, static blade testing

## ÖZ

# RÜZGAR TÜRBİNİ PERVANE KANATLARI TESTLERİ İÇİN YÜK AĞACI SİSTEMLERİNİN TASARIM ENİYİLEMESİ

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Yüksek Lisans, Havacılık ve Uzay Mühendisliği Bölümü

Tez Yöneticisi: Prof. Dr. Altan Kayran

Ocak 2014, 123 sayfa

Bu tezde, bir rüzgar türbini pervane kanadına dağıtılmış test yükleri uygulayarak seçilmiş olan bir tasarım yük koşulundaki yükleri benzetmekte kullanılan yük ağacının tasarım eniyilemesi yapılmıştır. İlk olarak, seçilen tasarım yük koşulu için dağıtılmış tasarım yükleri Microsoft (MS) EXCEL kullanılarak hesaplanmıştır. Daha sonra, tasarım yüklerine göre pervane kanat genişliği boyunca en iyi moment dağılımını veren yük semerlerinin en uygun yerlerini bulmak için MS EXCEL'in Çözücü Eklentisini kullanarak test yük eniyilemesi gerçekleştirilmiştir. Test yük eniyileme sürecini basitleştirmek ve genelleştirmek için Grafik Kullanıcı Ara Yüzü ve gömülü eniyileme algoritmaları olan bir araç MATLAB ile hazırlanmıştır. Test yük eniyilemesinde semer yerleri ve ilişkin yük değerlerini elde etmek için MATLAB'in genetik algoritma ve eğitim temelli eniyileme algoritmaları melez formda kullanılmıştır. Yük ağacı sisteminden farklı olan vinçle yükleme yöntemi seçeneğini göstermek ve geliştirilen eniyileme aracını daha uzun bir pervane kanadında uygulamak için NREL kıyından uzak 5-MW temel rüzgar türbini pervane kanadı için tasarım yükleri hesaplanmış ve test yük optimizasyonu yapılmıştır. Son

olarak, eniyileme ile elde edilen semer yerlerine göre semerlerle ana yük uygulama aparatını birleştiren yük ağacı tasarlanmıştır. Sonuçlar MATLAB içerisinde gömülü eniyileme algoritmalarını kullanarak geliştirilmiş eniyileme aracının, en uygun yük uygulama noktalarını ve ilişkin yük değerlerini yük ağacı sistemi ve vinçle yükleme yönteminin ikisi için de başarıyla elde ettiğini göstermiştir.

Anahtar Kelimeler: Yük ağacı tasarımı, rüzgar türbini pervane kanadı, test yük optimizasyonu, statik pervane kanat testi



*To my family*

## ACKNOWLEDGMENTS

I would like to express my gratitude to my supervisor, Prof. Dr. Altan Kayran, for his guidance, criticism and encouragements throughout my study.

I am grateful to my parents for their endless love and support. They were always encouraging me with their best wishes.

I would also like to thank to my friend and colleague Mesut Mert for his support throughout my study despite the enormous work pressures we were facing together.

I would like to offer my special thanks to my colleagues Cihan Gençer and Levent Ulu for their support and understanding. My research would not have been possible without their help.

Finally, for her great patience, understanding and support, I would like to thank Bürge Turan. She was always encouraging me and stood by me through the good and bad times of the study.

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# CHAPTER 1

## INTRODUCTION

### 1.1 Wind Turbine Blade Testing

Over the last years, due to the increasing price of the fossil fuels and its impact on the environment, wind energy came forward as a method of harnessing the earth's natural resources. Nowadays, developments on the wind turbines helped wind energy to become a pollution-free technology. Therefore, there is an increase, as shown in Figure 1, in the size of the wind turbines from approximately 50 kW to 2MW, with machines up to 5 MW under design [1].

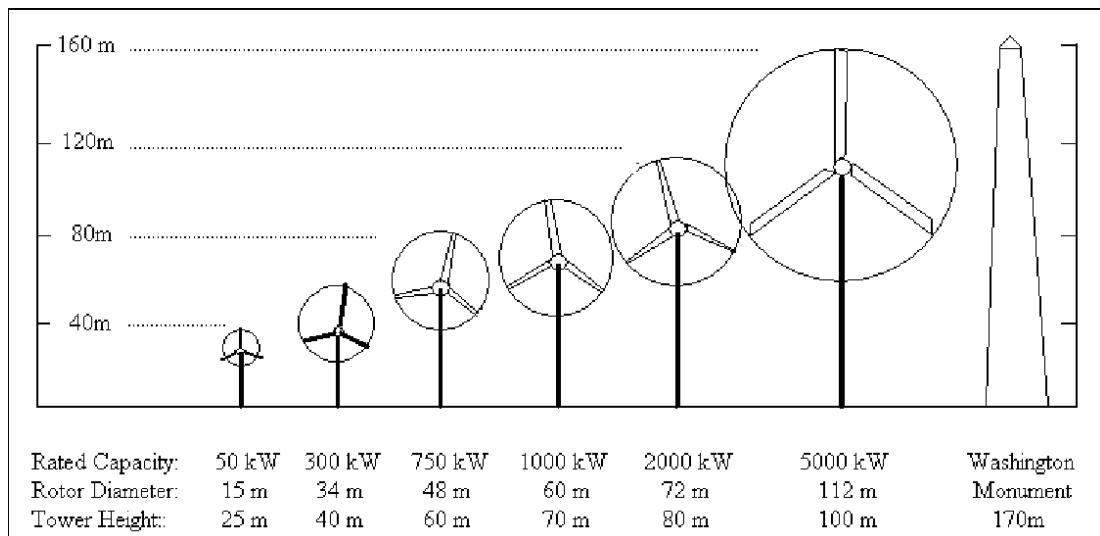


Figure 1: Representative size, height and diameter of wind turbines

The main focus of the developments in the wind turbine technology has been in the wind turbine blade which is regarded as the most critical component of the wind turbine system. In the overall development of a wind turbine, blade testing is one of the most essential tasks. For many years, structural testing of wind turbine blades has been performed by the wind turbine industry and structural blade testing has been

considered as a requirement by most of the wind turbine and blade manufacturers [2]. Moreover, full-scale structural testing that includes ultimate static testing and fatigue testing of wind turbine blades is required for the certification of every new type of blade according to the document “International Electrotechnical Commission (IEC) 61400-22” [3] which is approved by the IEC Technical Committee 88-Wind Turbine Blades. In addition to the certification purposes, there are many reasons for blade testing which includes [4]:

- Blade designs altered in production
- Blade strength is dependent on the production process and on the facility as well as the design
- Blade properties are not known in every location
- Blade designs cannot be fully represented by design and analysis
- Field repairs are extremely expensive

Although both the static and fatigue testing are required to ensure the optimum blade design and to conform to the certification requirements, the main focus of this thesis is the static testing only. The main purpose of the static testing is to verify that the blades do not fail under design load cases. The static tests are performed for up and down bending cases in flapwise and edgewise directions as shown in Figure 2.

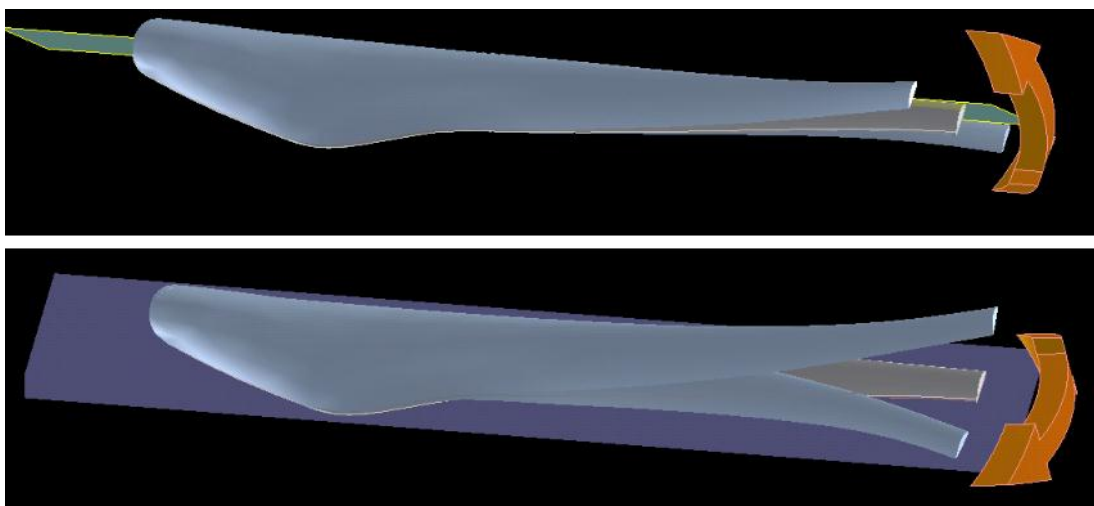


Figure 2: Schematic drawing of flapwise (upper panel) and edgewise (lower panel) bending of a blade [5]

The extremes of the blade cross-section are tested for tensile and compressive stresses, when the blade is bent in flapwise and edgewise directions. However, this does not mean that the complete cross-section is adequately tested [6].

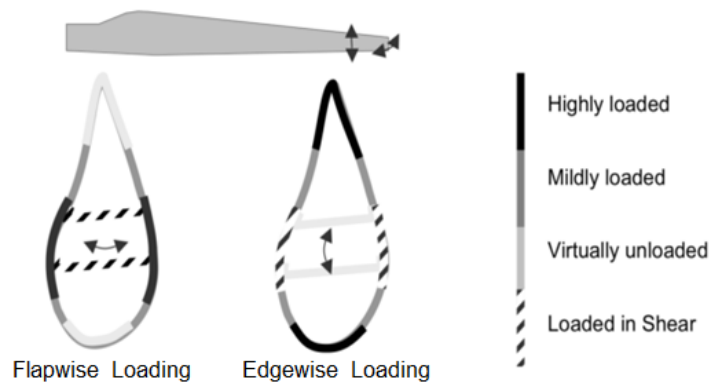


Figure 3: Stresses in a cross-section of the blade [6]

As seen from Figure 3, there are some parts of the cross-section which are not loaded to their maximum in either case and not adequately tested. This loading problem can be solved by applying loads to the blade in more directions, besides pure edgewise and flapwise [6]. However, it is not practical to load the blade in all directions specified in the design loads due to the limitations of the testing laboratory and the need for very complicated testing rig and hardware. Therefore, critical areas should be clearly defined before the tests. Examples of the flapwise and edgewise loadings are shown in Figure 4.

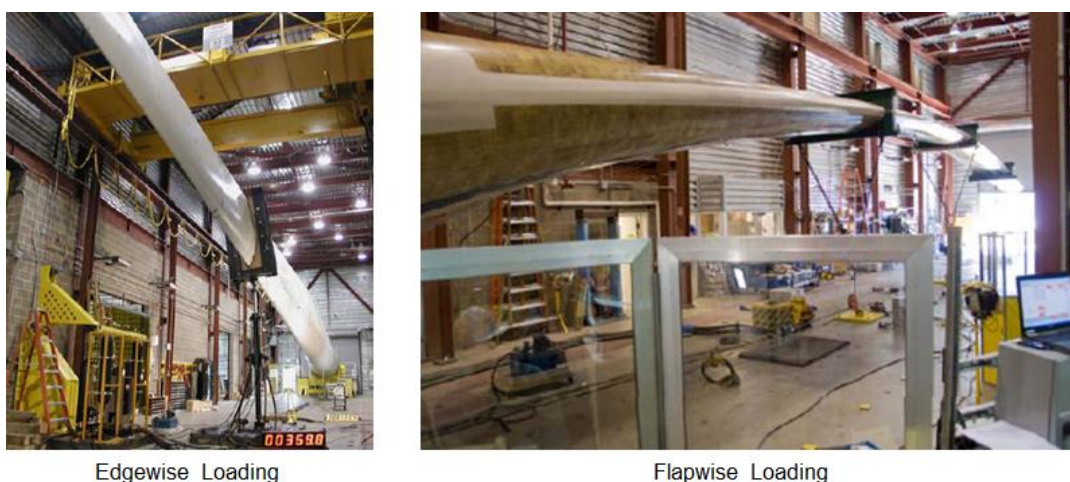


Figure 4: Edgewise and flapwise loading examples [7]

As stated in Reference 8, there are two types of loads applied to the blades during their service life: aerodynamic loads such as shear, drag, lift, etc., and inertial loads such as gravity, blade dynamics, etc. These loads generally occur in orthogonal bending directions as shown in Figure 2. To determine the test loads, design loads (aerodynamic and inertial loads) on the blade for the selected load case should be calculated. In this thesis, calculation methodology of the design loads is given for the load case selected for the “Unsteady Aerodynamics Experiment (UAE) research wind turbine” blade [9]. Blade data is given in detail in CHAPTER 2. The test loads should match with the design loads for the selected load case as much as possible. However, the blade design loads differ from the test loads since the test loads are applied at a restricted number of sections, whereas the ideal test load is continuous. An example test loading distribution plot is given in Figure 5 for the CX-100 and BSDS blade tests performed by Sandia National Laboratories. Three loading points are used for those tests and the differences between test and design moments can be seen through the blade span.

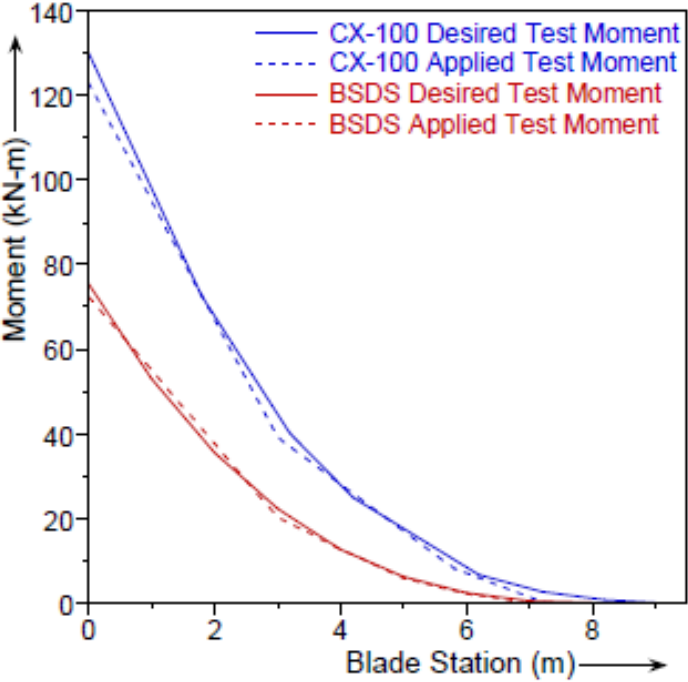


Figure 5: Test loading distributions for CX-100 and BSDS blade tests [10]



Generally, static test setup includes a large and rigid support where the blade is cantilevered and load saddles fixed to the blade as shown in Figure 6 [11].



Figure 6: Static test setup example [11]

In Figure 6, load saddles are pulled down by hydraulic winches for applying test loads to the blade. There are other concepts for loading which will be detailed in Section 1.2.

To measure the response of the test blade during the loading, strain gauges are applied at several cross-sections of the blade. In addition to the strain gauges, draw wire sensors are used for displacement measurements; load cells are used to measure the applied loads; and possibly angle sensors are used to measure the change in slope at various points on the blade. For a static test, loads are applied quasi-statically in a few load steps up to the 100% required test load. The experimental deflections and strains can be verified against the expected at each load step and the decision can be made whether to advance the test further. At the required test load, the test load should be maintained for a minimum of 10 seconds to allow for load settling. Then the load is released back to zero [11].

## 1.2 Wind Turbine Blade Testing Methods

There is a wide range of blade testing methods used by various test laboratories in the world for small and large wind turbines. Therefore, a technical specification document “IEC 61400-23” [12] has been written to provide guidelines on recommended practices and to reduce the variability of the methods. The instructions and recommendations given in [12] are used as the main reference in this thesis.

As mentioned in the previous section, all static tests require a test stand to attach the test blade and to react the test loads. The test blade is attached to the test stand by using an adaptor/fitting to adapt the blade’s bolt pattern to the test stand. If the root design is to be validated, the root fixture should create a representative distribution of stresses in the blade root [12]. A test stand, which is used by NREL for testing of large wind turbine blades, is shown in Figure 7.



Figure 7: Test stand example used by NREL [7]

For loading of the blades, load introduction fixtures should be designed according to the selected loading method. In general, load application consist of fitting one or more load clamps to the blade and pulling these load clamps in either the vertical or horizontal direction as stated in the blade testing section of the standard document “DNV-DS-J102” [13] for design and manufacture of wind turbine blades. An example of the load clamp attachment is shown in Figure 8. Load clamps can also be described as load saddles.

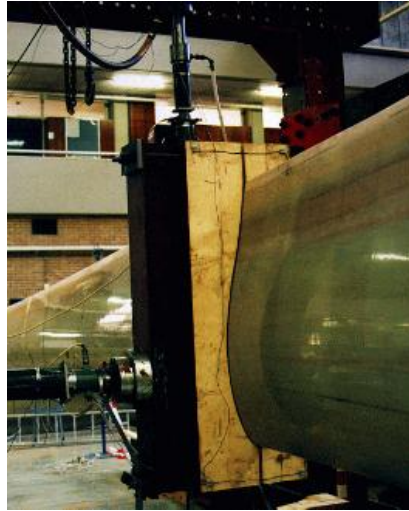


Figure 8: Load clamp attachment [12]

As seen from Figure 8, external sleeve of wood can be used for load clamp attachment. Local damages caused by concentrated pressure at skin contact area and high shear loading can be prevented by using these external sleeves [12].

There are different loading methods used in static testing of the blades. These methods are listed below [12]:

- Distributed surface loads
  - Heavy sandbags distributed over the blade surface
  - Best representation of the shear forces
  - Adding bags at extreme loads is dangerous
  - Limited to single axis
- Single point method
  - Single concentrated load at one section,
  - Shear loads are higher
  - Multiple tests are required to test different sections of the blade
  - Requires simple hardware
- Multiple point method
  - The desired test load distribution can be applied to the blade at one time
  - Shear forces and moments are more realistic than single point method
  - Requires more complicated hardware and test rig structures.

Figure 9 shows the single point and multiple point loading examples applied in wind turbine blade testing.

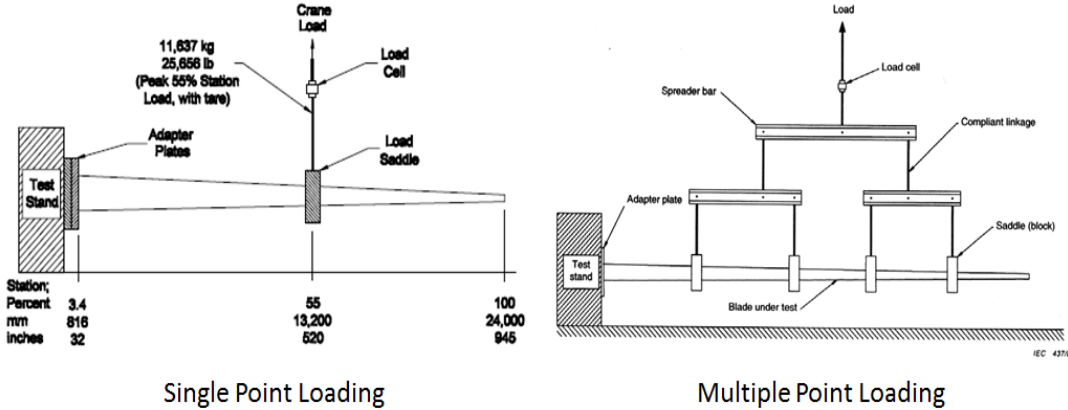


Figure 9: Example schematic for single and multiple point loadings [4]

A more representative load distribution of both bending and shear can be obtained by using a multiple load application in several positions simultaneously as given in the list above. However, it should be considered that the multiple load application contributes to the static stability of the blade during the loading. Therefore, the widths of the clamps should be as small as possible taking the surface pressure into account [13]. In addition, due to the wooden blocks, which clamp the blade at the position of the load introduction, the area where the load is introduced itself is not tested properly [6]. The effect of the load introduction blocks is shown in Figure 10 for both single and multiple load applications.

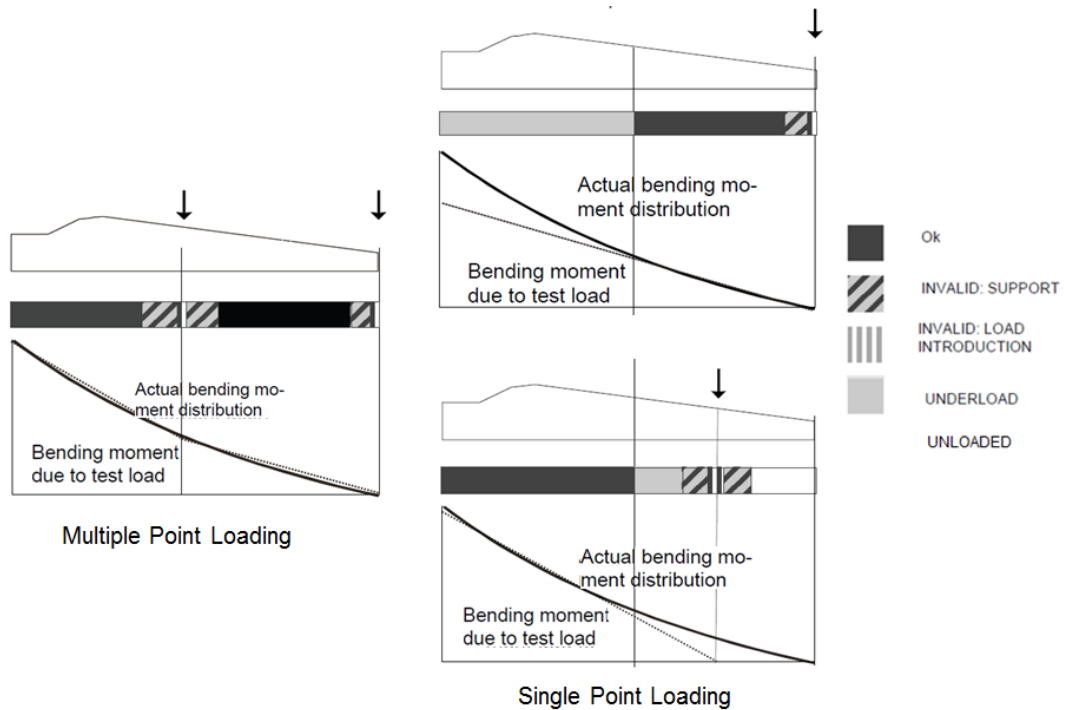


Figure 10: Comparison of single and multiple load applications [6]

Instead of using a multiple load application, static tests can also be performed by applying concentrated point loads at several points subsequently. On the right side of Figure 10, two concentrated loads are applied to the blade at different positions to simulate the actual moment distribution by test loading. However, the required time for testing the whole blade accurately is higher than the multiple load application. Each method has advantages and disadvantages as listed above. However, in this thesis multiple point method is selected for loading of the blade since shear force and moment distributions are more realistic and testing time is shorter.

### 1.3 Whiffletree System

To distribute the primary load applied by a crane to the different sections of the blade a structure called “Whiffletree” is needed as seen in Figure 9. The number of saddle points seen in Figure 9 can be altered according to the design loading and the test blade. There are several examples for different Whiffletree designs with different number of saddle points. These examples can be seen in Figure 11, Figure 12 and Figure 13.

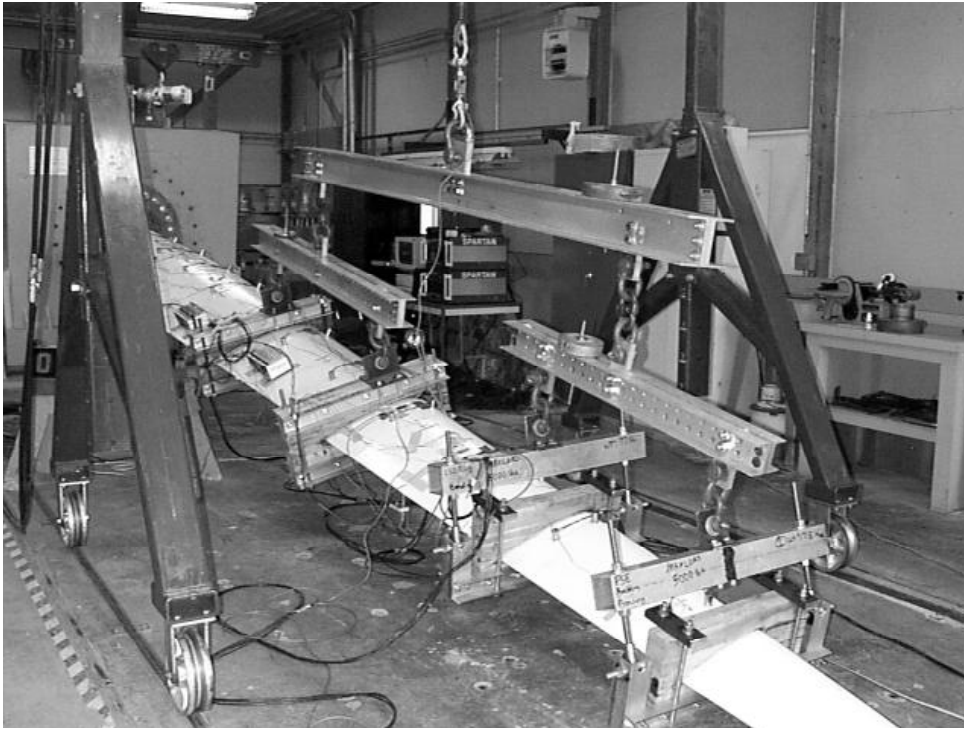


Figure 11: Four-saddle point whiffletree design used in ERS-100 blade test [14]



Figure 12: Three-saddle point whiffletree designs used in CX-100 (left) and BSDS (right) blade tests [10]



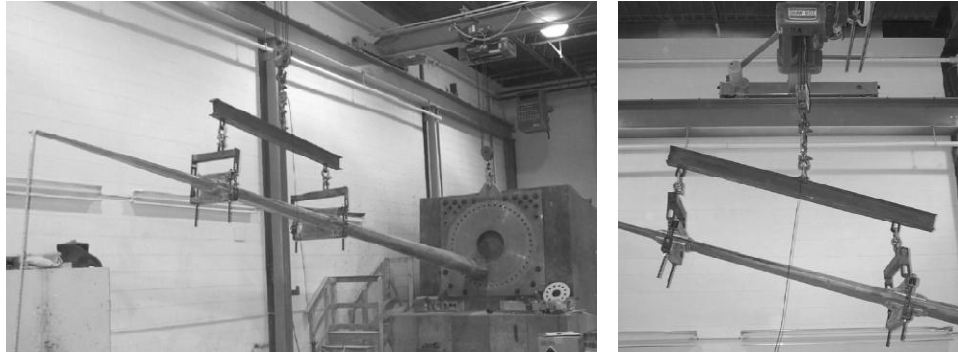


Figure 13: Two-saddle point whiffletree design used in NPS-100 blade test [14]

In addition to Whiffletree system, hydraulic actuators or winches can also be used to apply the distributed loading as seen in Figure 14. However, hydraulic actuator or winch options are more expensive than using the Whiffletree structure.



Hydraulic Actuators



Winches

Figure 14: Hydraulic actuators and winches for distributed loading [4]

In this thesis, the design optimization of a whiffletree system, which is used to simulate the loads for a selected design load case by applying discrete test loads on a wind turbine blade, is performed. The NREL UAE research wind turbine blade is taken as the reference blade to demonstrate the Whiffletree design process. Firstly, distributed design loads are calculated for the selected load case by using MS EXCEL. Then, the test load optimization is performed within the same MS EXCEL workbook with the Solver Add-In of the software in separate MS EXCEL sheets prepared to find the optimum locations of the load saddles which give the best

moment distribution along the blade span according to the design loads. To simplify and generalize the test load optimization process, a tool with GUI is prepared with MATLAB which has built-in optimization algorithms. Genetic algorithm and gradient based optimization algorithms of MATLAB are used in hybrid form to determine the saddle locations and associated force values give the closest moment distribution to that of the real distributed load case. Different designs are performed for different number of saddles and comparisons are made between the moment diagrams obtained from alternative Whiffletree design configurations. The optimization results obtained from each tool are compared and the optimum design solution is selected. Finally, the Whiffletree is designed to connect the primary load introduction apparatus with the saddles according to the saddle locations obtained by optimization. To demonstrate the winch loading method option, which is different from the whiffletree system, and to apply the developed optimization tool in a much longer blade, design loads for the NREL offshore 5-MW baseline wind turbine blade [15] is calculated and test load optimization is performed. Results show that the developed optimization tool which makes use of the built-in optimization algorithms in MATLAB successfully determines the optimum load introduction points and associated force values both for the Whiffletree system and winch loading case.

#### **1.4 Motivation of the Study**

Since the population of Turkey increases rapidly, energy demand is increasing as well. To reduce the energy dependence on gas imports, Turkey's goal is to increase its wind energy output to 20,000 MW by 2023. For this purpose, the government invests on the wind energy research activities. METUWIND (Center for Wind Energy) is one of the research facilities for the wind energy development supported by the government. As mentioned before, wind turbine blades are the most critical components for wind energy development, and blade testing is an important part of this development process. Therefore, METUWIND plans to have the capability for static and fatigue testing of 10 meter long wind turbine blades. It is considered that the outputs of this study can be used by METUWIND as a design guideline for static tests.



## CHAPTER 2

### DESIGN LOAD CALCULATION

#### 2.1 UAE Research Wind Turbine

Since the whiffletree design will be performed for the UAE Research Wind Turbine blade, in this section, firstly the basic parameters of the UAE Research Wind Turbine are introduced [9].

- Blade cross section and planform: NREL S809, tapered and twisted
- Each blade attaches to the hub at a point 0.508 m from the center of rotation. There is a cylindrical section at the root that extends from 0.508 m to 0.883 m. The airfoil transition begins at approximately the 0.883 m radial station.
- There is a transition from the cylindrical section to the S809 airfoil along the 0.883 m to 1.257 m region. The transition ends with a 0.737 m chord S809 airfoil at the 1.257 m span station.
- Blade tip pitch angle : 0 degrees
- Blade chord, twist and thickness distributions are given in Table 1 below.
- Twist and pitch conventions are positive towards feather. Values listed are relative to zero twist at the 3.772-m station [75% span on a 5.03-m blade].
- Number of blades: 2
- 10.058 m rotor diameter with standard tip or smoke tip
- Hub height: 12.192 m
- Rotational speed: 71.63 RPM (Revolution per Minute) synchronous speed
- Cut-in wind speed: 6 m/s
- Power regulation: stall
- Rated power: 19.8 kW

- Rotational direction: counterclockwise (viewed from upwind)

Figure 15 and Figure 16 describe the geometry of the wind turbine blade and Table 1 gives the blade chord and twist distribution along the blade span.

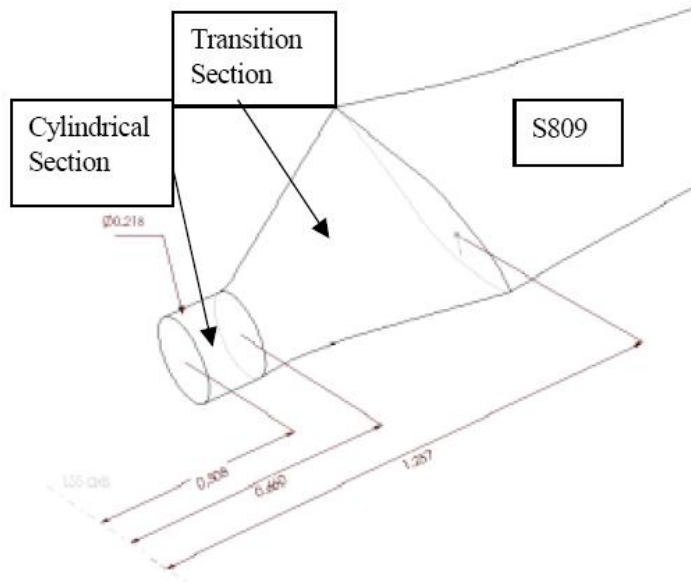


Figure 15: Blade root and transition region [9]

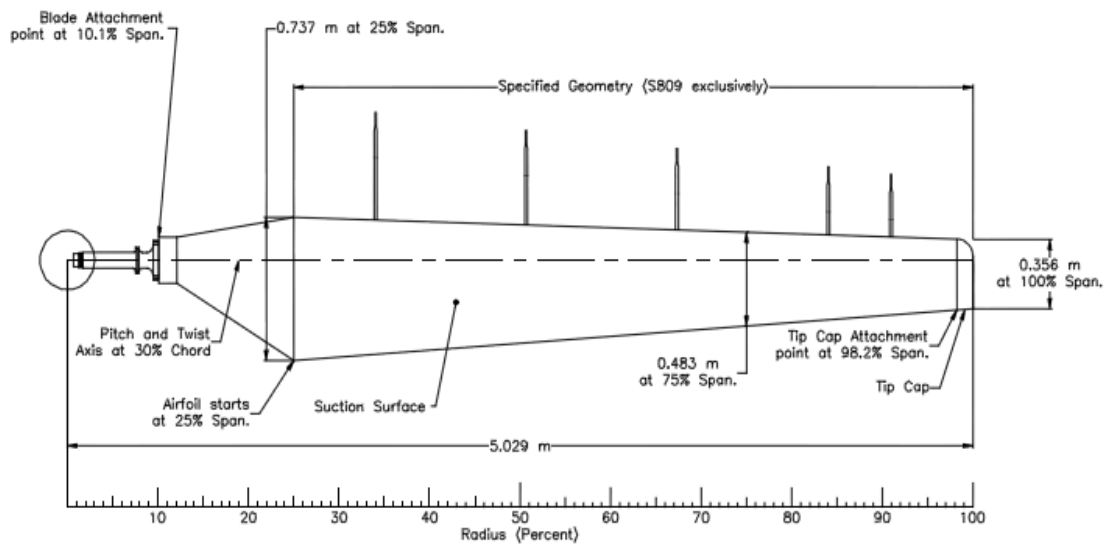


Figure 16: Blade planform and dimensions [9]

Table 1: Blade chord and twist distributions [9]

Radial distance (m)	Chord length (m)	Twist (degrees)	Thickness (m)
0.0	Hub-center of rotation	Hub-center of rotation	Hub-center of rotation
0.508	0.218 (root hub adapter)	0.0 (root hub adapter)	0.218
0.660	0.218	0.0	0.218
0.883	0.183	0.0	0.183
1.008	0.349	6.7	0.163
1.067	0.441	9.9	0.154
1.133	0.544	13.4	0.154
1.257	0.737	20.05	0.154
1.522	0.710	14.04	20.95% chord
1.798	0.682	9.67	20.95% chord
2.075	0.654	6.75	20.95% chord
2.352	0.626	4.84	20.95% chord
2.628	0.598	3.48	20.95% chord
2.905	0.570	2.40	20.95% chord
3.181	0.542	1.51	20.95% chord
3.458	0.514	0.76	20.95% chord
3.735	0.486	0.09	20.95% chord
3.772	0.483	0.00	20.95% chord
4.011	0.459	-0.55	20.95% chord
4.288	0.431	-1.11	20.95% chord
4.565	0.403	-1.55	20.95% chord
4.841	0.375	-1.84	20.95% chord
5.029	0.356	-2.00	20.95% chord

## 2.2 Design Load Calculation Methodology

Since the main purpose of this thesis is to design a whiffletree system which is a result of the test load optimization, the design load calculation part is kept simple in this study. Design loads are only needed as an input to the optimization process.

In general, according to the document “IEC 61400-1”, load types given below should be considered for design calculations [16].

- Gravitational and Inertial Loads
- Aerodynamic Loads
- Actuation Loads

- Other Loads (Wake, impact and ice loads)

In this thesis, only the aerodynamic loads applied on the airfoil sections, which are assumed to start at the 1.257 m span station of the blade, are considered for the design load calculations. According to IEC 61400-1, for the ultimate static testing, a design load case should be selected to calculate the design loads from the Table 2 of IEC 61400-1. In this study, power production design condition DLC 1.1 is selected for the operation at the cut-out wind speed of 20 m/s. According to IEC 61400-1, normal turbulence model (NTM) should be used to determine the wind speed. However, in this study only steady loading is considered and the change of the wind speed along the height is neglected since the hub height and blade radius is small. Firstly, aerodynamic loads per unit span of the blade are determined. In the calculation of the aerodynamic loading, convention shown in Figure 17 is used.

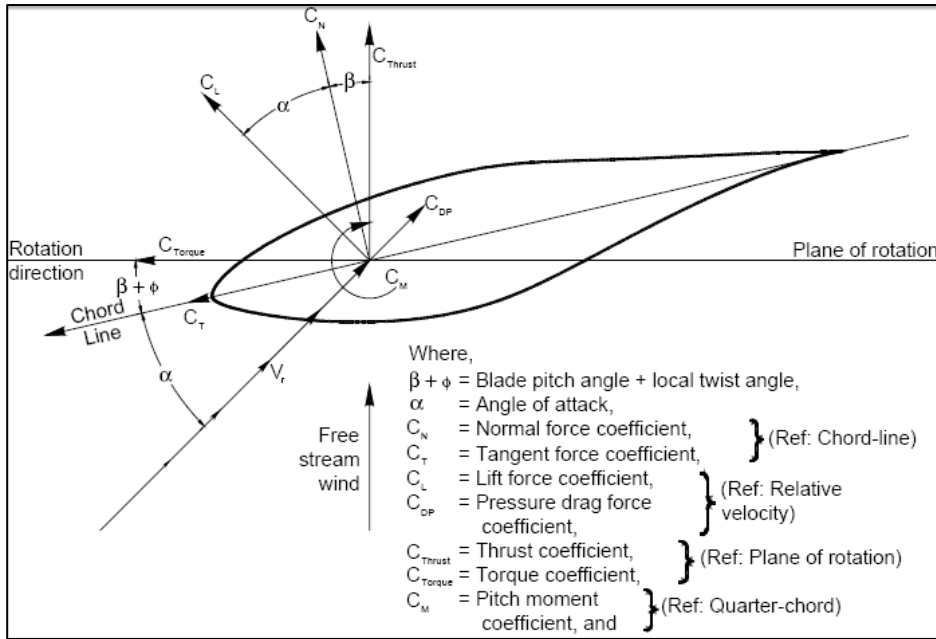


Figure 17: Convention for the aerodynamic loading [9]

To find the aerodynamic coefficients at the sections given in Table 1, angle of attack values should be determined at each section. Angle of attack is calculated by Eq. (1).

$$\alpha = \theta - \beta - \phi \quad (1)$$

where;

$$\theta = \tan^{-1} \left( \frac{V_{free\ stream\ wind}}{V_{tangential}} \right) = \tan^{-1} \left( \frac{V_{free\ stream\ wind}}{\omega * r} \right) \quad (2)$$

$\theta$ : Angle between relative velocity and plane of rotation

$\omega$ : Rotational velocity

$r$ : Distance between hub-center of rotation and the span wise section location

Once the angle of attack values for each section are calculated, aerodynamic coefficients can be determined from the wind tunnel data given in Table 57 of the document by Ramsay et.al. [17] by using linear interpolation when necessary. Since there is no wind tunnel data for the sections between the root and 1.257 m span station, it is assumed that the aerodynamic coefficients are equal to zero for those sections. Then, by multiplying the aerodynamic coefficients with the dynamic pressure aerodynamic forces at the aerodynamic center of the airfoil section are determined. Results of the calculations are given in Table 2 below.

Table 2: Aerodynamic coefficients and forces at each blade section

Radial Distance(m)	$C_l$	$C_{d,p}$	$C_m$	Lift per Unit Span(N/m)	Drag per Unit Span (N/m)	Pitching Moment per Unit Span (N)
0	0.0	0.0	0.0	0.0	0.0	0.0
1.257	1.1970	1.3087	-0.3464	264.18	288.82	-56.34
1.522	1.1854	1.3670	-0.3582	273.39	315.28	-58.66
1.798	1.1845	1.3707	-0.3590	287.93	333.17	-59.51
2.075	1.1933	1.3332	-0.3512	307.01	342.99	-59.10
2.352	1.1972	1.2734	-0.3398	326.50	347.28	-58.02
2.628	1.1976	1.2073	-0.3276	345.92	348.73	-56.58
2.905	1.1980	1.1420	-0.3155	365.89	348.80	-54.92
3.181	1.1770	1.0703	-0.3001	378.77	344.43	-52.35
3.458	1.1544	1.0016	-0.2852	389.91	338.29	-49.50
3.735	1.1339	0.9391	-0.2715	399.94	331.24	-46.55
3.772	1.1313	0.9314	-0.2699	401.82	330.81	-46.30
4.011	1.1048	0.8828	-0.2580	405.39	323.94	-43.46
4.288	1.0714	0.8297	-0.2445	405.76	314.21	-39.91
4.565	1.0391	0.7781	-0.2315	403.33	302.04	-36.21
4.841	1.0065	0.7262	-0.2183	397.30	286.67	-32.31
5.029	0.9845	0.6920	-0.2096	391.46	275.18	-29.67

Since the aerodynamic forces are with respect to the relative velocity direction and relative velocity direction changes in each section, aerodynamic forces should be defined in a global coordinate system. In this study, aerodynamic forces are calculated with respect to the pitch/twist axis which is at the 30% chord of the root section of the blade. Figure 18 shows the coordinate system on the root section of the blade.

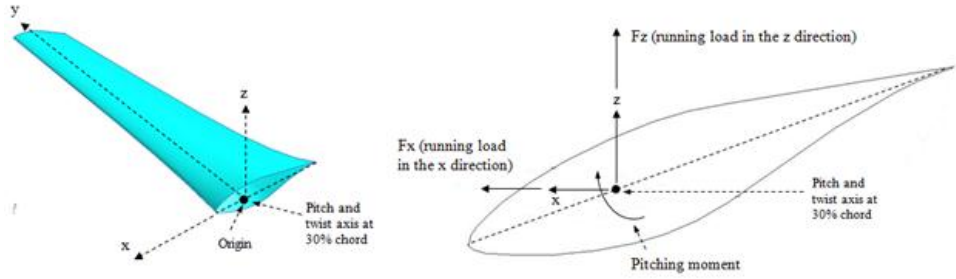


Figure 18: Aerodynamic loading decomposed with respect to XYZ axis passing through 30% chord

Loads per unit span in the X and the Z directions are calculated by using Eqs. (3) and the results are tabulated in Table 3. The effect of aerodynamic forces on the pitching moment is neglected.

$$F_z = Lift * \cos \theta + Drag * \sin \theta \tag{3}$$

$$F_x = Lift * \sin \theta - Drag * \cos \theta \tag{4}$$

Table 3: Aerodynamic loading decomposed with respect to XYZ axis passing through 30% chord

<b>Radial Distance(m)</b>	<b>F<sub>z</sub> (N/m)</b>	<b>F<sub>x</sub> (N/m)</b>	<b>M<sub>y</sub> (N)</b>
0.0	0.0	0.0	0.0
1.257	373.9033	115.7978	-56.34
1.522	409.3370	81.1295	-58.66
1.798	437.2134	52.4415	-59.51
2.075	459.2353	31.6324	-59.10
2.352	476.4257	15.1171	-58.02
2.628	491.1902	1.5657	-56.58
2.905	505.4130	-9.5619	-54.92
3.181	511.5398	-20.6587	-52.35
3.458	515.3462	-29.8203	-49.50
3.735	517.9618	-37.2214	-46.55
3.772	519.0734	-38.2015	-46.30
4.011	516.9395	-45.3531	-43.46
4.288	510.4914	-52.5714	-39.91
4.565	500.6052	-57.3959	-36.21
4.841	486.3087	-59.4307	-32.31
5.029	474.7484	-59.7923	-29.67

In the present study, MS EXCEL sheet that is used for the calculation of aerodynamic loads is given in Figure 19. Sheet is divided into two pieces for clarification.

	A	B	C	D	E	F	G	H	I	J	K	L
1	Radial distance	Chord (m)	Twist	Tangential	Relative	Theta (deg)	Blade tip	A.O.A(deg)	Reynold	C <sub>J</sub>	C <sub>m</sub>	C <sub>dp</sub>
2	(m)			Vel.(m/s)	Vel.(m/s)		Angle(deg)		number			
3	0	0.3	0	0.0	20.0	90.0	0.0	90.0	429824.6	0.000	0.000	0.000
4	1.257	0.737	20.05	9.4	22.1	64.8	0.0	44.7	1167398.0	1.197	-0.346	1.309
5	1.522	0.71	14.04	11.4	23.0	60.3	0.0	46.2	1171319.5	1.185	-0.358	1.367
6	1.798	0.682	9.67	13.5	24.1	56.0	0.0	46.3	1178548.8	1.185	-0.359	1.371
7	2.075	0.654	6.75	15.6	25.3	52.1	0.0	45.4	1187335.5	1.193	-0.351	1.333
8	2.352	0.626	4.84	17.6	26.7	48.6	0.0	43.7	1195991.7	1.197	-0.340	1.273
9	2.628	0.598	3.48	19.7	28.1	45.4	0.0	41.9	1203007.5	1.198	-0.328	1.207
10	2.905	0.57	2.4	21.8	29.6	42.5	0.0	40.1	1207749.9	1.198	-0.315	1.142
11	3.181	0.542	1.51	23.9	31.1	40.0	0.0	38.5	1208866.0	1.177	-0.300	1.070
12	3.458	0.514	0.76	25.9	32.8	37.6	0.0	36.9	1206051.8	1.154	-0.285	1.002
13	3.735	0.486	0.09	28.0	34.4	35.5	0.0	35.4	1198455.0	1.134	-0.272	0.939
14	3.772	0.483	0	28.3	34.6	35.3	0.0	35.3	1198886.1	1.131	-0.270	0.931
15	4.011	0.459	-0.55	30.1	36.1	33.6	0.0	34.2	1187938.5	1.105	-0.258	0.883
16	4.288	0.431	-1.11	32.2	37.9	31.9	0.0	33.0	1169437.4	1.071	-0.245	0.830
17	4.565	0.403	-1.55	34.2	39.7	30.3	0.0	31.8	1144843.9	1.039	-0.231	0.778
18	4.841	0.375	-1.84	36.3	41.5	28.8	0.0	30.7	1113679.6	1.006	-0.218	0.726
19	5.03	0.356	-2	37.7	42.7	27.9	0.0	29.9	1089062.7	0.984	-0.210	0.692
20	<b>INPUT PARAMETERS FOR AERODYNAMIC LOADS</b>											
22	Wind Speed	20	m/s									
23	Rot. Speed	71.63	rpm									
24	Rot. Speed	7.501	rad/s									
25	air density	1.225	kg/m <sup>3</sup>									
26	Blade Tip Angle	0	deg									
27	Viscosity of air	0.0000171										
	M	N	O	P	Q	R	S	T	U	V		
1	Lift per unit	Pitch. Mom. per	Drag per unit	Fz per unit	Fx per unit span	Table 57 airfoil data						
2	span (N/m)	unit span(N)	span (N/m)	span (N/m)	(N/m)	AOA	C <sub>J</sub>	C <sub>m</sub>	C <sub>dp</sub>			
3	0.0	0.0	0.0	0.0	0.0	-5.98	-0.53	-0.026	0.0179			
4	264.2	-56.3	288.8	373.9	115.8	-0.02	0.121	-0.045	0.0142			
5	273.4	-58.7	315.3	409.3	81.1	2.99	0.458	-0.054	0.0219			
6	287.9	-59.5	333.2	437.2	52.4	6.01	0.758	-0.058	0.0236			
7	307.0	-59.1	343.0	459.2	31.6	9	0.837	-0.042	0.0422			
8	326.5	-58.0	347.3	476.4	15.1	12	0.957	-0.04	0.0659			
9	345.9	-56.6	348.7	491.2	1.6	15	1.039	-0.043	0.0998			
10	365.9	-54.9	348.8	505.4	-9.6	17.95	0.955	-0.067	0.1676			
11	378.8	-52.3	344.4	511.5	-20.7	19.97	0.617	-0.112	0.3254			
12	389.9	-49.5	338.3	515.3	-29.8	23.99	0.705	-0.135	0.4271			
13	399.9	-46.5	331.2	518.0	-37.2	26.98	0.848	-0.172	0.5523			
14	401.8	-46.3	330.8	519.1	-38.2	29.96	0.986	-0.21	0.6936			
15	405.4	-43.5	323.9	516.9	-45.4	34.95	1.127	-0.267	0.9182			
16	405.8	-39.9	314.2	510.5	-52.6	39.93	1.198	-0.314	1.1341			
17	403.3	-36.2	302.0	500.6	-57.4	44.95	1.197	-0.348	1.3175			
18	397.3	-32.3	286.7	486.3	-59.4	59.95	1.062	-0.467	1.8928			
19	391.5	-29.7	275.2	474.7	-59.8	70.01	0.807	-0.542	2.1816			
20						79.96	0.485	-0.587	2.3273			
21						89.99	0.127	-0.617	2.3281			
22						119.96	-0.759	-0.627	1.7725			
23						150.01	-0.635	-0.388	0.571			
24						180	-0.013	-0.03	0.0077			
25						210	0.609	0.366	0.5605			
26						239.97	0.744	0.627	1.7779			
27						269.01	-0.06	0.621	2.3193			

Figure 19: MS EXCEL sheet for aerodynamic load calculation

By changing the input parameters such that wind speed, rotational speed and blade tip angle aerodynamic loads can be calculated for different load cases and design loads can be found for that load case. After the calculation of the aerodynamic loads is finalized, the internal forces are obtained. Span wise distribution of the shear



forces ( $V_z$  and  $V_x$ ), pitching moment ( $M_y$ ) and bending moments ( $M_x$  and  $M_z$ ) can be determined by using the methodology given in Table A5.1 of textbook by Bruhn [18]. Calculated aerodynamic loads per unit span at the span stations of the blade are converted to the distributed load on a strip. This strip load is taken as acting through the center of gravity of this distributed strip load. Calculations are performed by starting from the tip station of the blade up to the root station of the blade. To determine the strip loads ( $\Delta P_x$  and  $\Delta P_z$ ), the average running loads between the stations for the X and Z directions are calculated by using Eq. (5).

$$F_{ave,i-1 \rightarrow i} = \frac{F_i + F_{i-1}}{2} \quad i = 2, 3, \dots, N \quad (5)$$

where;

$F_i$ :  $F_x$  or  $F_z$  per unit span at the  $i^{\text{th}}$  station

$N$ : Total number of blade stations

By multiplying average running loads with the distances between stations, strip loads are calculated as shown in Eq. (6).

$$\Delta P_i = F_{ave,i-1 \rightarrow i} * d \quad (6)$$

where;

$\Delta P_i$ : Strip load ( $\Delta P_x$  or  $\Delta P_z$ ) between stations  $i-1$  and  $i$

$d$ : Distance between stations  $i-1$  and  $i$

The center of gravity of the distributed strip load between the stations is calculated by using the formulation given in Figure 20 for trapezoidal areas.

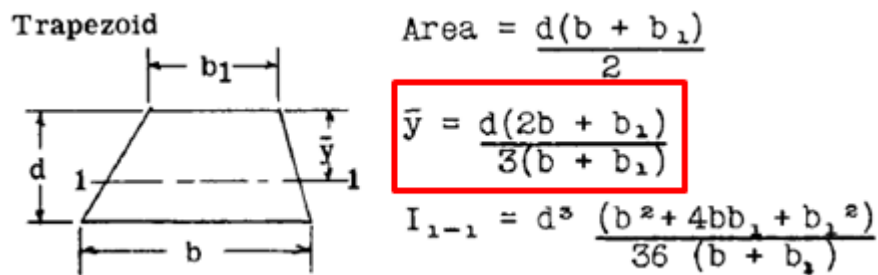


Figure 20: Centroids of trapezoidal areas [18]

In the formulation given in Figure 20, “ $d$ ” value is again the distance between subsequent stations; “ $b$ ” and “ $b_1$ ” values are the concentrated aerodynamic loads per

unit span at subsequent stations,  $i-1$  and  $i$ . In order to determine the shear forces ( $V_z$  and  $V_x$ ) at the stations, the strip loads of the previous stations are summed as shown in Eq. (7).

$$V_i = \sum_{j=1}^i \Delta P_j \quad (7)$$

where;

$V_i$ :  $V_x$  or  $V_z$  at the  $i^{\text{th}}$  station

In order to find the bending moment values ( $M_x$  and  $M_z$ ) at the stations; moment value at the previous station, moment created by the shear force of the previous station and the concentrated strip load between previous and the current station should be summed as shown in Eq. (8).

$$M_i = M_{i-1} + V_{i-1} * d + \Delta P_i * \bar{y} \quad (8)$$

where;

$M_i$ :  $M_x$  or  $M_z$  at the  $i^{\text{th}}$  station

$\bar{y}$ : Distance between the  $i^{\text{th}}$  station and the centroid of the trapezoidal area

Since the strip load values are calculated with respect to the global coordinate system, there is no effect of the strip loads on the pitching moment, which is about Y axis of the global coordinate system. In order to determine the pitching moment values ( $M_y$ ) at a specified station, aerodynamic pitching moment values per unit span at the previous stations are summed as shown in Eq. (9).

$$M_{y,i} = \sum_{j=1}^i M_{y,per\ unit\ span_j} \quad (9)$$

where;

$M_{y,i}$ :  $M_y$  at the  $i^{\text{th}}$  station

MS EXCEL sheet used for the calculation of the internal forces is given in Figure 21 by dividing the sheet into two pieces for clarification.

	A	B	C	D	E	F	G	H	I	J	K
1	Radial distance (m)	Chord (m)	Twist (deg)	Fz per unit span (N/m)	Fx per unit span (N/m)	Pitch. Mom. per unit span (N)	Average Running Load_Z (N/m)	Average Running Load_X (N/m)	Dist.Btw.Sta.(m)	Strip Load_Z(N)	Strip Load_X(N)
2	5.03	0.356	-2	474.75	-59.79	-29.67	-	-	-	-	-
3	4.841	0.375	-1.84	486.31	-59.43	-32.31	480.53	-59.61	0.19	90.82	-11.27
4	4.565	0.403	-1.55	500.61	-57.40	-36.21	493.46	-58.41	0.28	136.19	-16.12
5	4.288	0.431	-1.11	510.49	-52.57	-39.91	505.55	-54.98	0.28	140.04	-15.23
6	4.011	0.459	-0.55	516.94	-45.35	-43.46	513.72	-48.96	0.28	142.30	-13.56
7	3.772	0.483	0	519.07	-38.20	-46.30	518.01	-41.78	0.24	123.80	-9.98
8	3.735	0.486	0.09	517.96	-37.22	-46.55	518.52	-37.71	0.04	19.19	-1.40
9	3.458	0.514	0.76	515.35	-29.82	-49.50	516.65	-33.52	0.28	143.11	-9.29
10	3.181	0.542	1.51	511.54	-20.66	-52.35	513.44	-25.24	0.28	142.22	-6.99
11	2.905	0.57	2.4	505.41	-9.56	-54.92	508.48	-15.11	0.28	140.34	-4.17
12	2.628	0.598	3.48	491.19	1.57	-56.58	498.30	-4.00	0.28	138.03	-1.11
13	2.352	0.626	4.84	476.43	15.12	-58.02	483.81	8.34	0.28	133.53	2.30
14	2.075	0.654	6.75	459.24	31.63	-59.10	467.83	23.37	0.28	129.59	6.47
15	1.798	0.682	9.67	437.21	52.44	-59.51	448.22	42.04	0.28	124.16	11.64
16	1.522	0.71	14.04	409.34	81.13	-58.66	423.28	66.79	0.28	116.82	18.43
17	1.257	0.737	20.05	373.90	115.80	-56.34	391.62	98.46	0.27	103.78	26.09
18	0	0.15	0	0.00	0.00	0.00	186.95	57.90	1.26	235.00	72.78
	L	M	N	O	P	Q	R	S	T	U	V
1	Arm to centroid of strip load_Z	Arm to centroid of strip load_X	Shear_Z (N)	Shear_X (N)	Vz*dy (Nm)	Vx*dy (Nm)	Strip Load_z*d (Nm)	Strip Load_x*d (Nm)	Mx (Nm)	Mz (Nm)	My (Nm)
2	-	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-29.67
3	0.09	0.09	90.82	-11.27	0.00	0.00	8.55	-1.06	8.55	-1.06	-61.98
4	0.14	0.14	227.01	-27.39	25.07	-3.11	18.70	-2.21	52.32	-6.39	-98.18
5	0.14	0.14	367.05	-42.62	62.88	-7.59	19.33	-2.08	134.53	-16.05	-138.10
6	0.14	0.14	509.35	-56.18	101.67	-11.81	19.67	-1.83	255.87	-29.69	-181.56
7	0.12	0.12	633.15	-66.17	121.73	-13.43	14.78	-1.16	392.39	-44.27	-227.85
8	0.02	0.02	652.34	-67.56	23.43	-2.45	0.36	-0.03	416.17	-46.75	-274.40
9	0.14	0.13	795.45	-76.85	180.70	-18.71	19.84	-1.24	616.71	-66.70	-323.91
10	0.14	0.13	937.68	-83.84	220.34	-21.29	19.72	-0.91	856.77	-88.90	-376.25
11	0.14	0.12	1078.02	-88.01	258.80	-23.14	19.41	-0.51	1134.98	-112.54	-431.17
12	0.14	0.07	1216.04	-89.12	298.61	-24.38	19.21	-0.08	1452.79	-137.00	-487.75
13	0.14	0.07	1349.58	-86.81	335.63	-24.60	18.52	0.17	1806.94	-161.43	-545.77
14	0.14	0.12	1479.16	-80.34	373.83	-24.05	18.06	0.79	2198.83	-184.68	-604.87
15	0.14	0.13	1603.32	-68.70	409.73	-22.25	17.34	1.48	2625.90	-205.46	-664.38
16	0.14	0.13	1720.15	-50.26	442.52	-18.96	16.30	2.36	3084.72	-222.06	-723.04
17	0.13	0.12	1823.93	-24.17	455.84	-13.32	13.96	3.25	3554.51	-232.12	-779.38
18	0.84	0.84	2058.92	48.61	2292.68	-30.38	196.93	60.99	6044.12	-201.51	-779.38

Figure 21: MS EXCEL sheet for internal load calculation

The resulting internal force distribution is given in Table 4. Figure 22 and Figure 23 show the shear force and bending moment distribution along the blade span, respectively.

Table 4: Internal force distribution

<b>Radial Distance (m)</b>	<b>V<sub>z</sub> (N)</b>	<b>V<sub>x</sub> (N)</b>	<b>M<sub>x</sub> (Nm)</b>	<b>M<sub>y</sub> (Nm)</b>	<b>M<sub>z</sub> (Nm)</b>
5.029	0.0000	0.0000	0.0000	-29.6674	0.0000
4.841	90.8199	-11.2666	8.5481	-61.9790	-1.0636
4.565	227.0140	-27.3886	52.3184	-98.1848	-6.3851
4.288	367.0509	-42.6191	134.5332	-138.0986	-16.0503
4.011	509.3501	-56.1817	255.8735	-181.5560	-29.6881
3.772	633.1536	-66.1664	392.3925	-227.8528	-44.2747
3.735	652.3388	-67.5618	416.1742	-274.4021	-46.7485
3.458	795.4519	-76.8470	616.7100	-323.9065	-66.7018
3.181	937.6756	-83.8384	856.7725	-376.2519	-88.8982
2.905	1078.0151	-88.0088	1134.9767	-431.1723	-112.5426
2.628	1216.0447	-89.1163	1452.7949	-487.7537	-137.0033
2.352	1349.5757	-86.8141	1806.9442	-545.7691	-161.4284
2.075	1479.1647	-80.3393	2198.8347	-604.8680	-184.6848
1.798	1603.3229	-68.6950	2625.9000	-664.3813	-205.4591
1.522	1720.1468	-50.2622	3084.7158	-723.0426	-222.0573
1.257	1823.9261	-24.1693	3554.5128	-779.3804	-232.1224
0.0	2058.9244	48.6096	6044.1165	-779.3804	-201.5145

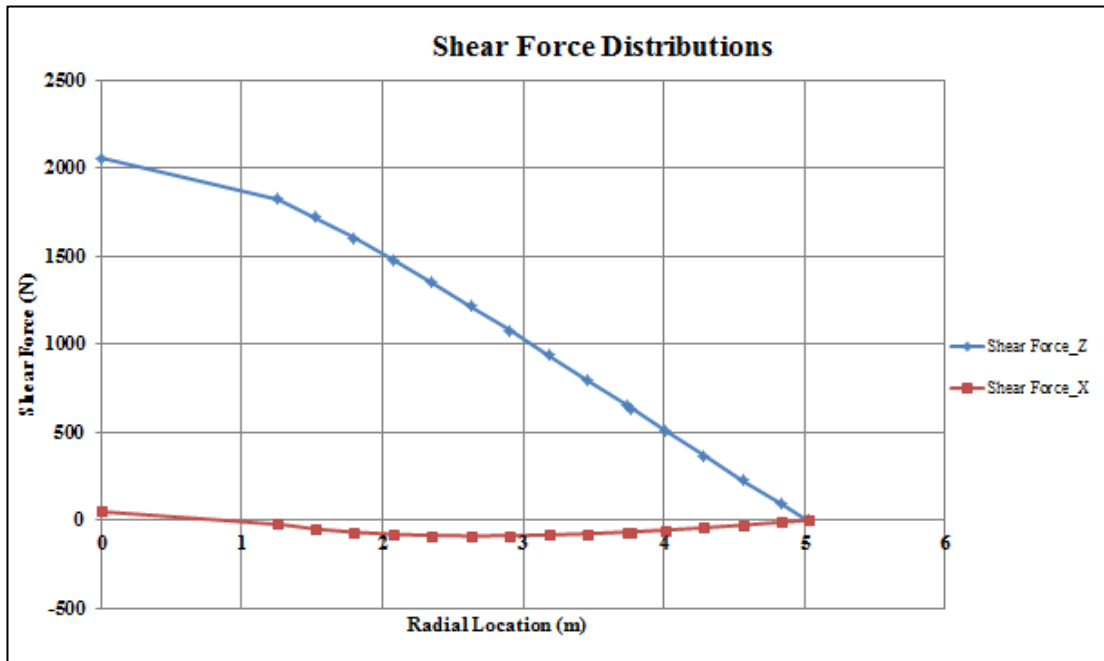


Figure 22: Shear force distributions along the span

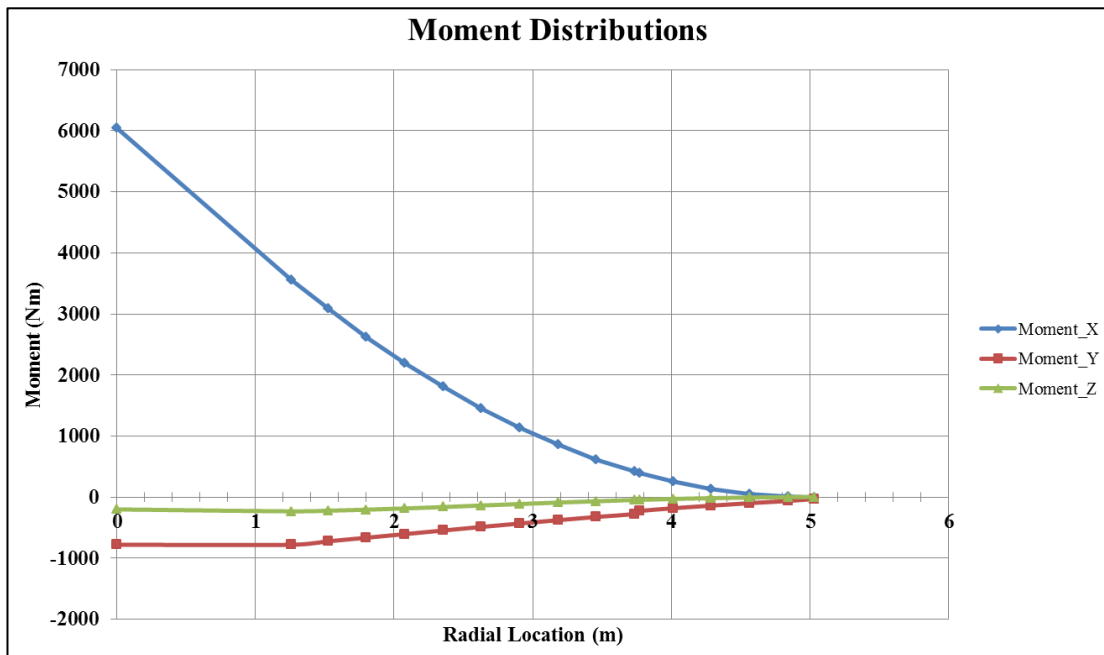


Figure 23: Moment distribution along the blade span

As seen from Figure 22 and Figure 23, only the shear force in Z direction and the bending moment about X-axis are the most critical loads. Therefore, those loads are considered as the design loads for the Whiffletree design. Also, as stated in

Reference 6, to take the uncertainties in load calculations into account, a partial safety factor is applied. For the selected load case, partial safety factor is taken as 1.35 as given in Table 3 of IEC 61400-1 [16]. Therefore, final design loads are determined by multiplying the calculated loads with the partial safety factor and final loads are given in Table 5.

Table 5: Final design loads

<b>Radial Distance (m)</b>	<b>V<sub>z</sub>(N)</b>	<b>M<sub>x</sub>(Nm)</b>
5.029	0.000	0.000
4.841	122.607	11.540
4.565	306.469	70.630
4.288	495.519	181.620
4.011	687.623	345.429
3.772	854.757	529.730
3.735	880.657	561.835
3.458	1073.860	832.558
3.181	1265.862	1156.643
2.905	1455.320	1532.219
2.628	1641.660	1961.273
2.352	1821.927	2439.375
2.075	1996.872	2968.427
1.798	2164.486	3544.965
1.522	2322.198	4164.366
1.257	2462.300	4798.592
0.0	2779.548	8159.557

It should be noted that the design loads summarized in Table 5 are simplified design loads that do not take into account all the load cases that should be considered in the design of wind turbine blades. In addition, only the critical shear force and bending moment components are taken as the design loads for demonstration purposes. The main aim of the thesis is to determine the optimum test load values and their positions which give the closest bending moment distribution as the distributed load case. To perform the main task of the thesis, any distributed load, which does not necessarily represent the real load case, could be taken and test loads could be calculated. However, in the present study, to be more realistic, simplified design loads are calculated considering aerodynamic loading only. Since the main scope of the thesis is not to perform a complete design of a wind turbine blade, simplified

design loads calculated are considered to be sufficient in demonstrating the calculation of the optimum discrete test loads that give the closest bending moment as the distributed load. It should again be stressed that in wind turbine blade testing, matching the variation of the bending moment is more important, because with discrete test loads, shear force can only match the shear force of the distributed load at discrete locations and shear force distribution looks like a staircase.





## CHAPTER 3

### TEST LOAD OPTIMIZATION

#### 3.1 Test Load Optimization Methodology

In this chapter, the methodology to determine the optimum discrete test loading to be applied through a Whiffletree is explained. Discrete test loading is determined such that it gives the best moment distribution along the blade span calculated for the selected load case. Two different tools are used separately for the test load optimization for comparison purposes. First tool utilized is MS EXCEL Solver add-in and the second one is the MATLAB tool developed for optimization. For each tool, different number of saddle points, as seen in Figure 11, Figure 12 and Figure 13 in Chapter 1, is used for optimization and the results obtained by each tool are compared with each other. Firstly, the optimization is performed for a Whiffletree with four saddle points as seen in Figure 11 in Chapter 1. In the subsequent optimization analysis, the number of saddle points is decreased to two. Detailed information about the use of the tools and how they are managed to solve the optimization problem associated with the discrete loading case is given in the following sections.

#### 3.2 Definition of the Optimization Problem

An optimization problem is defined by using the notation given in Eq. (10).

$$\min_x f(x) \text{ such that } \begin{cases} c(x) \leq 0 \\ ceq(x) = 0 \\ A.x \leq b \\ Aeq.x = beq \\ lb \leq x \leq ub \end{cases} \quad (10)$$

where  $f(x)$  is the objective function.

First two constraints are nonlinear inequality and equality constraints; next two constraints are linear inequality and equality constraints and the last constraint is the lower and upper bounds for the optimization variables which are the elements of the “x” vector.

For a Whiffletree configuration with  $N$  saddle points, there are  $2N$  design variables, since the load percentage values are optimized together with the locations of the saddle points. This means that the design variable vector “x” vector has  $2N$  elements. The first  $N$  elements are the load percentages, and the last  $N$  elements are the saddle locations. Therefore, for a Whiffletree with four saddle points;  $x_1, x_2, x_3, x_4$  corresponds to load percentages and  $x_5, x_6, x_7, x_8$  are saddle locations. The objective function, which is used in the optimization definition, is the sum of the absolute values of the percentage errors between test and design moments about X axis at each section. For the optimization of the saddle locations, moment distribution is selected since it is more critical than the shear force distribution for most of the load cases for the strength check of the blade. The objective function is defined by Eq. (11).

$$f(x) = \sum_{i=1}^T g(x)_i$$

$$g(x)_i = \begin{cases} 0 & M_{Design,i} = 0 \\ \left| \frac{M_{Design,i} - M_{Test,i}}{M_{Design,i}} * 100 \right| & M_{Design,i} \neq 0 \end{cases} \quad (11)$$

where;

i: The number of the section

T: Total number of the sections

$M_{Design}$ : Known design moment values

$M_{Test}$ : Calculated test moment values

To demonstrate the linear constraints and the bounds of the design variables used in the optimization, notations, which are related to the constraints, are given in Figure 24 for the Whiffletree with four saddle points.

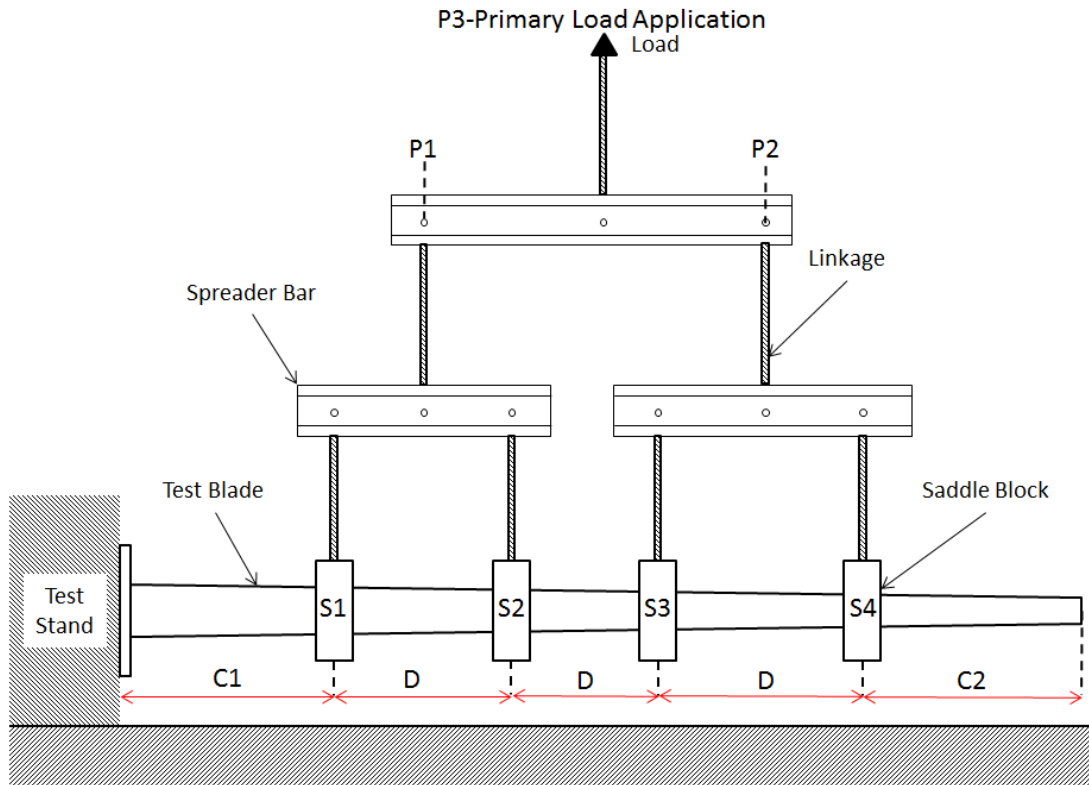


Figure 24: Notations used in the optimization

where;

S: Saddle point

P: Spreader bar connection point

C1: Minimum distance between the first saddle point and the root station of the blade

C2: Minimum distance between the last saddle point and the tip station of the blade

D: Minimum distance between saddle points

The primary load value applied through the top point of the whiffletree is taken as the shear force at the root section of the blade. Since the primary load is distributed to saddle point in percentages, the loads on the saddles can not be larger than the primary load and smaller than zero. Therefore, the upper and lower bounds for the load percentages are 1 and 0 respectively. For a Whiffletree with  $N$  saddle points, upper and lower bounds of the load percentages are shown in Eq. (12).

$$0 \leq x_i \leq 1 \quad i = 1, 2, \dots, N \quad (12)$$

where;

$x_i$ : Elements of the design variable vector corresponding to the load percentages

For uniform loading, saddles should be attached to the surfaces which do not have sharp curvature transitions. In general, wind turbine blades have transition surfaces between the root of the blade and the span station where airfoil sections start. Therefore, “C1” value shown in Figure 24 should be used for the lower bound of the saddle points in the optimization. It is possible that at the tip of the blades there may be some weak areas that should not be loaded that can result local failures. Therefore, for the last saddle location, “C2” is used as a constraint. For a Whiffletree with N saddle points, upper and lower bounds of the saddle points are shown in Eq. (13).

$$C1 \leq x_i \leq Tip - C2 \quad i = N + 1, N + 2, \dots, 2N \quad (13)$$

where;

Tip: Tip station location of the blade

$x_i$ : Elements of the design variable vector corresponding to the saddle points

As a result, “lb” and “ub” vectors, which are given in Eq. (10), can be written for a Whiffletree with four saddle points as shown in Eq. (14).

$$LB = [0 \ 0 \ 0 \ 0 \ C1 \ C1 \ C1 \ C1] \quad (14)$$

$$UB = [1 \ 1 \ 1 \ 1 \ (Tip - C2) \ (Tip - C2) \ (Tip - C2) \ (Tip - C2)]$$

To make reasonable measurements during the test, there should be space between loading points. Therefore, distance “D”, shown in Figure 24, is used as a constraint. It should be noted that since there is no information about the critical areas of the blade which should be tested accurately, in the present study design optimization of the Whiffletree system is performed for a generic case. Also, the order of the saddle locations is constrained by using the “D” value shown in Figure 24. For a Whiffletree with N saddle points, linear inequality constraints are shown in Eq. (15).

$$x_{i+1} - x_i \geq D \quad i = N + 1, N + 2, \dots, 2N - 1 \quad (15)$$

where;

$x_i$ : Elements of the design variable vector corresponding to the saddle points

The linear inequality constraints can be written in the matrix form as shown in Eq. (10) by multiplying the inequality relation given in Eq. (15) by (-1). The “A” matrix is generated with the coefficients of the design variables and the “b” vector is generated with the right hand side of the multiplied inequality relation. For a Whiffletree with four saddle points, the inequality constraint relation can be written in matrix form as shown in Eq. (16).

$$\begin{bmatrix} 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 \end{bmatrix} \cdot x \leq \begin{bmatrix} -D \\ -D \\ -D \end{bmatrix} \quad (16)$$

There is only one linear equality constraint used in the optimization. To get reasonable optimization results, the sum of the load percentages is equated to 1.0 since the total of the saddle loads should be same with the primary load value. For a Whiffletree with N saddle points, linear equality constraint for the saddle points is shown in Eq. (17).

$$\sum_{i=1}^N x_i = 1 \quad (17)$$

where;

$x_i$ : Elements of the design variable vector corresponding to the load percentages

The linear equality constraint can be written in the matrix form as shown in Eq. (10). The “Aeq” matrix is generated with the coefficients of the design variables and the “beq” vector is generated with the right hand side of the equality relation, which is 1. For a Whiffletree with four saddle points, the equality constraint relation can be written in matrix form as shown in Eq. (18).

$$[1 \ 1 \ 1 \ 1 \ 0 \ 0 \ 0 \ 0] \cdot x = [1] \quad (18)$$

In addition to the linear constraints, nonlinear constraints are used in the optimization problem. However, only nonlinear inequality constraints are added to the problem. These constraints are written as functions in “c(x)” vector, which is given in Eq. (10), respectively. The nonlinear constraints used in the optimization problem and the corresponding functions used in “c(x)” vector are defined in the following part of the section.

As a design recommendation given in Reference 19, the moment arm ratios of spreader bars should not exceed 2.0 for proper loading. Therefore, to satisfy this requirement, load ratio constraints are added to the optimization problem since the load ratio is directly related to the moment arm value. For instance, for the Whiffletree configuration with two saddle points, there is only one spreader bar in the Whiffletree system. Therefore, the number of the nonlinear inequality constraints related to the load ratio is also one and the function definition is given in Eq. (19).

$$c(x)_i \leq 0$$

$$c(x)_i = \begin{cases} \frac{x_2}{x_1} - 2 & x_2 \geq x_1 \\ \frac{x_1}{x_2} - 2 & x_1 \geq x_2 \end{cases} \quad (19)$$

where;

$x_1, x_2$ : Elements of the design variable vector corresponding to the load percentages

$i$ : The number of the element of the nonlinear inequality constraint vector “ $c(x)$ ”

The number of the constraints related to the load ratio for the Whiffletree with two saddle points is one. However, for other Whiffletree configurations, the number of nonlinear inequality constraints related to the load ratio is higher, although the same function definitions are used with minor changes.

In general, the region of the blade, which is close to the root section, is very critical, since the maximum bending moment occurs at the root. The error between the test load and the design load should be small at the root section for proper loading. Therefore, the allowable absolute value of the percentage error at the root section is added as nonlinear inequality constraint to the optimization problem. The allowable error constraint at the root section is defined in Eq. (20).

$$c(x)_i \leq 0$$

$$c(x)_i = \left| \frac{M_{Design,r} - M_{Test,r}}{M_{Design,r}} * 100 \right| - Allowable Error \quad (20)$$

where;

$r$ : Number of the root section

Allowable Error: Allowable absolute percentage error value

i: The number of the element of the nonlinear inequality constraint vector “c(x)”

To be more conservative during the loading, test loads should be higher than the design loads at each station. Therefore, the differences between the test and the design loads at each station are also used as nonlinear inequality constraints and the constraints are defined as shown in Eq. (21).

$$c(x)_i \leq 0$$

$$c(x)_i = \begin{cases} 0 & M_{Test}(j) = 0 \\ M_{Design,j} - M_{Test,j} & M_{Test}(j) \neq 0 \end{cases} \quad (21)$$

where;

j: The number of the station

i: The number of the element of the nonlinear inequality constraint vector “c(x)”

The “if” condition is added to the constraint definition because if the test load is zero at some section, it means that there is no saddle that affects the section, and there is no chance that the test load can become higher than the design load.

Since there is no nonlinear equality constraint, “ceq” vector, which is given in Eq. (10), is not used in the optimization problem. All of the required information is defined for the optimization problem. These definitions are implemented on the optimization tools developed for the solution of the problem in the following sections.

### 3.3 Test Load Optimization via MS EXCEL

MS EXCEL sheets are prepared for all different Whiffletree configurations separately and these sheets are added to the same workbook where design loads are calculated. In this way, calculated design loads for different load cases can be used in the optimization directly for the selected Whiffletree configuration by using the Solver add-in tool of the software. Detailed information of the Solver add-in tool is given in the following section for the test load optimization for the Whiffletree with four saddle points.

#### 3.3.1 Whiffletree with Four Saddle Points

Firstly, the optimization is performed for the Whiffletree configuration with four saddle points. Details of the prepared MS EXCEL sheet are given in this section. It

should be noted that the notations given in Figure 24 for the optimization parameters are also used in the MS EXCEL sheets. After introducing the MS EXCEL sheet, the definition of the optimization problem is implemented on the Solver add-in tool of the software.

An overview of the MS EXCEL sheet can be seen in Figure 25. As seen from Figure 25, the MS EXCEL sheet consists of seven main parts such that;

1. Design loads at the sections of the blade
2. Definition of the design variables and constraints
3. Determination of the Whiffletree connection points
4. Determination of the loading check matrix
5. Calculation of the moment values at the section due to saddle loads
6. Calculation of the test loads at the sections
7. Calculation of the absolute values of the percentage errors at the sections



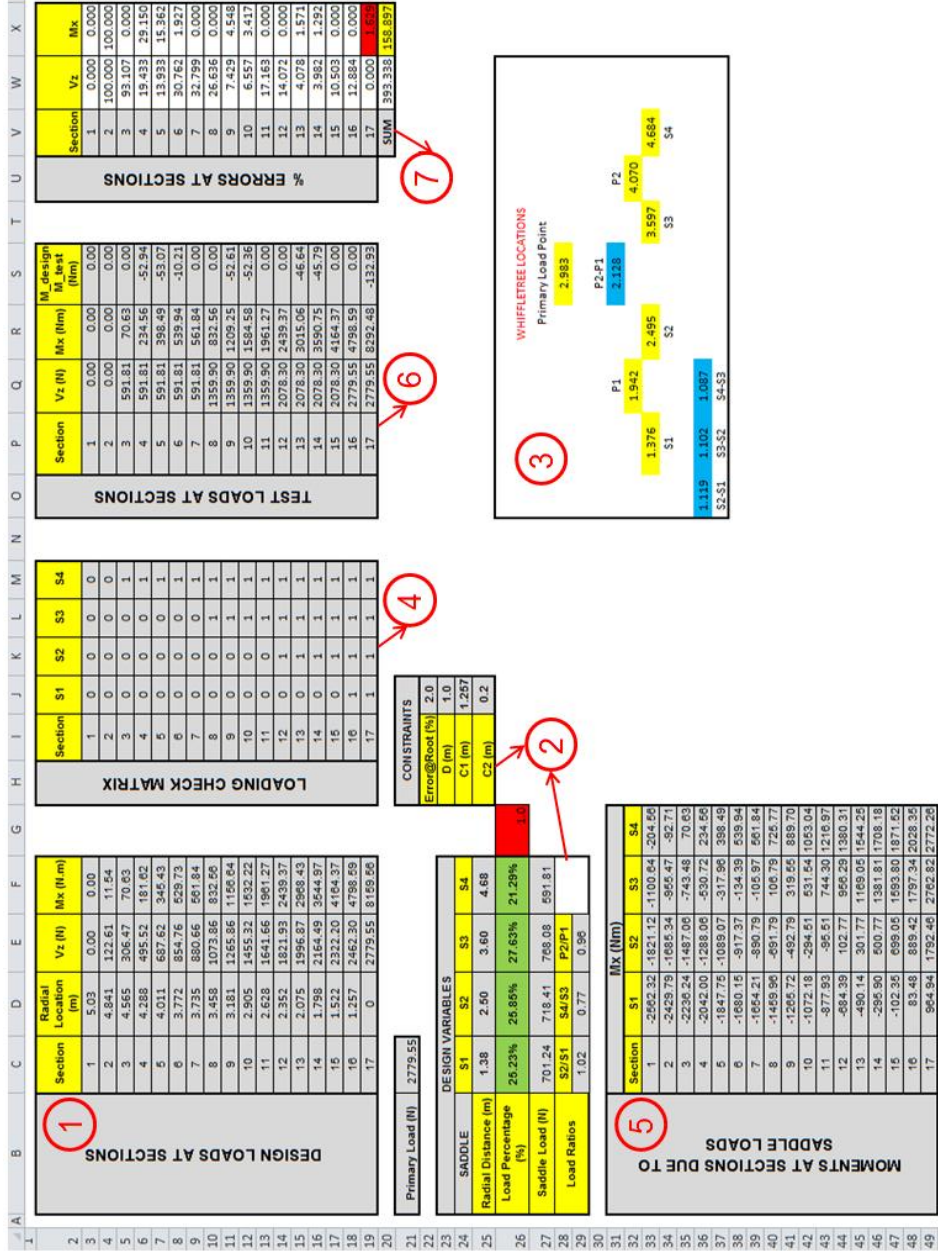


Figure 25: An overview of the MS EXCEL sheet

In Figure 26, the first part of the MS EXCEL sheet can be seen in detail. In this part of the MS EXCEL sheet, design loads, which include the shear force in the Z direction and the bending moment about the X axis of the global coordinate system of the blade, are taken directly from the MS EXCEL sheets used for the calculation of design loads.

<b>DESIGN LOADS AT SECTIONS</b>	Section	Radial Location (m)	Vz (N)	Mx (N.m)
	1	5.03	0.00	0.00
	2	4.841	122.61	11.54
	3	4.565	306.47	70.63
	4	4.288	495.52	181.62
	5	4.011	687.62	345.43
	6	3.772	854.76	529.73
	7	3.735	880.66	561.84
	8	3.458	1073.86	832.56
	9	3.181	1265.86	1156.64
	10	2.905	1455.32	1532.22
	11	2.628	1641.66	1961.27
	12	2.352	1821.93	2439.37
	13	2.075	1996.87	2968.43
	14	1.798	2164.49	3544.97
	15	1.522	2322.20	4164.37
	16	1.257	2462.30	4798.59
17	0	2779.55	8159.56	

Figure 26: Part of the MS EXCEL sheet for design loads

The second part of the MS EXCEL sheet includes the design variables and the constraints used in the optimization problem as seen in Figure 27.

<b>Primary Load (N)</b>	2779.55			
DESIGN VARIABLES				
SADDLE	S1	S2	S3	S4
Radial Distance (m)	1.38	2.50	3.60	4.68
Load Percentage (%)	25.23%	25.85%	27.63%	21.29%
Saddle Load (N)	701.24	718.41	768.08	591.81
Load Ratios	S2/S1	S4/S3	P2/P1	
	1.02	0.77	0.96	

CONSTRAINTS	
Error@Root (%)	2.0
D (m)	1.0
C1 (m)	1.257
C2 (m)	0.2

Figure 27: Part of the MS EXCEL sheet defining the design variables and the constraints

As seen from Figure 27, the primary load value applied through the top point of the Whiffletree is taken as the shear force at the root section of the blade which is determined as 2779.55 N in Chapter 2 for the UAE research wind turbine blade. Before starting the optimization, random numbers can be assigned to the cells, which includes the radial distance of the saddle points and the corresponding load percentages. Those cells are selected as design variables while defining the optimization problem in the Solver add-in tool of the software. The cell, which is highlighted with red, gives the summation of the load percentages. It is used as an equality constraint in the optimization problem definition according to the relation given in Eq. (16). The cells, which give the load ratios, are constrained in the optimization problem definition such that the cell values can not be larger than 2.0 as defined in Eq. (19). The upper and lower bounds of the load percentages are defined according to the relation given in Eq. (12). The upper and lower bounds of the saddle locations are defined by using the entered values for “C1”, “C2” and the radial location of section 1 given in Figure 26, according to the relation given in Eq. (13). “C1” value is taken as 1.257 m, since the airfoil sections start at that location and “C2” value is taken as 0.2 m for this study as an assumption since there is no detailed information about the strength of the blade used in the optimization problem. The linear inequality constraints for the saddle locations are defined according to the relation given in Eq. (15) by using the entered value for “D” and the calculated distance values between the saddle locations. The distance values between the saddle locations are given in the third part of MS EXCEL sheet, which is shown in Figure 28. It should be noted that since there is no information about the critical areas of the blade, which should be tested accurately, in the present study design optimization of the Whiffletree system is performed for a generic case. Therefore, “D” is taken as 1.0 m for this study. In addition, allowable absolute percentage error value between the test and the design moments at the root section should be entered to the cell, which is next to the label “Error@Root (%)” in this part of the MS EXCEL sheet. This value is used as a constraint according to the relation given in Eq. (20) with the absolute error value calculated at the root section in the last part of the MS EXCEL sheet,

which is shown in Figure 34, and highlighted with red. It should be noted that the values given in Figure 27 are the optimization results for the Whiffletree with four saddle points.

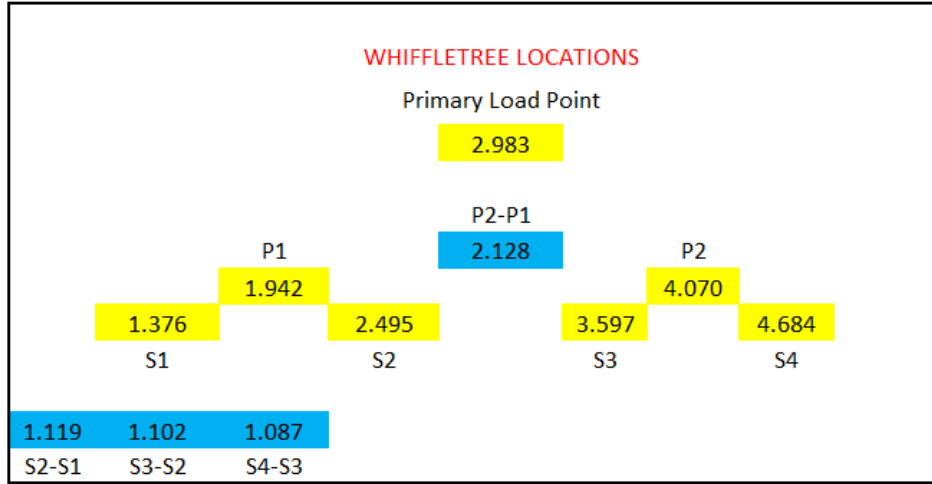


Figure 28: Part of the MS EXCEL sheet showing the connection/saddle points and distances between connection/saddle points

For the calculation of the distances between saddle points and the resulting Whiffletree connection points, a separate part is prepared in the MS EXCEL sheet and it is shown in Figure 28. The cells, which are highlighted with yellow in Figure 28, are the connection/saddle points of the Whiffletree and the cells, which are highlighted with blue in Figure 28, are the distances between connection/saddle points. To find the connection points of the Whiffletree, relations given in Eqs. (21-23) are used.

$$P1 = \frac{S1 * LP_1 + S2 * LP_2}{LP_1 + LP_2} \quad (21)$$

$$P2 = \frac{S3 * LP_3 + S4 * LP_4}{LP_3 + LP_4} \quad (22)$$

$$P3 = P1 * (LP_1 + LP_2) + P2 * (LP_3 + LP_4) \quad (23)$$

where;

LP<sub>i</sub>: Load percentage of i<sup>th</sup> saddle

P3: Primary load application point

The relations given in Eqs. (21-23) are derived by equating the moment values created by the loads applied through the ends of the spreader bars about the connection points of the spreader bars. For instance, for the spreader bar, which connects the saddles 1 and 2, the moment equation about connection point P1 can be written as given in Eqs. (24-25).

$$\text{Primary Load} * LP_1 * (P1 - S1) = \text{Primary Load} * LP_2 * (S2 - P1) \quad (24)$$

$$LP_1 * P1 - LP_1 * S1 = LP_2 * S2 - LP_2 * P1 \quad (25)$$

By collecting the terms with “P1” on the left hand side of the Eq. (25), the following relation is obtained.

$$P1 * (LP_1 + LP_2) = LP_2 * S2 + LP_1 * S1 \quad (26)$$

By dividing both of the sides of Eq. (26) with  $(LP_1 + LP_2)$ , Eq. (21) is obtained. It should be noted that the values given in Figure 28 are the optimization results for the Whiffletree with four saddle points.

LOADING CHECK MATRIX	Section	S1	S2	S3	S4
	1	0	0	0	0
	2	0	0	0	0
	3	0	0	0	1
	4	0	0	0	1
	5	0	0	0	1
	6	0	0	0	1
	7	0	0	0	1
	8	0	0	1	1
	9	0	0	1	1
	10	0	0	1	1
	11	0	0	1	1
	12	0	1	1	1
	13	0	1	1	1
	14	0	1	1	1
	15	0	1	1	1
	16	1	1	1	1
17	1	1	1	1	

Figure 29: Part of the MS EXCEL sheet for determination of the loading check matrix

A loading check matrix, which is shown in Figure 29, is prepared to check the influence of the applied loading on the sections of the blade through the saddles.

Loading check matrix works as a singularity function for determination of the test shear force and moment values. According to the loading check matrix, if the radial distance, measured from the root of the blade, of the section is smaller than the saddle location, the applied loading through that saddle is included in the shear and moment calculations for that section. The methodology for the determination of the elements of the loading check matrix is given in Eq. (27).

$$LCM_{i,j} = \begin{cases} 1, & \text{Section Location}_i \leq \text{Saddle Location}_j \\ 0 & \text{Section Location}_i > \text{Saddle Location}_j \end{cases} \quad (27)$$

$$i = 1, 2, 3, \dots, T ; \quad j = 1, 2, \dots, N$$

where;

i: Number of the section

j: Number of the saddle

$LCM_{i,j}$ : The value of the element in the  $i^{\text{th}}$  row and  $j^{\text{th}}$  column of the matrix

T: Total number of sections

N: Total number of saddles

For instance, since the radial location of the section 8 is 3.458 m, which is higher than the radial locations of the first two saddle points and lower than the radial locations of the last two saddle points, the values of the loading check matrix elements corresponding to the section 8 are 0 for the first two columns and 1 for the last two column.

MOMENTS AT SECTIONS DUE TO SADDLE LOADS	Mx (Nm)			
	Section	S1	S2	S3
1	-2562.32	-1821.12	-1100.64	-204.56
2	-2429.79	-1685.34	-955.47	-92.71
3	-2236.24	-1487.06	-743.48	70.63
4	-2042.00	-1288.06	-530.72	234.56
5	-1847.75	-1089.07	-317.96	398.49
6	-1680.15	-917.37	-134.39	539.94
7	-1654.21	-890.79	-105.97	561.84
8	-1459.96	-691.79	106.79	725.77
9	-1265.72	-492.79	319.55	889.70
10	-1072.18	-294.51	531.54	1053.04
11	-877.93	-95.51	744.30	1216.97
12	-684.39	102.77	956.29	1380.31
13	-490.14	301.77	1169.05	1544.25
14	-295.90	500.77	1381.81	1708.18
15	-102.35	699.05	1593.80	1871.52
16	83.48	889.42	1797.34	2028.35
17	964.94	1792.46	2762.82	2772.26

Figure 30: Part of MS EXCEL sheet for moment calculations at sections due to saddle loads

In the fifth part of the MS EXCEL sheet, moment values at the sections due to the saddle loads are calculated by multiplying the saddle loads with the distance between the saddle location and the section location and the results are presented in Figure 30. In the calculation, saddle location and load values, which are determined in the second part of the MS EXCEL sheet, are used with the radial locations of the blade sections as shown in Eq. (28).

$$M_{i,j} = Saddle\ Load_j * (Saddle\ Location_j - Section\ Location_i) \quad (28)$$

$$i = 1, 2, 3, \dots, T ; \quad j = 1, 2, \dots, N$$

where;

i: Number of the section

j: Number of the saddle

$M_{i,j}$ : Moment value at section i due to saddle j

T: Total number of sections

N: Total number of saddles

TEST LOADS AT SECTIONS	Section	Vz (N)	Mx (Nm)	M_design- M_test (Nm)
	1	0.00	0.00	0.00
	2	0.00	0.00	0.00
	3	591.81	70.63	0.00
	4	591.81	234.56	-52.94
	5	591.81	398.49	-53.07
	6	591.81	539.94	-10.21
	7	591.81	561.84	0.00
	8	1359.90	832.56	0.00
	9	1359.90	1209.25	-52.61
	10	1359.90	1584.58	-52.36
	11	1359.90	1961.27	0.00
	12	2078.30	2439.37	0.00
	13	2078.30	3015.06	-46.64
	14	2078.30	3590.75	-45.79
	15	2078.30	4164.37	0.00
	16	2779.55	4798.59	0.00
17	2779.55	8292.48	-132.93	

Figure 31: Part of MS EXCEL sheet for calculation of the test loads at the sections

As seen from Figure 31, in this part of the MS EXCEL sheet, shear forces in the Z direction and bending moments about the X-axis for test loading are calculated. In addition, the difference between the design and the test moment values is determined to constrain the test loads to be larger than design loads at each section as given in the constraint definition by Eq. (21). It should be noted that the values given in Figure 31 are the optimization results for the Whiffletree with four saddle points. By using the built-in SUMPRODUCT function of MS EXCEL, test loads are obtained at the sections. For the test shear forces at the sections, saddle loads given in “Saddle Load” row in the second part of the sheet, which is shown in Figure 27, are used with each section row of the loading check matrix, which is shown in Figure 29, in the SUMPRODUCT function. An example calculation step is shown in Figure 32.



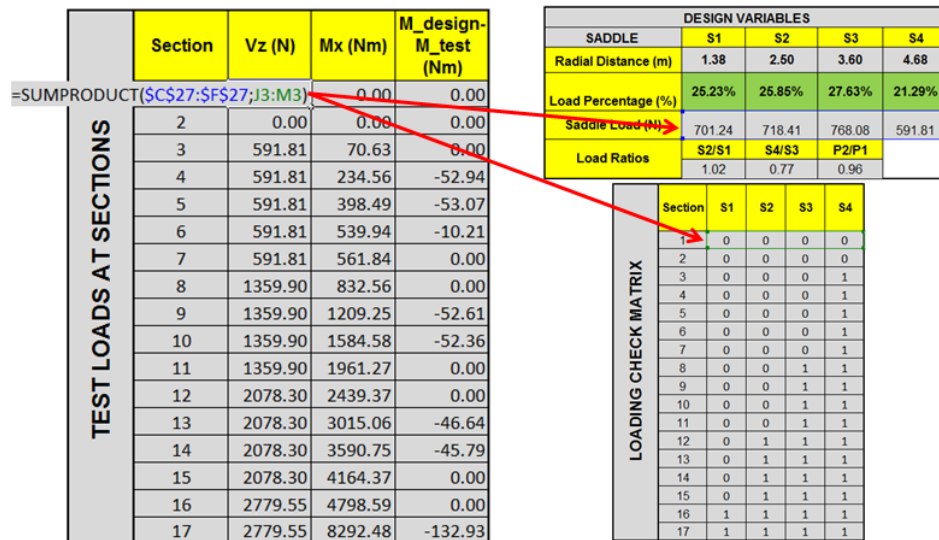


Figure 32: The methodology for the test shear force determination in MS EXCEL sheet

In other words, the saddle loads are summed for shear force calculation if the radial location of the specified section is lower than the radial distance of the corresponding saddles. For the test moment values at the sections, SUMPRODUCT function is used in a similar manner as the shear force calculations. However, for moment calculations, each row of the fifth part of the MS EXCEL sheet, which includes the moment values calculated at the sections due to saddle loads, are used with each section row of the loading check matrix. An example calculation step is shown in Figure 33.

TEST LOADS AT SECTIONS	Section	Vz (N)	Mx (Nm)	M_design- M_test (Nm)	MOMENTS AT SECTIONS DUE TO SADDLE LOADS	Mx (Nm)				
	Section	S1	S2	S3		S4				
	1	-2562.32	-1821.12	-1100.64		-204.56				
2	-2429.79	-1685.34	-955.47	-92.71						
3	2236.24	-1487.06	-743.48	70.63						
4	-2042.00	-1288.06	-530.72	234.56						
5	-1847.75	-1089.07	-317.96	398.49						
6	-1680.15	-917.37	-134.39	539.94						
7	-1654.21	-890.79	-105.97	561.84						
8	-1459.96	-691.79	106.79	725.77						
9	-1265.72	-492.79	319.55	889.70						
10	-1072.18	-294.51	531.54	1053.04						
11	-877.93	-95.51	744.30	1216.97						
12	-684.39	102.77	956.29	1380.31						
13	-490.14	301.77	1169.05	1544.25						
14	-295.90	500.77	1381.81	1708.18						
15	-102.35	699.05	1593.80	1871.52						
16	83.48	889.42	1797.34	2028.35						
17	964.94	1792.46	2762.82	2772.26						

Section	S1	S2	S3	S4
1	0	0	0	0
2	0	0	0	0
3	0	0	0	1
4	0	0	0	1
5	0	0	0	1
6	0	0	0	1
7	0	0	0	1
8	0	0	1	1
9	0	0	1	1
10	0	0	1	1
11	0	0	1	1
12	0	1	1	1
13	0	1	1	1
14	0	1	1	1
15	0	1	1	1
16	1	1	1	1
17	1	1	1	1

Figure 33: The methodology for the test bending moment determination in MS EXCEL sheet

In the final part of the MS EXCEL sheet, which is shown in Figure 34, the absolute values of the percentage errors between the test and design loads are calculated for each section and the sum of the absolute values are determined for shear force and bending moment respectively.

% ERRORS AT SECTIONS	Section	Vz	Mx
	1	0.000	0.000
2	100.000	100.000	
3	93.107	0.000	
4	19.433	29.150	
5	13.933	15.362	
6	30.762	1.927	
7	32.799	0.000	
8	26.636	0.000	
9	7.429	4.548	
10	6.557	3.417	
11	17.163	0.000	
12	14.072	0.000	
13	4.078	1.571	
14	3.982	1.292	
15	10.503	0.000	
16	12.884	0.000	
17	0.000	1.629	
<b>SUM</b>	<b>393.338</b>	<b>158.897</b>	

Figure 34: Part of MS EXCEL sheet for calculation of the absolute value of the percentage errors between the test and design loads

The absolute values of the percentage errors between the test and design loads are calculated by the Eqs. (29-30).

$$|V_{Error,i}| = \begin{cases} 0 & V_{Design,i} = 0 \\ \left| \frac{V_{Design,i} - V_{Test,i}}{V_{Design,i}} * 100 \right| & V_{Design,i} \neq 0 \end{cases} \quad (29)$$

$$|M_{Error,i}| = \begin{cases} 0 & M_{Design,i} = 0 \\ \left| \frac{M_{Design,i} - M_{Test,i}}{M_{Design,i}} * 100 \right| & M_{Design,i} \neq 0 \end{cases} \quad (30)$$

where;

i: Number of the section

Finally, the sum of the absolute values of the percentage errors between the test and design loads is calculated at the bottom of the part. As mentioned before, the cell, which is highlighted with red, is the absolute value of the percentage error at the root section. This cell is used in the constraint definition given by the relation in Eq. (20). The cell, which is highlighted with yellow, is the sum of the absolute values of the percentage errors between the test and design moments. This cell is used as the objective value while defining the optimization problem in the Solver add-in tool of the software.

After preparation of the MS EXCEL sheet is completed for the optimization, Solver add-in tool of the software can be used. A screenshot of the Solver add-in tool is given in Figure 35.

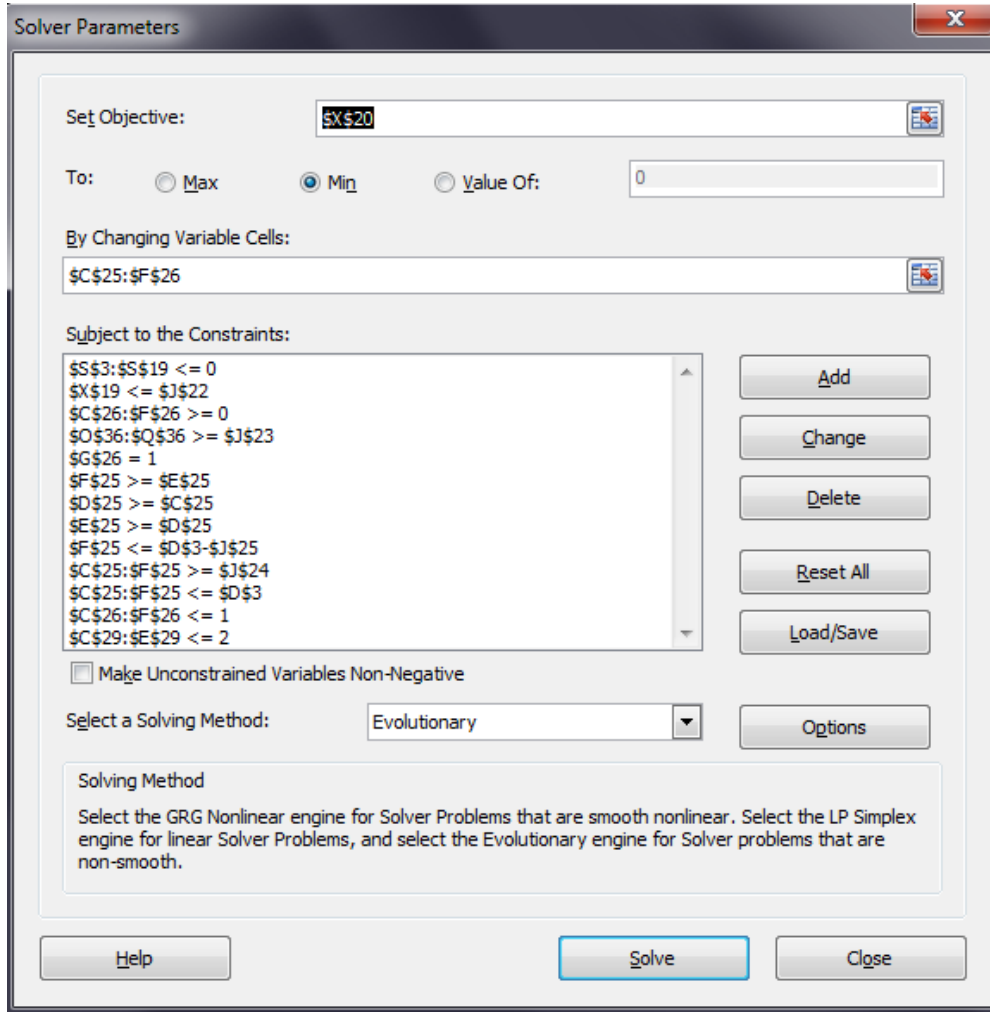


Figure 35: Screenshot of the Solver add-in tool of MS EXCEL

In the Solver add-in interface, which is given in Figure 35, the cell, which is highlighted with yellow in Figure 34, is selected for the “Set Objective” field. Since the cell, which is selected for the “Set Objective” field, should contain the objective function value. The type of the optimization performed in this study is the minimization of the objective function. Therefore, the “Min” option is selected. The cells, which contain the design variables shown in Figure 27, are selected for the “By Changing Variable Cells” field. The constraints of the optimization problem, which are defined in Section 3.2, are added one by one by using the “Add” button and selecting the cells which are related with the constraints. The list of the constraints used in the optimization problem can be seen in the “Subject to the Constraints”

field, which is shown in Figure 35, and the cells, which are related with the constraints, are mentioned before while introducing the parts of the MS EXCEL sheet. Evolutionary algorithm is selected as the method for optimization since there are discontinuities in shear force calculation which affects moment calculations. A variety of genetic algorithm and local search method are used in this method [20]. To select the options for the optimization method, “Options” button should be clicked. Firstly, the general options for all methods are shown to the screen as shown in Figure 36.

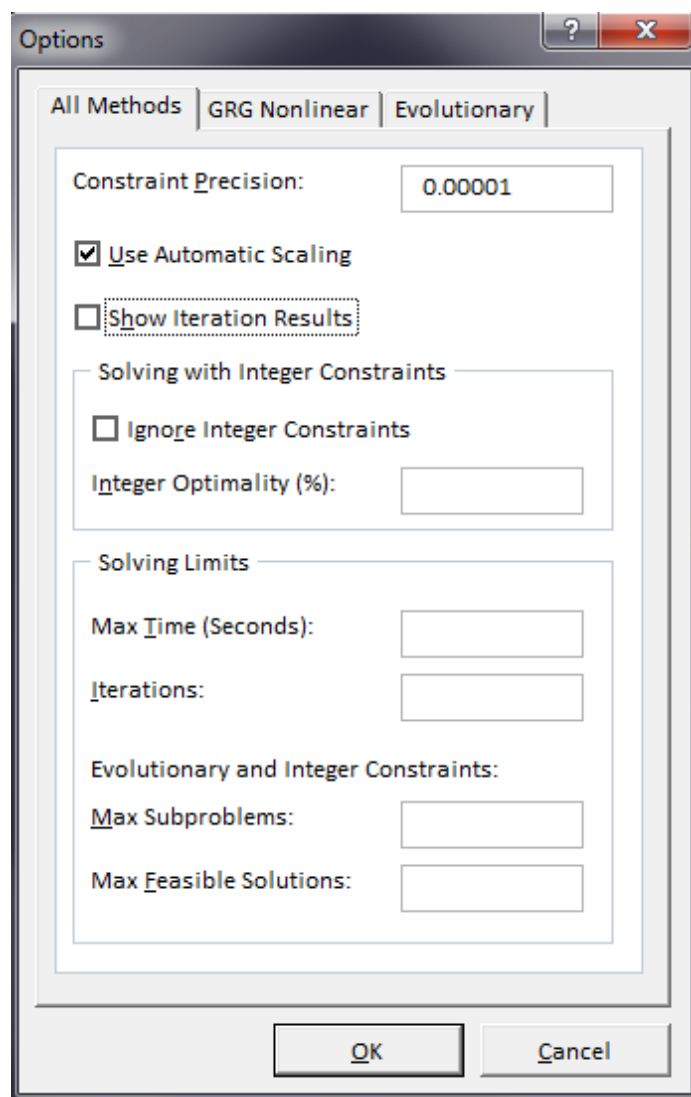


Figure 36: General optimization options for all methods in Solver add-in tool

The definitions of the options for all methods in Solver add-in tool are given below [21].

**Constraint Precision:** Constraint precision is the degree of precision for any constraint defined in the optimization problem. A constraint is considered as satisfied, when the relationship between the values related to the constraint is not violated by more than this amount.

**Use Automatic Scaling:** When the “Use Automatic Scaling” check box is selected, Solver add-in tool internally rescale the values of variables, constraints and the objective to similar magnitudes, to reduce the impact of extremely large or small values on the accuracy of the solution process.

**Show Iteration Results:** When the “Show Iteration Results” check box is selected, the values of each trial are shown to the screen.

**Ignore Integer Constraints:** When the “Ignore Integer Constraints” check box is selected, all integer, binary and all different constraints are ignored.

**Integer Optimality:** Integer Optimality is the maximum percentage difference Solver add-in tool should accept between the objective value of the best integer solution found and the best known bound on the true optimal objective value before stopping.

**Max Time (Seconds):** Max time is the total number of seconds that the Solver add-in tool is allowed to run.

**Iterations:** Maximum number of iteration that the Solver add-in tool is allowed to perform.

**Max Subproblems:** Maximum number of subproblems is allowed for the problems which the Evolutionary method is used or for the problems which have integer constraints on variables.

**Max Feasible Solutions:** Maximum number of feasible solutions is allowed for the problems which the Evolutionary method is used or for the problems which have integer constraints on variables.

As seen from Figure 36, only the constraint precision is defined for the optimization problem, which is  $10^{-5}$  and the “Use Automatic Scaling” option is selected. Since

there are no integer constraints, options related to the integer constraints are left blank. In addition, no solving limit is defined for the problem. After the selection of the general options for the optimization method is completed, the specific options related to the Evolutionary algorithm should be selected. In Figure 37, options for the evolutionary algorithm are given.

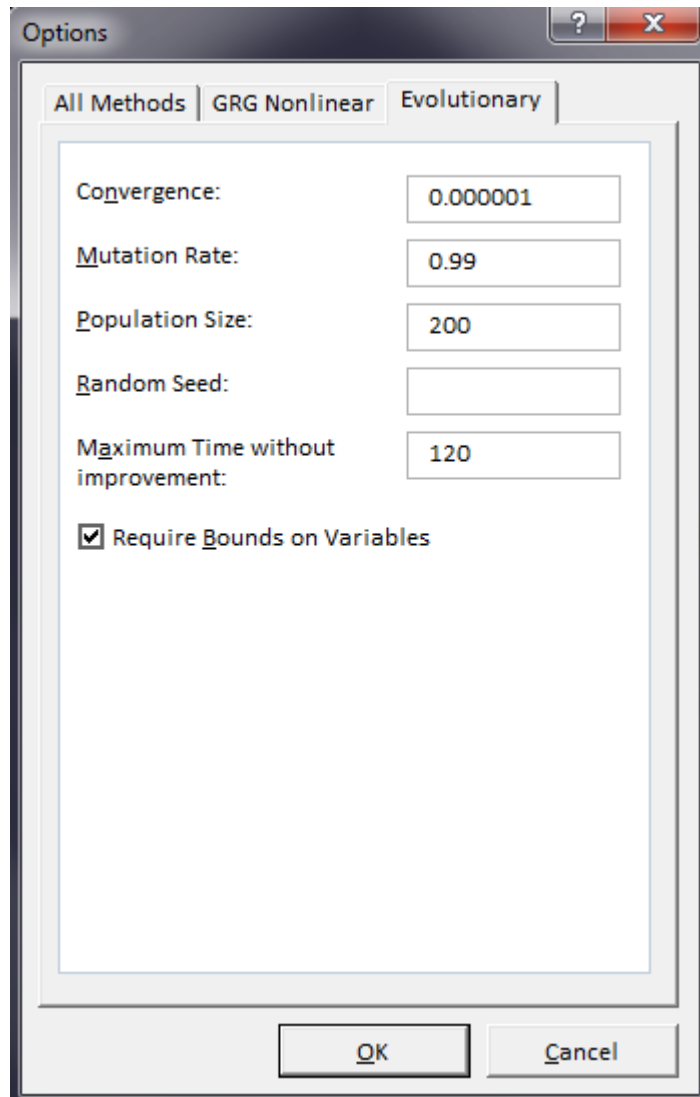


Figure 37: Options for the evolutionary algorithm for optimization

The definitions of the options for the evolutionary algorithm for optimization are given below [22].

**Convergence:** Convergence is the maximum percentage difference in objective values for the 99% of the population that Solver add-in should allow to stop.

**Mutation Rate:** Mutation rate is the relative frequency with which some member of the population will be altered or mutated to create a new trial solution, during each generation considered by the Evolutionary method. The value for the mutation rate should be entered between 0 and 1. A higher mutation rate value increases the diversity of the population and the chance of a new, better solution. However, the total solution time may increase with higher mutation rate values.

**Population Size:** Population size is the number of different points (values for the decision/design variables) that the Evolutionary method maintains at any given time in the population of candidate solutions. The minimum population size is 10 members; if a value less than 10 is entered in this field, or left blank, the Evolutionary method uses a population size of 10 times the number of decision/design variables in the problem. The maximum population limit is 200 members.

**Random Seed:** A positive integer number should be entered in this field to be used as the fixed seed for the random number generator used for a variety of random choices in the Evolutionary method. If a number is entered in this field, the Evolutionary method uses the same choices each time the optimization is started. If the field is left blank or 0 is entered to the field, the random number generator uses a different seed each time the optimization is started, which may result a different (better or worse) final solution.

**Maximum Time without Improvement:** Maximum time without improvement is the maximum number of seconds that the Evolutionary method is allowed to continue without a meaningful improvement in the objective value of the best solution in the population.

**Require Bounds on Variables:** When the check box is selected, the Evolutionary method runs only if the lower and upper bounds on all decision/design variables are defined in the constraints list box. The Evolutionary method is far more effective when the bounds on all variables are defined.

As seen from Figure 37, convergence value is entered as  $10^{-6}$ . No further improvement is observed for smaller tolerances. The selected mutation rate is



selected very close to 1, which is the maximum value that can be assigned, to increase the diversity of the population. Different population sizes are used for convergence study. However, the minimum solution is obtained for the population size of 200 which is the maximum value that can be assigned. Random seed value is entered as 1 during the convergence studies to observe the effects of different population sizes. Since, as given in the definition, when a positive integer number is entered for the random seed, a fixed seed is used for the random number generator and the Evolutionary method uses the same choices each time the optimization is started. However, for the final population size value, this value is left blank, as seen in Figure 37, to observe the different final solution values. Maximum time without improvement value is set to 2 minutes which is again considered to be sufficient for the Whiffletree design optimization problems considered in this thesis. The checkbox for “Require Bounds on Variables” are ticked since the Evolutionary method is more effective when the bounds on variables are defined, as given in the definition.

After the selection of the options for the Evolutionary method is completed, the optimization can be started by clicking the “Solve” button in the main Solver add-in tool interface, which is shown in Figure 35.

As a result of the optimization, shear force and moment distributions obtained by the test loads are plotted together with the design load distributions for the Whiffletree with four saddle points and the plots are given in Figure 38 and Figure 39.

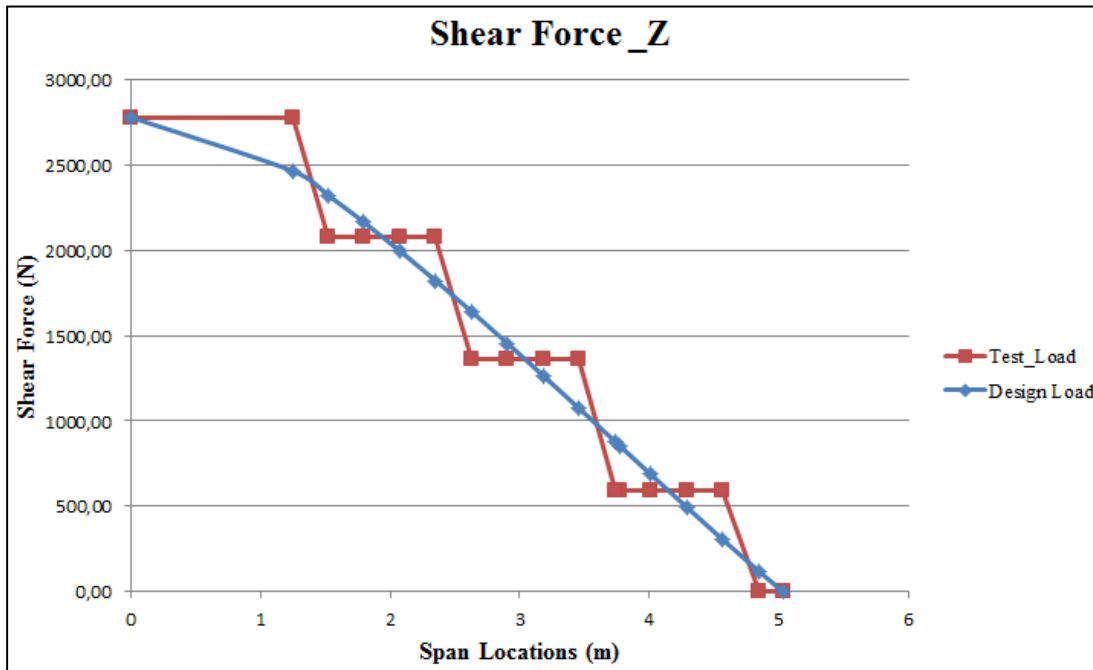


Figure 38: Shear force distributions for the optimized whiffletree with four saddle points

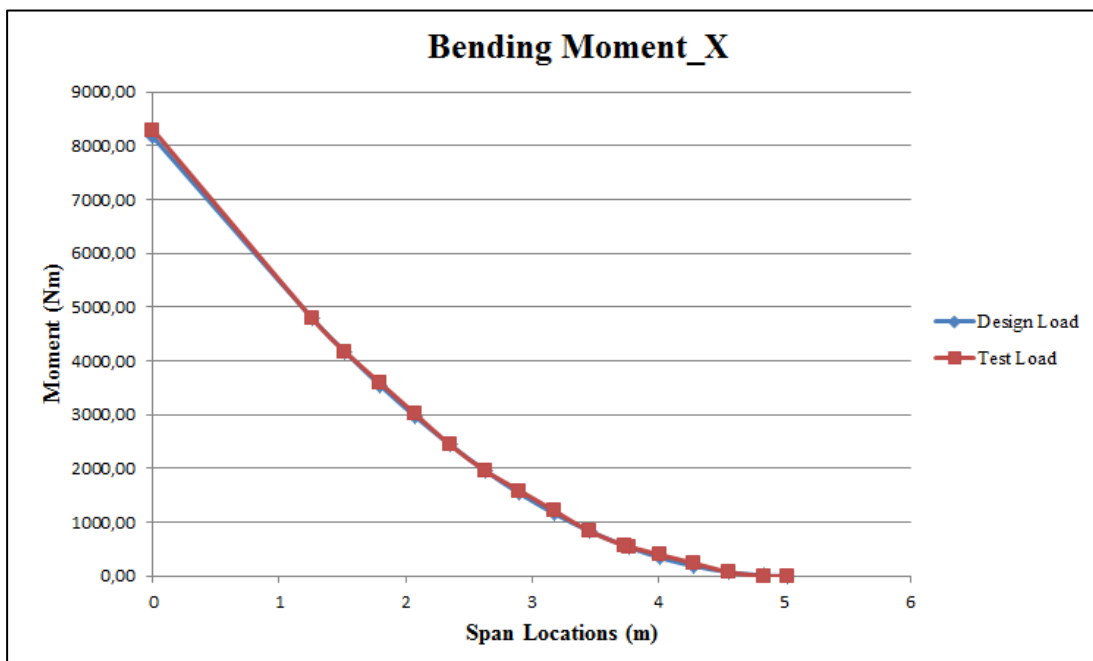


Figure 39: Moment distributions for the optimized whiffletree with four saddle points. For the other Whiffletree configurations with three or two saddle points, same methodology is used with some minor changes in the second and third parts of the

MS EXCEL sheet, which are used for the definition of the design variables and constraints, and the determination of the Whiffletree connection points. These changes are given in the following sections for each configuration.

### 3.3.2 Whiffletree with Three Saddle Points

For the Whiffletree with three saddle points, there are different options for loading. For these different options, two separate MS EXCEL sheets are prepared since the constraints, which are related to the connection points, are different. These options are given in Figure 40, and the nomenclature given in Figure 24 for the optimization parameters is also valid for the two configurations having three saddle points.

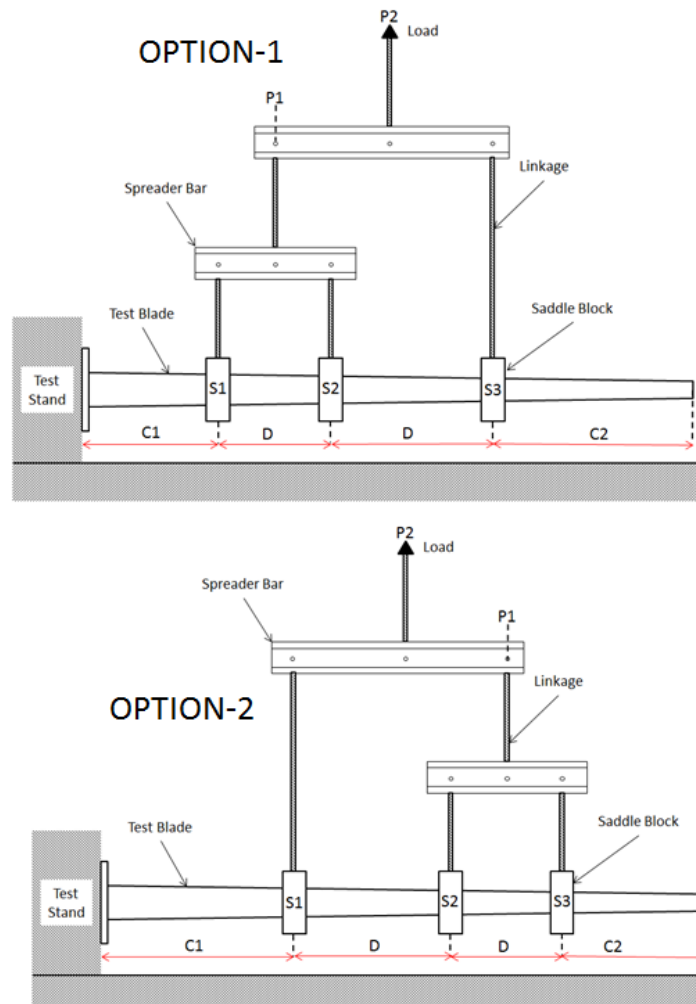


Figure 40: Loading options for whiffletree with three saddle points

To perform the optimization for the Whiffletree with three saddle points, following changes are made in the MS EXCEL sheets.

- For the fourth saddle point, radial distance and load percentage values are entered as zero in the MS EXCEL sheet, and design variable and constraint selections related to the fourth saddle point are omitted.

<b>Primary Load (N)</b>	2779.55			
-------------------------	---------	--	--	--

DESIGN VARIABLES				
SADDLE	S1	S2	S3	S4
Radial Distance (m)	1.41	2.98	4.48	0.00
Load Percentage (%)	31.53%	35.14%	33.33%	0.00%
Saddle Load (N)	876.33	976.70	926.52	0.00
Load Ratios	S2/S1	S3/P1		
	1.11	0.50		

CONSTRAINTS	
Error@Root (%)	2.0
D (m)	1.0
C1 (m)	1.257
C2 (m)	0.2

Figure 41: Part of the MS EXCEL sheet showing the design variable selection and constraints for the three-saddle point configuration option-1

As seen from Figure 41, radial distance and load percentage values are entered as zero in the MS EXCEL sheet for the fourth saddle point. In addition, only “S2/S1” and “S3/P1” are used for load ratio calculations. It should be noted that the values given in Figure 41 are the optimization results for option-1. For option-2, instead of using load ratios shown in Figure 41, “S3/S2” and “P1/S1” are used as optimization constraints for load ratios as shown in Figure 42. It should be noted that the values given in Figure 42 are the optimization results for option-2. The constraining values, which are “Error@Root”, “D”, “C1” and “C2”, are not changed for both of the options as seen in Figure 41 and Figure 42.

Primary Load (N)	2779.55			
------------------	---------	--	--	--

DESIGN VARIABLES				
SADDLE	S1	S2	S3	S4
Radial Distance (m)	1.43	3.55	4.68	0.00
Load Percentage (%)	38.08%	40.62%	21.29%	0.00%
Saddle Load (N)	1058.57	1129.16	591.81	0.00
Load Ratios	S3/S2	P1/S1		
	1.07	1.63		

CONSTRAINTS	
Error@Root (%)	2.0
D (m)	1.0
C1 (m)	1.257
C2 (m)	0.2

Figure 42: Part of the MS EXCEL sheet showing the design variable selection and constraints for the three-saddle point configuration option-2

- For the calculation of the distances between saddle points and the resulting Whiffletree connection points, part of the MS EXCEL sheet for that purpose is modified for both of the options. The modified parts are shown in Figure 43 and Figure 44.

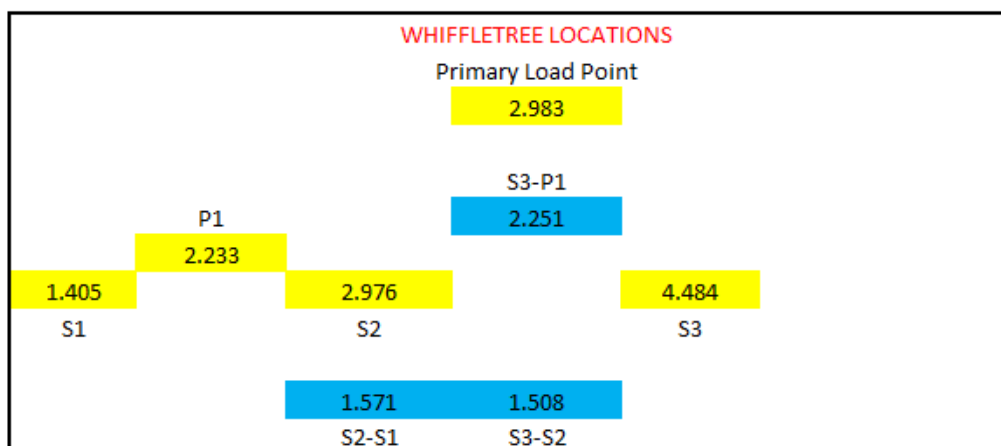


Figure 43: Part of the MS EXCEL sheet showing the connection points and the distances between saddle points for option-1

As seen in Figure 43, the third saddle point is directly connected to the spreader bar, which the primary load is applied, for option-1. To simulate this configuration, the part of the MS EXCEL sheet is modified as shown in Figure 43 by removing the cell for the fourth saddle point and the cell for the connection of the third and the fourth saddle points. In addition, the cell, which calculates the distance between the third

and the fourth saddle points, is removed. It should be noted that the values given in Figure 43 are the optimization results for option-1.

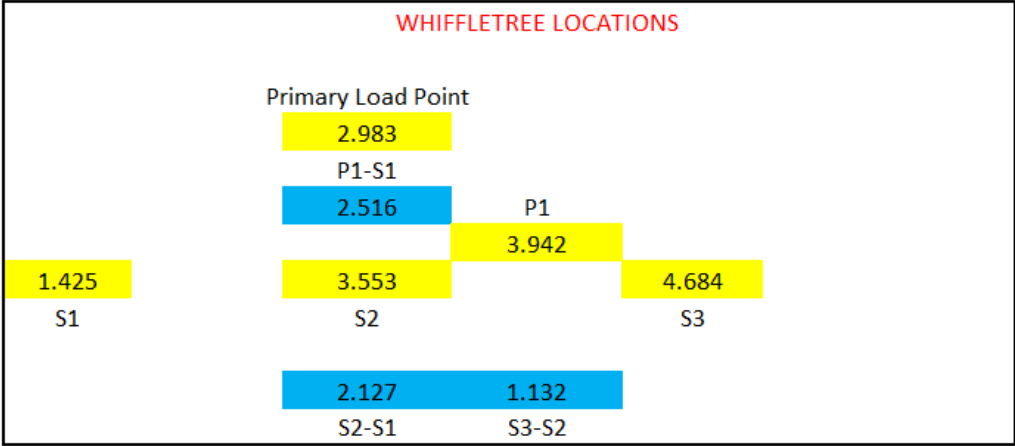


Figure 44: Part of the MS EXCEL sheet showing the connection points and the distances between saddle points for option-2

For option-2, the configuration shown in Figure 43 is slightly changed to the configuration shown in Figure 44 by placing the connection point “P1” between the second and the third saddle points, and the resulting distances are calculated accordingly. It should be noted that the values given in Figure 44 are the optimization results for option-1.

As a result of the optimization, shear force and moment distributions obtained by the test loads are plotted together with the design load distributions for the two options of the Whiffletree with three saddle points and the plots are given in Figure 45-48.

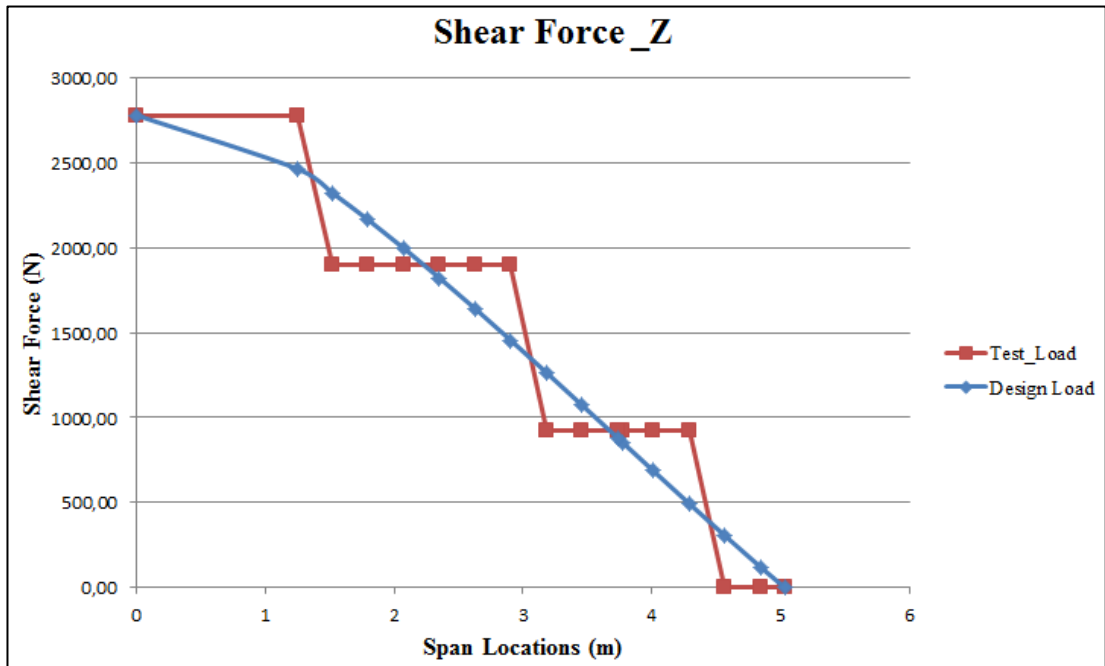


Figure 45: Shear force distributions for the optimized whiffletree with three saddle points option-1

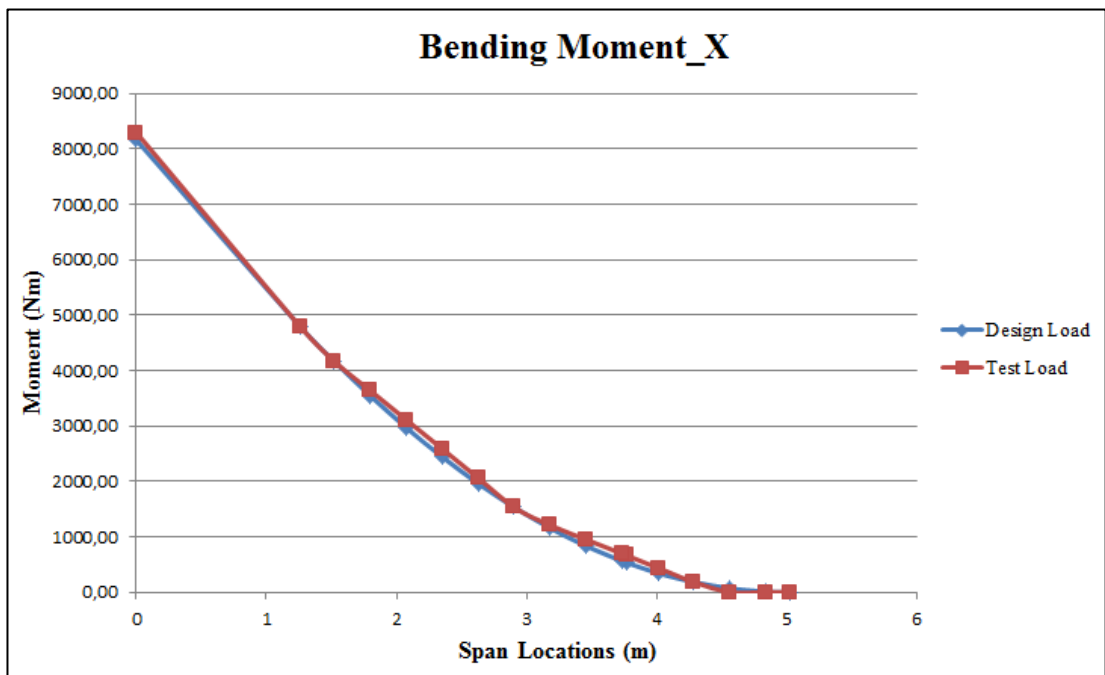


Figure 46: Moment distributions for the optimized whiffletree with three saddle points option-1

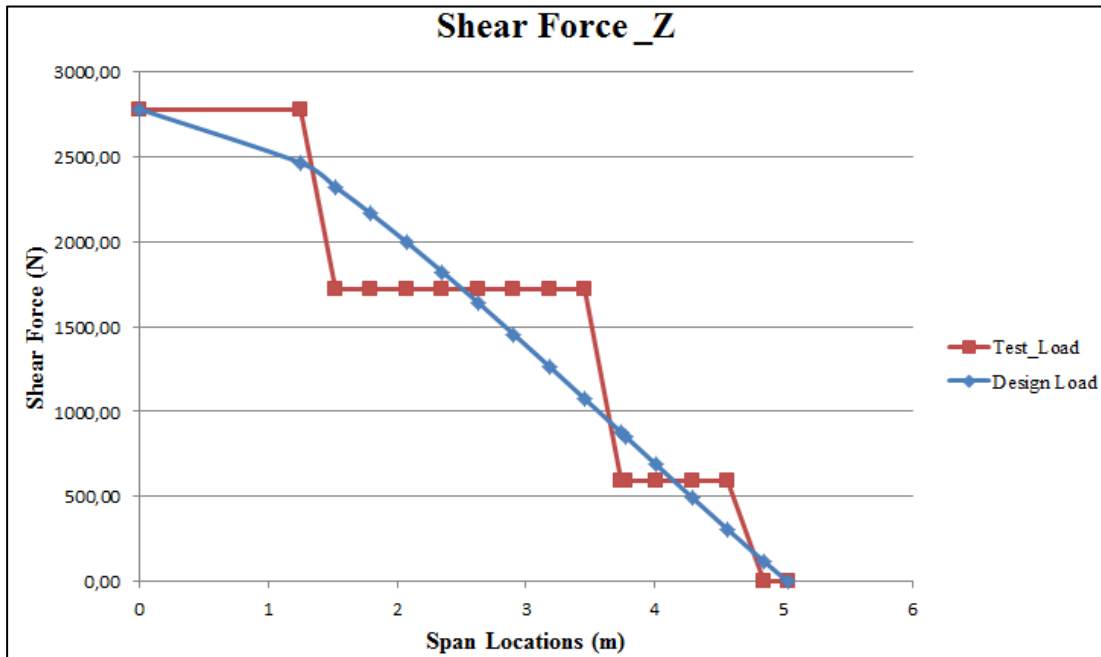


Figure 47: Shear force distributions for the optimized whiffletree with three saddle points option-2

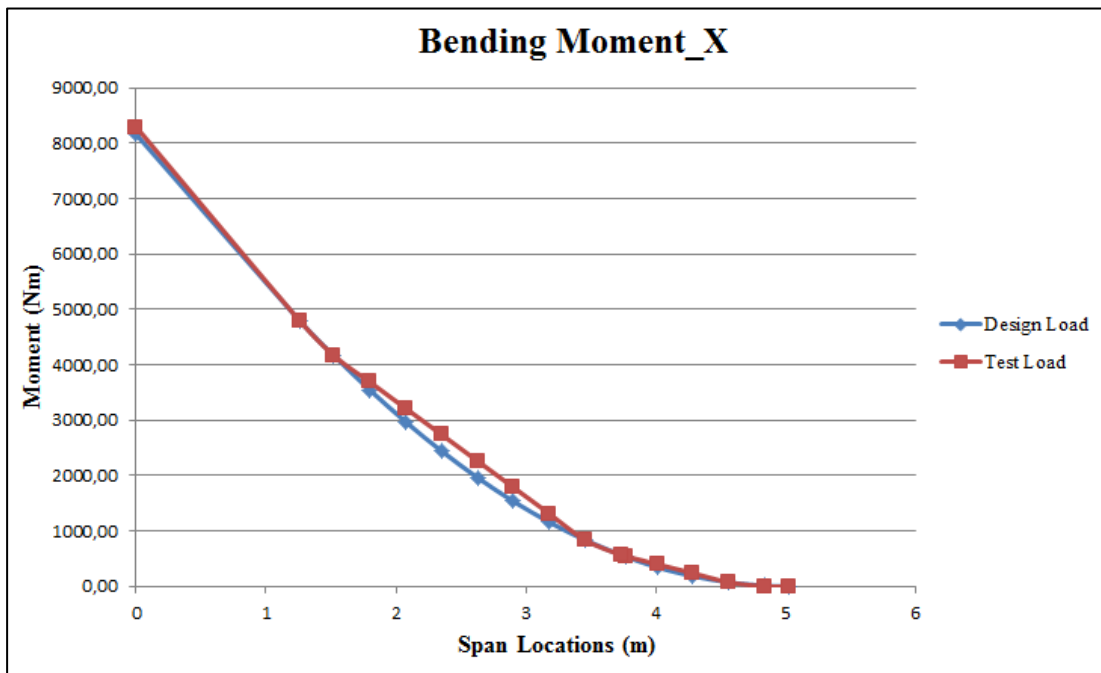


Figure 48: Moment distributions for the optimized whiffletree with three saddle points option-2



### 3.3.3 Whiffletree with Two Saddle Points

The configuration of the Whiffletree with two saddle points is shown in Figure 49. A separate MS EXCEL sheet is also prepared for this configuration. The nomenclature given in Figure 24 for the optimization parameters is also valid for this configuration.

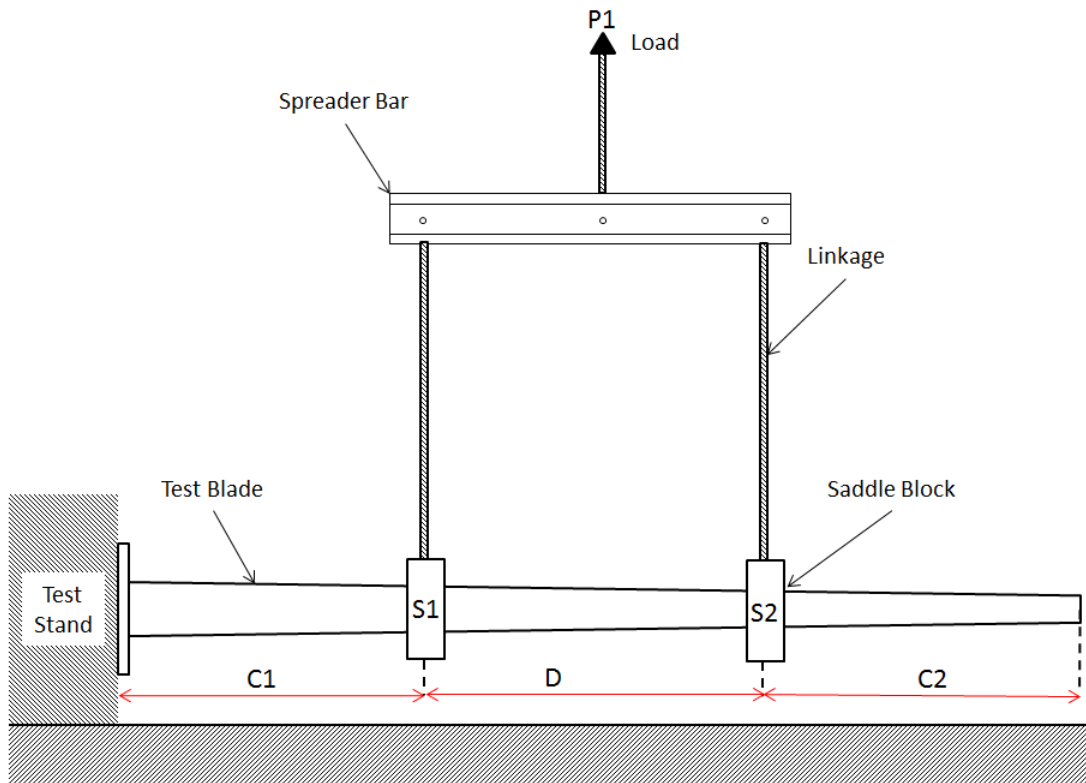


Figure 49: Configuration for the whiffletree with two saddle points

To perform the optimization for the Whiffletree with two saddle points, following changes are made in the MS EXCEL sheet.

- For the fourth and third saddle points, radial distance and load percentage values are entered as zero in the EXCEL sheet, and for design variable selection those values are omitted.

Primary Load (N)	2779.55			
------------------	---------	--	--	--

DESIGN VARIABLES				
SADDLE	S1	S2	S3	S4
Radial Distance (m)	1.44	4.24	0.00	0.00
Load Percentage (%)	44.80%	55.20%	0.00%	0.00%
Saddle Load (N)	1245.22	1534.33	0.00	0.00
Load Ratios	S2/S1			
	1.23			

CONSTRAINTS	
Error@Root (%)	2.0
D (m)	1.0
C1 (m)	1.257
C2 (m)	0.2

Figure 50: Part of the MS EXCEL sheet showing the design variable selection and constraints for the two-saddle point configuration

As seen from Figure 50, radial distance and load percentage values are entered as zero in the MS EXCEL sheet for the fourth and third saddle points. In addition, only “S2/S1” is used for load ratio calculations. The constraining values, which are “Error@Root”, “D”, “C1” and “C2”, are not changed for this configuration as seen in Figure 50. It should be noted that the values given in Figure 50 are the optimization results for the Whiffletree with two saddle points.

- For the calculation of the distances between saddle points and the resulting Whiffletree connection points, part of the MS EXCEL sheet for that purpose is modified. The modified part is shown in Figure 51.

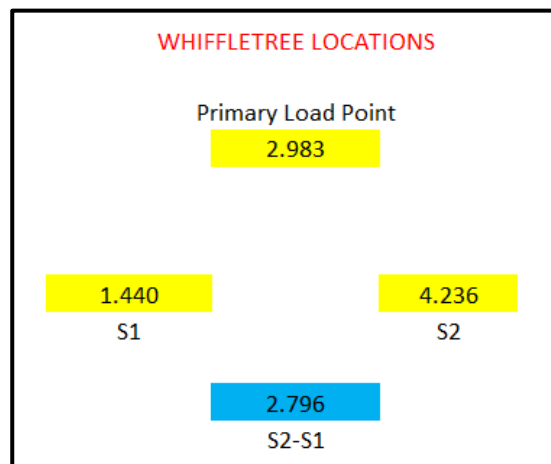


Figure 51: Part of the MS EXCEL sheet showing the connection points and distances between points for two saddle point configuration

As seen in Figure 51, the first and the second saddle points are directly connected to the spreader bar, which the primary load is applied. To simulate this configuration, the part of the MS EXCEL sheet is modified as shown in Figure 51 by removing the cells for the fourth and the third saddle points and the cell for the connection of the third and the fourth saddle points. In addition, the cells, which calculate the distance between the third and the fourth saddle points and the distance between the second and the third saddle points, are removed. It should be noted that the values given in Figure 51 are the optimization results for the Whiffletree with two saddle points.

As a result of the optimization, shear force and moment distributions obtained by the test loads are plotted together with the design load distributions for the Whiffletree with two saddle points and the plots are given in Figure 52 and Figure 53.

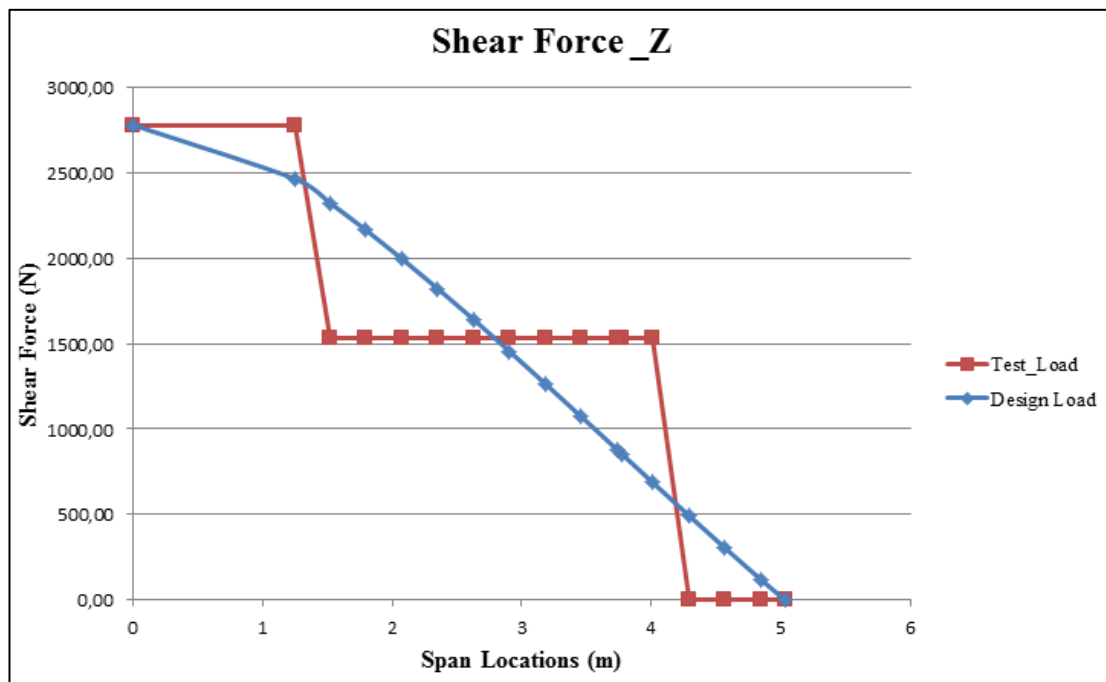


Figure 52: Shear force distributions for the optimized whiffletree with two saddle points

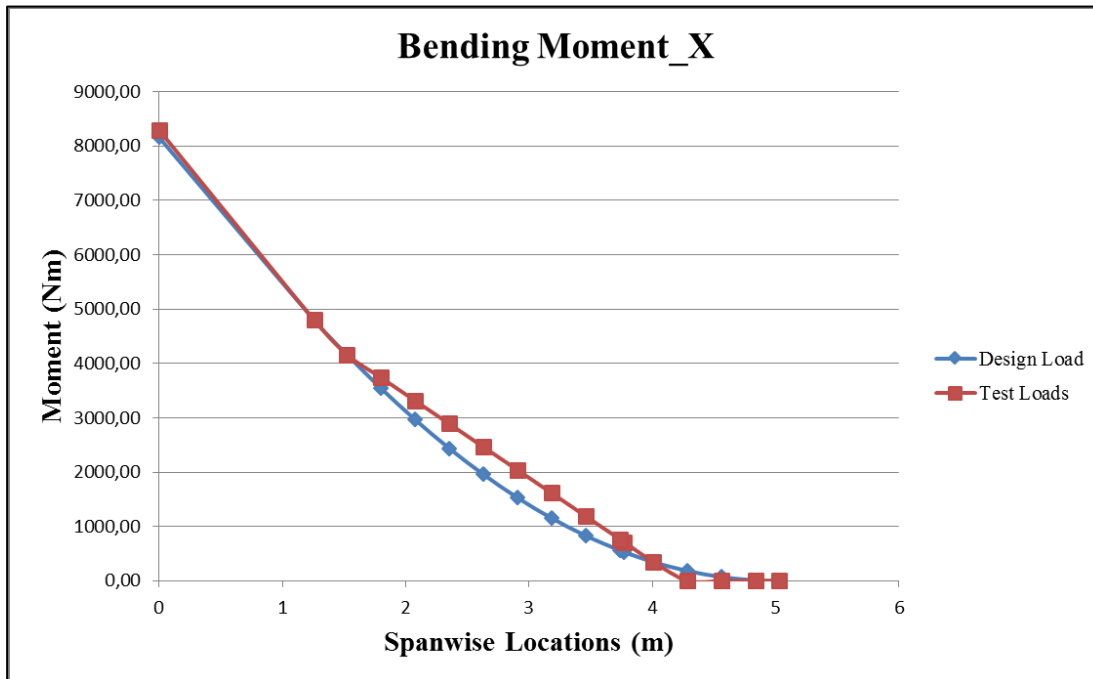


Figure 53: Moment distributions for the optimized whiffletree with two saddle points

### 3.3.4 Comparison of the Optimization Results for MS EXCEL Tool

The best correlation between the test and the design loads occurred for the Whiffletree configuration with four saddle points, as expected. If there is a requirement that the error between test and design loads should be lower than %5 for most of the sections, then the four-point saddle configuration should be selected. If that requirement is extended to 10%, three-point saddle configuration can also be used and the cost of the system is less. In addition, better moment distribution is obtained for option-1 than option-2 for the case studied in this thesis. For the two-point configuration, the errors are between 15% and 25% for most of the sections; however the cost of the system is very low. In addition, the assembly time is shorter if the number of saddle points is less, because there are few connections used in the system.

To demonstrate the performance of the MS EXCEL test load optimization tool, final objective function values, which are the sum of the absolute values of the percentage errors between test and design moments, are compared with the value of the objective function for the initial point. Although random initial points can be defined

in the tool, an initial point is defined for each Whiffletree configuration by placing the saddles with equal distances between the upper and lower bounds of the saddle locations and the load percentages are distributed equally according to the number of saddles. For instance, the initial point for the Whiffletree with four saddle points is given in Table 6.

Table 6: Initial point definition for the Whiffletree with four saddle points

	S1	S2	S3	S4
Saddle Location	1.257 m	2.448 m	3.639 m	4.830
Load Percentage	25%	25%	25%	25%

For other whiffletree configurations, initial points are generated by using the same methodology and the initial values of the objective functions are obtained. In Table 7, initial values of the objective function are compared to the final values which are obtained at the end of the optimization for each Whiffletree configuration.

Table 7: Comparison of the initial and final objective function values for MS EXCEL tool

Whiffletree Type	Initial Objective Function Value	Final Objective Function Value	Decrease in Objective Function Value (%)
Whiffletree with 4 Saddle Points	638.913	158.897	75.1
Whiffletree with 3 Saddle Points- Option 1	1005.517	313.508	68.8
Whiffletree with 3 Saddle Points- Option 2	1005.517	217.453	78.4
Whiffletree with 2 Saddle Points	1878.514	551.02	70.7

As seen from Table 7, the minimum improvement obtained by the test load optimization tool on the objective function value, which is the sum of the absolute values of the percentage errors between test and design moments, is 68.8% of the initial function value. This result shows that the performance of the optimization tool prepared by using the MS EXCEL Solver add-in is reasonably well.

For the four saddle configuration, as seen from Figure 39, moment distributions for the test and the design loads are almost same for the optimized saddle locations given in Figure 27. However, as it can be seen from Figure 38, there are differences between test and design loadings for the shear force distribution. Shear force distribution looks like the staircase as expected. Because, continuous design load can only be approximated by a staircase shear force distribution due to the application of discrete external test loads through the saddle points.

### **3.4 Test Load Optimization via MATLAB Optimization Tool**

MS EXCEL Solver add-in tool gives reasonable results for test load optimization as detailed in the previous section. However, the optimization process which includes the preparation of separate MS EXCEL sheets for different Whiffletree configurations and selecting the variables and constraints for the Solver add-in tool is a complicated process. Therefore, to simplify and generalize the test load optimization process, a tool with a simple user interface is prepared with MATLAB which has built-in optimization algorithms. In addition to the optimization of the Whiffletree systems, the developed MATLAB tool has the capability of the optimization of the loading systems with any number of loading devices, such as actuators and winches. The methodology used in the MATLAB tool for the test load optimization is almost the same with the MS EXCEL Solver add-in tool. The design variables, constraints and objective function, which are defined in Section 3.2, are also used in the MATLAB tool.

For the optimization process, hybrid optimization algorithm is used in the tool. In the hybrid optimization process, firstly, genetic algorithm is invoked, and after it terminates gradient based optimization algorithm starts in order to improve the value of the objective function determined by the genetic algorithm. In other words, the

final values of the design variables that are determined from the genetic algorithm are used by the gradient based optimization algorithm as initial values of the design variables. Genetic algorithm, which is a global optimization algorithm, is used in the tool since it is observed that the optimization results depend on the initial value selected when a gradient based algorithm is used only. In addition, to check the need for the usage of the hybrid optimization algorithm, the results obtained from the genetic algorithm only are compared with the results obtained by the hybrid optimization algorithm. For this purpose, optimization runs are performed with genetic and hybrid algorithms separately and the results are given in Table 8. Improvements are observed when the results are compared such that the value of the objective function, which is the sum of the absolute values of the percentage errors between the test and the design moment values at each station of the blade under consideration, after the hybrid algorithm ends is smaller than the objective function value when only the genetic algorithm is employed in the optimization process.

Table 8: Comparison of objective function values for genetic and hybrid algorithms

<b>Whiffletree Configuration</b>	<b>Genetic Algorithm</b>	<b>Hybrid Algorithm</b>
Four Saddle Points	171.646	158.897
Three Saddle Points	294.699	217.453
Two Saddle Points	678.969	651.54

In Table 8, the objective function values, which are obtained by the genetic and hybrid algorithms separately for the optimization of the Whiffletrees with different saddle points, are given.

In the following sections, basic information about the optimization algorithms used is given. The methodology to implement the optimization problem on MATLAB tool is outlined and the test load optimization tool that is developed is demonstrated. At the end, optimization results are presented, and results obtained by the optimization tool are compared with the solution obtained by the MS EXCEL Solver add-in tool.

### 3.4.1 Genetic Algorithm

Both constrained and unconstrained optimization problems can be solved by the genetic algorithm method which is based on natural selection. In the genetic algorithm process, a population of individual solutions is modified repeatedly through the optimization run. At each step, random individuals are selected from the current population to be parents, and they are used to produce the children for the next generation. The population evolves toward an optimal solution after successive generations [23]. The main differences between a gradient based optimization algorithm and genetic algorithm are listed in Table 9:

Table 9: Comparison of genetic algorithm and gradient based algorithm [23]

<b>Gradient Based Algorithm</b>	<b>Genetic Algorithm</b>
A single point is generated at each step. Optimal solution is obtained by generation of the sequence of points.	A population of points is generated at each step. The best point in the population approaches an optimal solution.
The next point in the sequence is selected by a deterministic computation.	The next population is selected by computation which uses random number generators.

Terminology used in the genetic algorithm is given below as defined in Reference 24:

**Fitness Function:** Basically, fitness function is the function that is optimized through the algorithm.

**Individual:** An individual is any point which the fitness function is applied.

**Population and Generation:** An array of individuals is a population. At each iteration, a series of computations on the current population are performed to create a new population. Each successive population is called a new population.

**Diversity:** The average distance between individuals in a population is referred as diversity. If the diversity is high, the algorithm searches a larger space of the space.

**Fitness Value and Best Fitness Value:** The value of the fitness function for any individual is the fitness value of that individual. The smallest fitness value of any individual is the best fitness value of the population.



**Parent and Children:** Parents are the certain individuals selected by the algorithm to create the next generation. Parents are used to create individuals in the next generation which are called children.

The basic flowchart of the genetic algorithm is given in Figure 54.

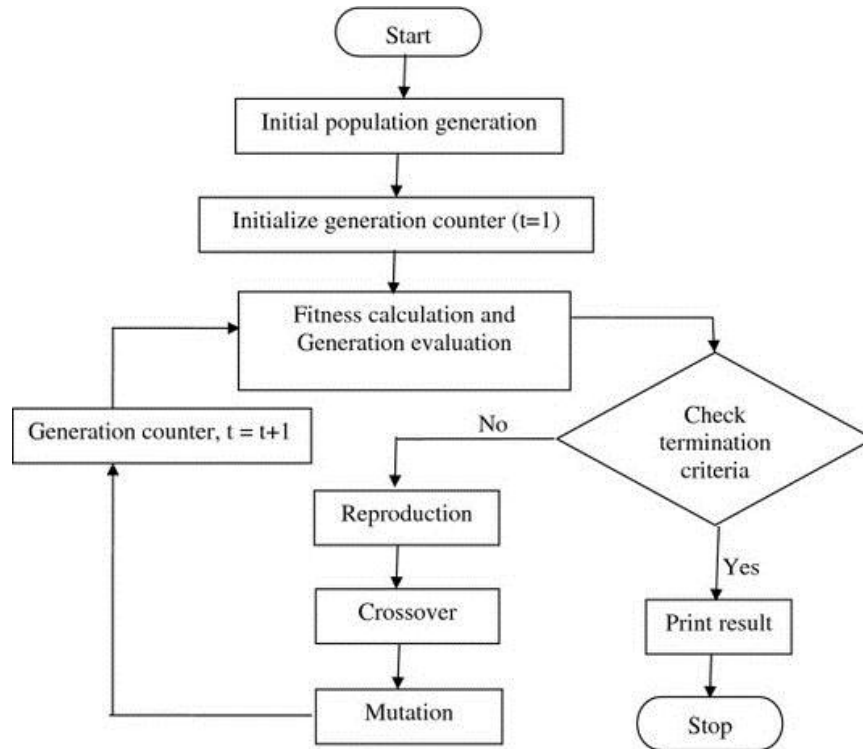


Figure 54: Genetic algorithm flowchart [25]

As seen from Figure 54, firstly an initial population should be created. For this purpose, population size and the creation function used to create the initial population should be selected. In the developed MATLAB tool, population size is selected as 100 to increase the diversity and randomness of the variables. Since, there are constraints in the problem, feasible population function is selected as the creation function. One individual of the initial population is defined in the tool by evenly distributing the saddle locations and the load percentages. The initial range for the individuals of the initial population is defined by using upper and lower bounds for the design variables.

Once the initial population is created, fitness function calculation is performed for the individuals. As defined above, fitness function is the objective function of the

optimization problem, which is the sum of the absolute values of the percentage errors between the test and the design moment values at each station of the blade under consideration for this study.

If the termination criteria are not satisfied, fitness function values are scaled to obtain suitable values for the selection of the parents. The performance of the genetic algorithm is affected by the range of the scaled values. For a wide range of the scaled values, the individuals with highest scaled values reproduce too rapidly and take over the population gene pool too quickly which prevents the genetic algorithm from searching other areas of the solution space. On the other hand, for a narrow range of the scaled values, the search progress very slowly since all the individuals have approximately the same chance of reproduction. In the developed tool, rank fitness scaling, which scales the fitness functions values based on the rank of each individual instead of its value, is used since it removes the effect of the spread of the fitness values [26].

The parents for the next generation are selected by using a selection function according to the scaled fitness values of the individuals. Stochastic uniform selection function is used in the tool because in the stochastic uniform selection, individuals with low fitness values also have a chance to be chosen due to the nature of the function. After the parents are selected, reproduction of the population is performed by using different methods. These methods for children creation are given below in Figure 55.

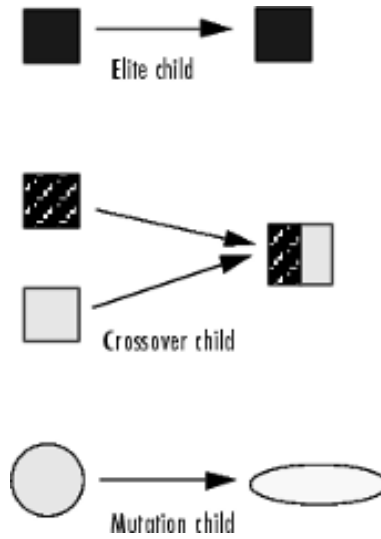


Figure 55: Methods for reproduction [27]

As defined in Reference 27, elite children automatically survive to the next generation since they have the best fitness values. The vectors of a pair of parents are combined to create crossover children while random changes are introduced to a single parent to create mutation children. Detailed information about the reproduction options can be found in Reference 28. In the developed tool, the values and functions selected for reproduction are given in Table 10:

Table 10: Selected values and functions for reproduction in the developed MATLAB tool

Elite Count	2
Crossover Fraction	0.6
Crossover Function	Intermediate
Mutation Function	Adaptive Feasible

As seen from Table 10, elite count, which is the number of individuals that are guaranteed to survive to the next generation, is selected as 2, which is the default value for noninteger problems. Elite count must be a positive integer less than or equal to the population size. Crossover fraction is the fraction of the individuals of the next population, other than elite children, that are produced by crossover. For instance, a crossover fraction of 1 means that all children, other than elite children,

are crossover children and a crossover fraction of 0 means that all children, other than elite children, are mutation children. In the examples studied for the selection of the crossover fraction, the value of 0.6 gives the minimum value of the objective function value. Therefore, this value is selected. Crossover function is the function that performs crossover by specifying how the genetic algorithm combines two individuals. Since there are linear constraints in the defined optimization problem, “intermediate” crossover function”, which is the default option for the optimization problems with linear constraints and creates children by taking a weighted average of the parent, is selected. Mutation function is the function that specifies how the genetic algorithm makes small random changes in the individuals in the population to create the mutation children. “Adaptive feasible” mutation function is selected in the developed tool, since there are constraints in the defined optimization problem. This function randomly creates search direction and chooses a direction and a step length that satisfies the bound and the linear constraints of the problem [28].

Once the new population is created, fitness function calculation is performed again and the termination criteria are checked. The whole process is repeated iteratively until the termination criteria are satisfied. Detailed information about the termination criteria of the algorithm can be found in [28]. The termination criteria used in the developed tool is given in Table 11.

Table 11: Selected termination criteria of the algorithm

Generations	100
Time Limit	Infinity
Fitness Limit	-Infinity
Stall Generations	10
Stall Time Limit	Infinity
Function Tolerance	$10^{-6}$
Nonlinear Constraint Tolerance	$10^{-6}$

As seen from Table 11, the maximum number of generations, which is allowed to perform by the genetic algorithm, is selected as 100. In the examples studied for the

optimization problem defined in this thesis, it is observed that the number of generations is always below the selected value. “Time limit”, which is the maximum time in seconds that the genetic algorithm is allowed to run, is selected as infinity. The genetic algorithm stops when the best fitness value of the population is less than or equal to the value of “fitness limit” which is selected as  $-\infty$  in the developed tool. If the weighted average change in the best fitness function value is less than or equal to the value of “function tolerance” defined for the algorithm, which is  $10^{-6}$ , between subsequent generations, these generations are called “stall generations”. The genetic algorithm stops when the defined number of stall generations, which is 10, is reached. When there is no improvement in the best fitness value in the interval of time in seconds defined as “Stall time limit” the genetic algorithm stops to run. In the developed tool, this value is selected as infinity. “Nonlinear constraint tolerance” is used to determine the feasibility with respect to nonlinear constraints [28].

### 3.4.2 Gradient Based Algorithm

Gradient based algorithm is used to solve optimization problems by using the search directions defined by the gradient of the objective function at the current point. The type of the gradient based algorithm used in the developed tool is the active set method. As stated in Reference 29, the purpose of the method is to predict the active set, the set of constraints that are satisfied with equality, at the solution of the problem. There are two phases of the method; the first phase is feasibility and the second one is optimality. In the first phase, a feasible point is found by ignoring the objective function and in the second phase, the objective function is minimized while feasibility is maintained [29]. For a feasible point  $x_0$ , active set method computes a sequence of feasible points  $x_k$  such that;

$$x_{k+1} = x_k + \alpha_k p_k \quad (31)$$

$$f(x_{k+1}) \leq f(x_k) \quad (32)$$

where;

f: Objective function

$\alpha_k$ : Nonnegative step length

$p_k$ : Nonzero search direction

Since, the optimization problem defined in the developed tool has nonlinear constraints, to find the values of  $\alpha_k$  and  $p_k$ , sequential quadratic programming (SQP) which is a nonlinear programming method is used as a part of the active set algorithm. SQP is based on the solution of the Karush-Kuhn-Tucker (KKT) equations which are given by Eq. (33) [30]:

$$\begin{aligned} \nabla f(x^*) + \sum_{i=1}^m \lambda_i \cdot \nabla G_i(x^*) &= 0 \\ \lambda_i \cdot G_i(x^*) &= 0, \quad i = 1, \dots, m_e \\ \lambda_i &\geq 0, \quad i = m_e + 1, \dots, m \end{aligned} \tag{33}$$

where;

$\nabla f(x^*)$ : Gradient of the objective function at the solution point

$\nabla G_i(x^*)$ : Gradient of the constraints at the solution point

$\lambda_i$ : Lagrange multipliers

m: Total number of constraints

Gradients of the objective function and the active constraints cancel each other at the solution point as described in the first relation of the KKT equations. The deviations in magnitude of the objective function and constraint gradients are balanced necessarily by the Lagrange multipliers for the gradients to be cancelled. Inactive constraints must not be included in the canceling operation defined in the first relation. Therefore, Lagrange multipliers for inactive constraints are equal to 0. This situation is stated implicitly in the last two KKT relations [30].

The implementation of SQP consists of three main steps which are given below. However, the steps are not given in detail here. The details of the steps can be found in Reference 30.

- Updating the Hessian Matrix
- Quadratic Programming Solution
- Line Search and Merit Function

In the hybrid optimization algorithm, the initial point of the gradient based algorithm is the final point obtained by the genetic algorithm. The default options defined in MATLAB for the selected algorithm is used in the tool except for the options for the maximum number of iterations, which is 100 times the number of variables, maximum number of function evaluations, which is 1000, and the finite differencing method, which is forward finite differencing, [31]. For maximum number of iterations and functions evaluations, 10000 is used to prevent the termination of the algorithm before obtaining the optimum value, and central finite differencing method is selected to improve the accuracy of the solution.

### 3.4.3 Implementation of the Optimization Problem on MATLAB Tool

MATLAB code that is used in the developed tool is not given in detail here. However, to demonstrate the code for the test load optimization, the definitions of the inputs shown in Eq. (34) are outlined for the execution of the genetic algorithm. Before giving the definitions of the inputs, it should be noted that the output vector “x” consists of the design variables that are load percentages and saddle locations. In MATLAB, the syntax given by Eq. (34) is used to find the minimum of a function by the genetic algorithm [32].

$$x = ga(fitnessfcn, nvars, A, b, Aeq, beq, LB, UB, nonlcon, options) \quad (34)$$

where;

**fitnessfcn:** It is the function handle to the fitness (objective) function of the optimization problem. The definition of the objective function for the optimization problem, which is given in Eq. (11) in Section 3.2, is implemented on the MATLAB tool. In the objective value calculation, the term related with the test moment values at the sections are calculated by using the summation formulation with the singularity function for a specific blade section as shown in Eq. (35).

$$M_{Test,j} = \sum_{i=1}^N Primary\ Load * x_i * \ll section_j - x_{i+N} \gg \quad (35)$$

where;

j: Section number

N: Total number of saddles

Primary Load: Primary load applied to the Whiffletree

section<sub>j</sub>: Location of the j<sup>th</sup> section

x<sub>i</sub>: Load Percentages

x<sub>i+N</sub>: Saddle point locations

The singularity function written in Eq. (35) as “<< >>” is defined in Eq. (36).

$$\ll x - a \gg = \begin{cases} 0 & x > a \\ a - x & x \leq a \end{cases} \quad (36)$$

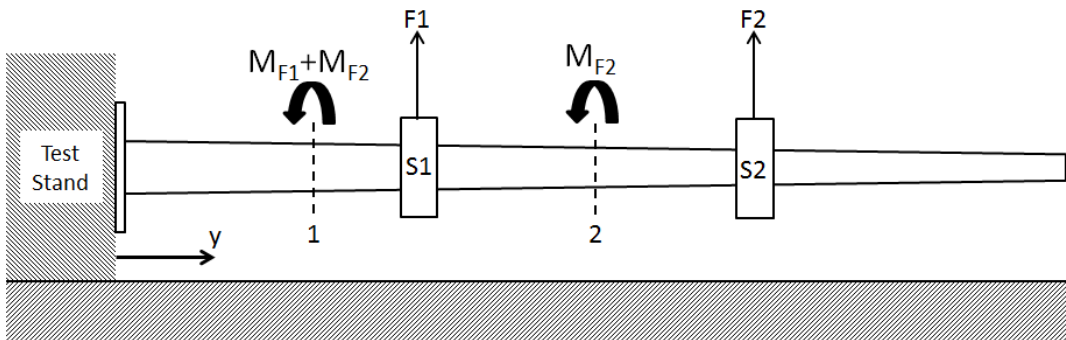


Figure 56: Schematic for bending moment calculation in MATLAB tool

To illustrate the test moment calculation relation given in Eq. (35), two different blade sections, which are labeled as “1” and “2”, are shown in Figure 56. For section 1, since the location of the section is closer to the root of the blade than the locations of the both saddles, both of the saddle loads are included in the test moment calculation. On the other hand, for section 2, only the load of the second saddle is included in the test moment calculation, since the location of the second section is further to the root section of the blade than the location of the first saddle location.

**nvars:** It is the positive integer representing the number of variables. This value is set to  $2N$  for any loading method with  $N$  saddle points for the implementation of the number of design variables.

**A, b:** They are used to define the linear inequality constraints. The methodology to define the “A” matrix and the “b” vector is given by the Eqs. (15-16) in Section 3.2.

**Aeq, beq:** They are used to define the linear equality constraints. There is only one equality constraint used in the optimization problem and the methodology to define the “Aeq” matrix and the “beq” vector is given in Eqs. (17-18) in Section 3.2.



**LB, UB:** They are used to define the lower and upper bounds of the design variables used in the optimization problem. The methodology to define the “LB” vector and the “UB” vector is given by the Eq. (14) in Section 3.2.

**nonlcon:** It is the function handle which returns nonlinear inequality and equality constraints “c” and “ceq” in vector form. The function definitions, which are the elements of “c” vector, are given in Eqs. (19-21) in Section 3.2. Since there are no nonlinear equality constraint, “ceq” vector is taken as empty vector.

**options:** The options of the genetic algorithm are defined by using the options handle. The selected options for the developed tool are outlined in Section 3.4.1 for genetic algorithm. In addition, the selection of the method and the options for the gradient based optimization algorithm is made in the hybrid optimization function handle defined in the options. The hybrid optimization function handle starts the gradient based optimization algorithm with final point of the genetic algorithm when the genetic algorithm terminates.

As seen from Eq. (34), all the constraints given in Eq. (10) in Section 3.2 for an optimization problem can be implemented on MATLAB.

All of the required MATLAB definitions for the optimization problem are finalized. Therefore, graphical user interface (GUI) part of the developed tool is detailed in the next section.

#### **3.4.4 Test Load Optimization Program**

To prepare the graphical user interface of the developed tool, MATLAB GUIDE Toolbox is used. The tool is named as “Test Load Optimization Program”. The tool is compiled by MATLAB Compiler to run the program as a standalone application in Microsoft operating systems without installing MATLAB. The program consists of four main parts and one auxiliary part to give information about the nomenclature used in optimization. The main parts are given below.

- Loading Method Selection
- Design Constraints
- Loading Data Input and Optimization Start
- Plot of the Optimization Results

The start-up screen of the program is given in Figure 57 which shows the main parts.

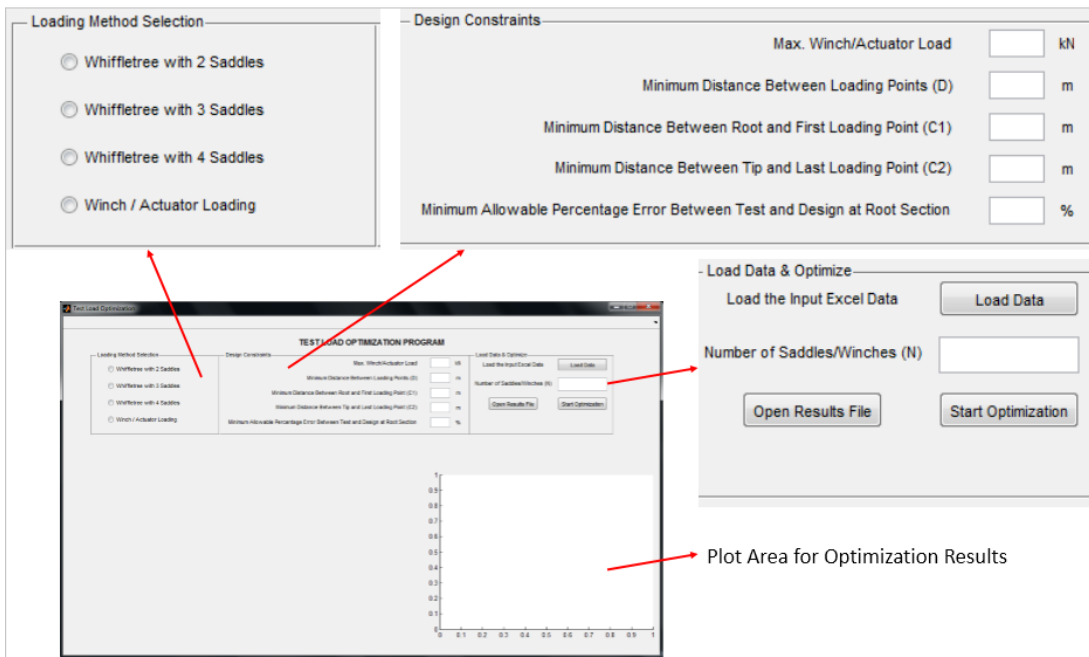


Figure 57: Start-up screen of the test load optimization program

When a user runs the program, firstly, the loading method should be selected. In addition to the Whiffletree loading methods, there is an extra loading method, which is the winch/actuator loading. The details of the winch/actuator loading method are given in the following section for a demonstrative long blade test example. When the user selects the loading method, a figure is shown on the auxiliary part of the user interface which gives information about the nomenclature used in the optimization problem. For demonstration, “Whiffletree with 4 saddles” option is selected and the related figure is shown in Figure 58.

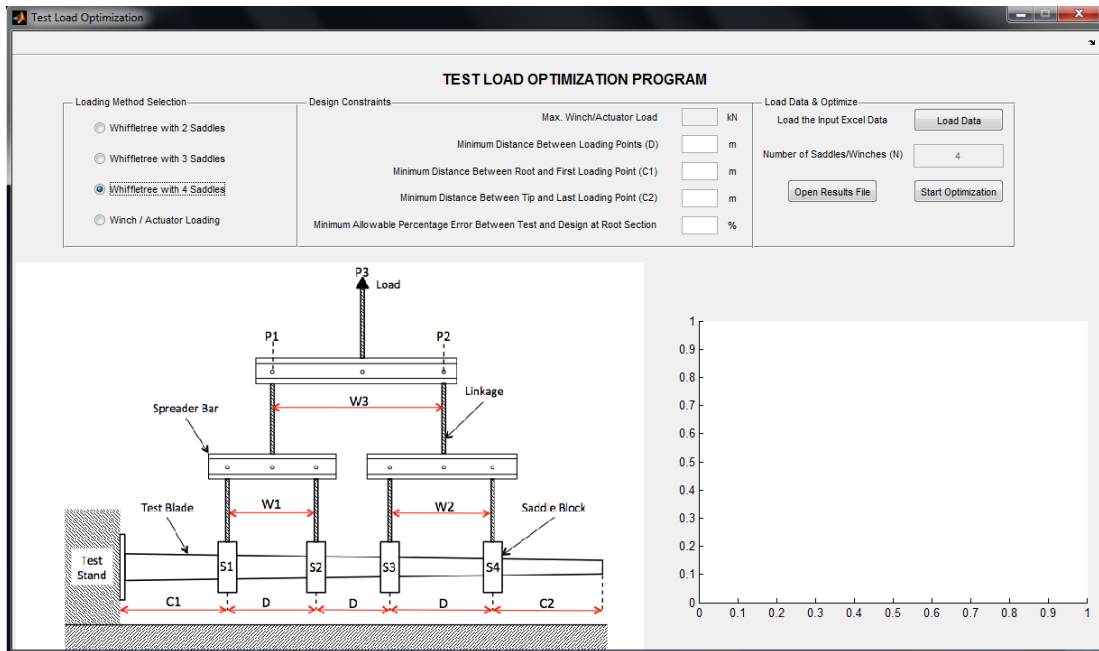


Figure 58: Auxiliary figure for nomenclature used in optimization

If a Whiffletree loading method is selected, the input box for the maximum winch/actuator load that is related to the extra loading method becomes disabled. In addition, the input box for the number of saddles/winches is set to the selected saddle number value and it becomes disabled. After the selection of the loading method, design constraints should be entered to the related input boxes according to the figure shown in the auxiliary part of the user interface of the test load optimization program. The units of the design constraints are also shown in the design constraints part for each constraint separately. The constraints used in MS EXCEL tool are also entered to this program as shown in Figure 59.

**Design Constraints**

Max. Winch/Actuator Load	<input type="text"/>	kN
Minimum Distance Between Loading Points (D)	<input type="text" value="1"/>	m
Minimum Distance Between Root and First Loading Point (C1)	<input type="text" value="1.257"/>	m
Minimum Distance Between Tip and Last Loading Point (C2)	<input type="text" value="0.2"/>	m
Minimum Allowable Percentage Error Between Test and Design at Root Section	<input type="text" value="2"/>	%

Figure 59: Design constraints used in the MATLAB test load optimization tool for the Whiffletree loading method

Finally, design load data should be given as input to the program. For this purpose, a MS EXCEL input file should be used. A sample input file is shown in Figure 60 showing the design load data which is also used with the MS EXCEL solver add-in optimization tool.

	A	B	C	D
1	Station (m)	Shear (N)	Moment (Nm)	
2	5.03	0	0	
3	4.841	122.607	11.54	
4	4.565	306.469	70.63	
5	4.288	495.519	181.62	
6	4.011	687.623	345.429	
7	3.772	854.757	529.73	
8	3.735	880.657	561.835	
9	3.458	1073.86	832.558	
10	3.181	1265.862	1156.643	
11	2.905	1455.32	1532.219	
12	2.628	1641.66	1961.273	
13	2.352	1821.927	2439.375	
14	2.075	1996.872	2968.427	
15	1.798	2164.486	3544.965	
16	1.522	2322.198	4164.366	
17	1.257	2462.3	4798.592	
18	0	2779.548	8159.557	
19				
20				

Figure 60: Sample load input file for the MATLAB test load optimization tool

As seen in Figure 60, there are three separate sheets which are “Design Loads”, “WT Test Loads&Connection Points” and “Winch-Act Test Loads&Connection Points”. Only the “Design Loads” sheet should be modified for design load input since the optimization results are written to other sheets according to the loading method selected after the optimization is completed. As shown in Figure 60, design loads should be written in an order from tip to root section and the units given at the header row should be used. To load the data to the program, “Load Data” button should be clicked and the input file should be selected. For demonstration, sample file shown in Figure 60 is selected. After the input file selection, “Start Optimization” button should be clicked to run the optimization. If there is any missing or wrong input, error messages can be seen on the screen related to the input with error. Once the optimization starts correctly, “Running Optimization” message is written on the screen to give information about the status of the program. The location of the status message is shown in Figure 61.

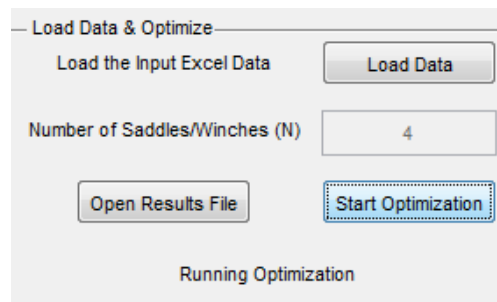


Figure 61: Location of the status message of the MATLAB test load optimization tool

If the program cannot find any optimum solution, an error message is written to status part of the program which says “Optimization failed. Change design constraints”. By changing design constraints, the program can be started again. If the program finds an optimum solution, “Optimization Completed” message is written to the status part of the program and the comparison plot between test and design moments is plotted on the program screen. For the Whiffletree with three saddles, since there are two different options, the tool compares the optimization results for each option and the option with lower objective function value is selected. Therefore,

when the optimization is completed successfully, the selected option is written to the status part of the program. The final view of the program is shown in Figure 62.

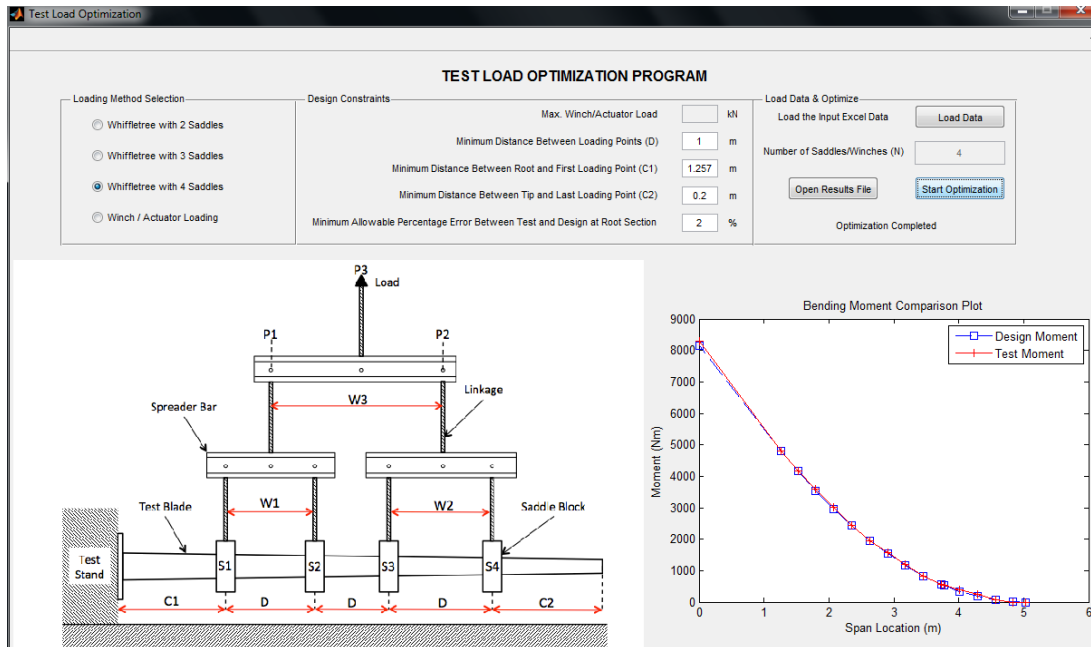


Figure 62: Final view of the MATLAB program

After the optimization is completed, the results are written to the related sheet of the MS EXCEL. When the “Open Results File” button is clicked, optimization results can be obtained. MS EXCEL sheet includes the following information:

- Saddle locations
- Spreader bar connection points
- Loads transferred through the saddle and the connections points
- Approximate spreader bar lengths
- Maximum moments applied to spreader bars
- Test and design moment values at each section
- Percentage error values between test and design moments at each section
- Plots for the comparison of the test and the design moment values

A sample output file is shown in Figure 63 for the Whiffletree with four saddle points.

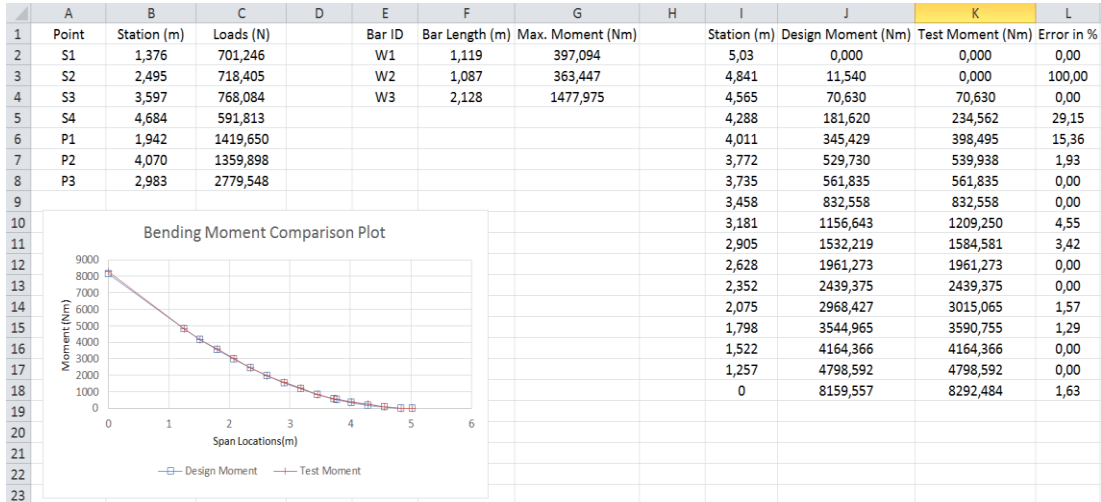


Figure 63: Sample output file of the MATLAB test load optimization tool for the Whiffletree with four saddle points

### 3.4.5 Comparison of the Optimization Results Obtained by the MATLAB Tool and the MS EXCEL Solver Add-In Tool

As seen from Figure 63, optimization results obtained by the MATLAB tool for Whiffletree with four saddle points are exactly same with the optimization results obtained by the MS EXCEL Solver add-in tool which are given in Figure 27 and Figure 28. For the whiffletree with three saddle points, option-2 is selected by the MATLAB tool. Since, the objective function value is smaller for option-2 than the value determined for option-1. It is observed that the optimization results for the Whiffletree with three saddle points are also exactly same with the results obtained by the MS EXCEL Solver add-in tool. However, for the Whiffletree with two saddle points, the optimization results are slightly different. The locations of the saddles and the magnitudes of the loads applied through the saddle points obtained by the MATLAB tool and the MS EXCEL Solver add-in tool are compared in Table 12-14.

Table 12: Comparison of the optimization results for the Whiffletree with four saddle points

Tool	S1 (m)	S2 (m)	S3 (m)	S4 (m)	Load 1 (N)	Load 2 (N)	Load 3 (N)	Load 4 (N)
MS EXCEL	1.376	2.495	3.597	4.684	701.24	718.41	768.08	591.81
MATLAB	1.376	2.495	3.597	4.684	701.24	718.41	768.08	591.81

Table 13: Comparison of the optimization results for the Whiffletree with three saddle points option-2

Tool	S1 (m)	S2 (m)	S3 (m)	Load 1 (N)	Load 2 (N)	Load 3 (N)
MS EXCEL	1.425	3.553	4.684	1058.57	1129.16	591.81
MATLAB	1.425	3.553	4.684	1058.57	1129.16	591.81

Table 14: Comparison of the optimization results for the Whiffletree with two saddle points

Tool	S1 (m)	S2 (m)	Load 1 (N)	Load 2 (N)
MS EXCEL	1.440	4.236	1245.22	1534.33
MATLAB	1.446	4.414	1339.65	1439.89

As given in Table 14, the locations of the first saddle obtained by each tool are almost the same which results same moment distribution about the root of the blade. On the other hand, the location of the second saddle obtained by the MATLAB tool is closer to the tip of the blade which results better moment distribution about the tip of the blade. However, between the saddle locations, the absolute values of the percentage errors between the test and design moments are smaller for the optimization results obtained by the MS EXCEL Solver add-in tool. A comparison plot is given in Figure 64 which shows the test moment distributions obtained by the MATLAB and MS EXCEL tools separately.



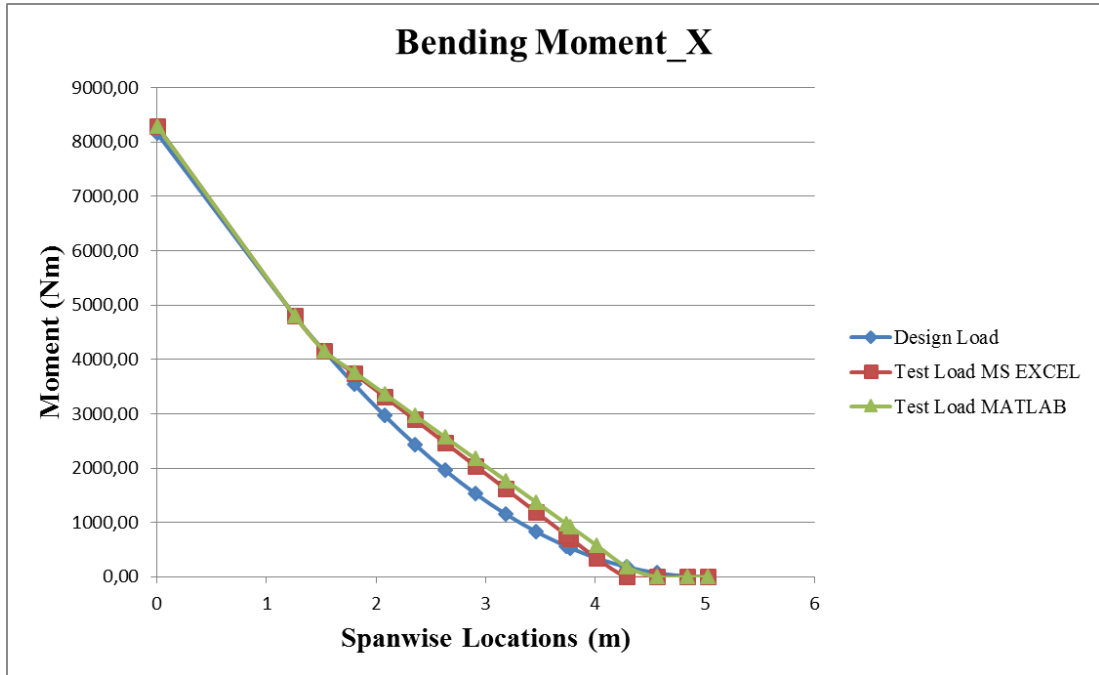


Figure 64: Comparison of MS EXCEL and MATLAB tools for the Whiffletree with two saddle points

As seen from Figure 64, test load values are slightly closer to the design load values for the MS EXCEL tool between the blade span stations 2 m and 4 m. In addition, the value of the objective function is smaller for the MS EXCEL tool than the MATLAB tool. Although there is no difference in the optimization results for the Whiffletrees with four and three saddle points, there is a slight difference for the Whiffletree with two saddle points. However, it should be noted that the optimization algorithms are also different for each of the tool. Therefore, the difference between the optimization results for the Whiffletree with two saddle points could arise due to the difference in optimization algorithms. Only for the Whiffletree with two saddle points, MS EXCEL tool gives better results than the MATLAB tool although for other configurations same results are obtained.

### 3.4.6 Winch/Actuator Loading Option of the MATLAB Tool

To demonstrate the winch/actuator loading option of the MATLAB tool, a longer blade is selected. For this purpose, NREL's offshore 5-MW baseline wind turbine blade is selected. The properties of the selected wind turbine are given in Table 15.

Table 15: Properties of the selected wind turbine [15]

Rating	5 MW
Rotor, Hub Diameter	126 m, 3 m
Hub Height	90 m
Cut-In, Rated, Cut Out Wind Speed	3 m/s, 11.4 m/s, 25 m/s
Cut-In, Rated Rotor Speed	6.9 rpm, 12.1 rpm

According to the rotor and hub diameter values, the selected wind turbine blade is 61.5 m long. Testing a blade of this length with the Whiffletree loading requires long and heavy loading apparatus such that spreader bars and linkages. The assembly and the operation of the Whiffletree are not practical due to the size and the weight of the Whiffletree components. In addition, due to the large displacement values of the longer blades, the Whiffletree method may prevent the intended moment distribution during the test, which makes the Whiffletree method infeasible. Instead of the Whiffletree method, loading with actuators or winches from separate points should be used for longer blades. To find the loading points and the magnitudes of the loads applied through the loading points, developed MATLAB tool can be used for any number of loading points.

To demonstrate the test load optimization process for the selected blade, design loads should be known as input. Design load calculation is performed by using the same methodology outlined in Chapter 2 for rated wind speed operation condition. The detailed aerodynamic and structural properties given in Reference 15 are used in the calculation of design loads. The final design loads are calculated at the sections given in Table 16. Blade stations are given with respect to the rotor center. Therefore, root section span location is 1.5 m.

Table 16: Final design loads for the NREL 5-MW wind turbine blade

<b>Radial Distance (m)</b>	<b>V<sub>z</sub> (kN)</b>	<b>M<sub>x</sub> (kNm)</b>
63.000	0.000	0.000
61.633	12.836	8.829
58.900	29.607	82.354
56.167	63.740	209.887
52.750	105.603	499.704
48.650	153.182	1031.281
44.550	197.431	1751.245
40.450	239.177	2646.796
36.350	277.720	3708.118
32.250	311.262	4917.262
28.150	339.903	6253.766
24.050	364.071	7698.353
19.950	384.314	9233.782
15.850	399.681	10843.063
11.750	410.800	12505.360
8.333	415.304	13918.783
5.600	415.929	15054.769
2.867	416.535	16192.484
1.500	416.792	16761.942

The design loads are given in the units of kN and kNm in Table 16 for clarity. However, as mentioned before, the design loads should be converted to the units of N and Nm to be used in the developed MATLAB tool. Therefore, design loads are written to the input file by converting the values given in Table 16 to the required units.

For the test load optimization, in the program, winch/actuator loading method should be selected. Once the winch/actuator loading method is selected, the corresponding auxiliary figure which shows the nomenclature used in the optimization is shown on the screen, as seen in Figure 65.

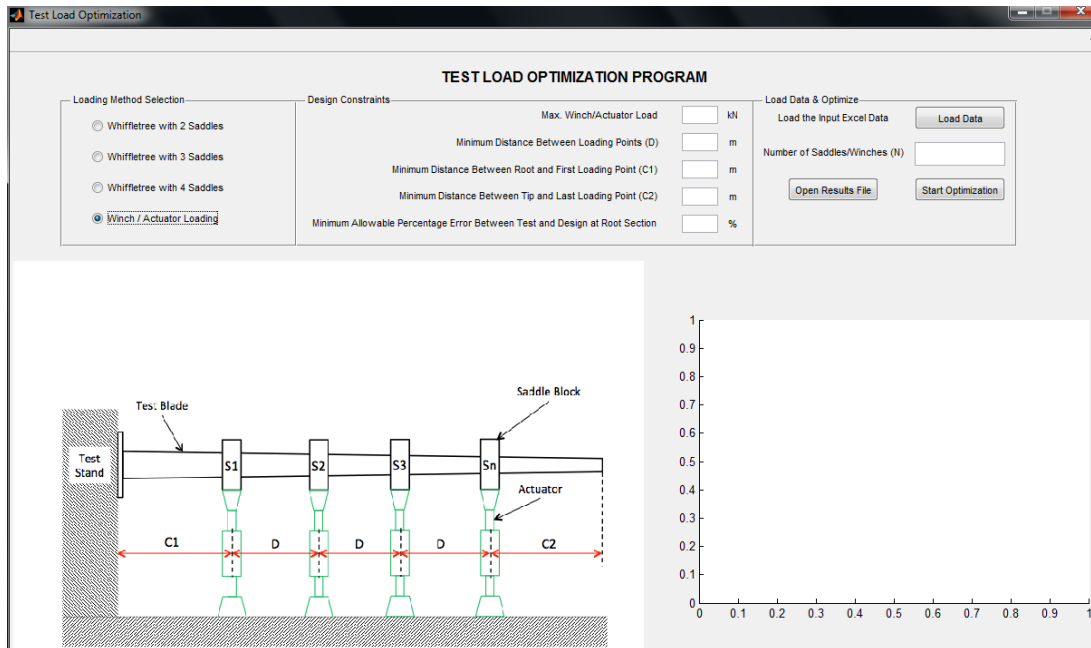


Figure 65: Auxiliary figure for the winch/actuator loading

As seen in Figure 65, input boxes for all design constraints and the number of saddles/winches are enabled for this loading method. Any integer value larger than one can be entered to the input box for the number of saddles. In addition to the design constraints used for the Whiffletree loading method, there is a constraint for the loading capacities of the actuators/winches to be used in the test. In this case, it is assumed that all the actuators/winches in hand have 100 kN loading capacity. Minimum distance between loading points “D” is limited to 1 meter. According to the distributed blade aerodynamic properties given in Reference 15, first airfoil section is located at the 11.75 meter span location. Therefore, minimum distance between root and the first loading point “C1” is taken as 11.75 meter. Since, there is no specific information about the strength of the tip location of the selected blade; minimum distance between tip and the last loading point “C2” is taken as 0.2 meter. Finally, the allowable percentage error between test and design load moments at root section is entered as 1. It should be noted that the load ratio constraint, which is defined for the optimization of the whiffletree systems, is not used when the winch/actuator loading method is selected. Since the applied loads through the loading points are independent from each other for winch/actuator loading method.

Since the shear force value at the root section is about 417 kN, the number of loading points should be higher than four because the loading capacity value assumed for the actuator/winch is 100 kN. The view of the MATLAB test load optimization tool before the execution of the optimization is given in Figure 66 for 8 loading points.

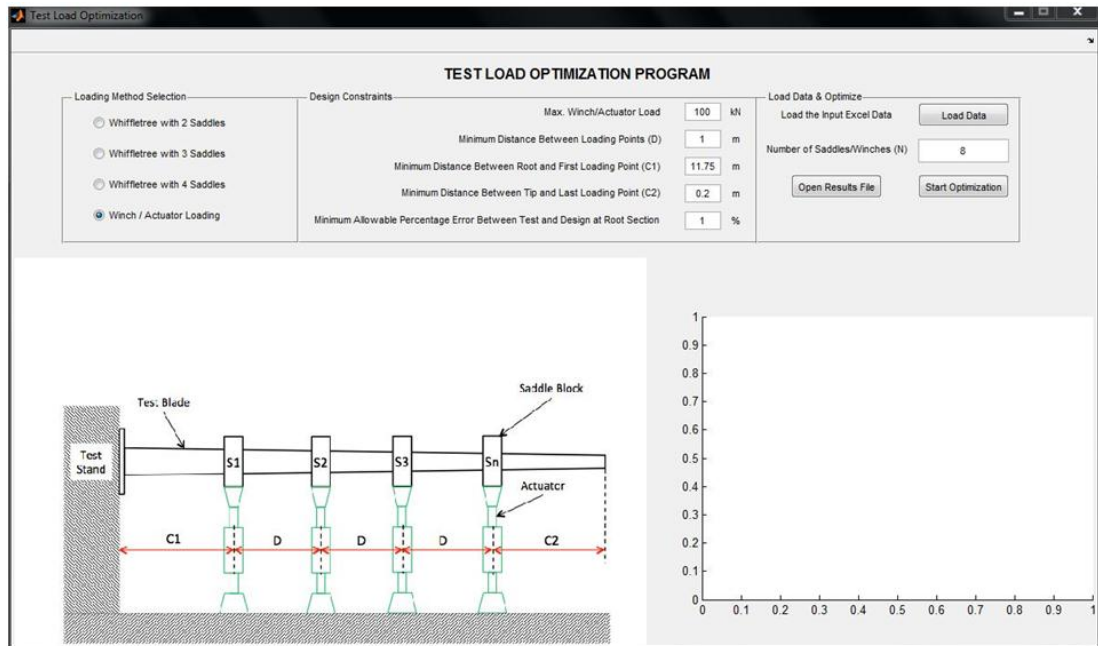


Figure 66: The view of the MATLAB test load optimization tool for winch/actuator loading option before optimization

For demonstration, the test load optimization is performed for the number of loading points from 5 to 8. The resulting locations of the loading point and the magnitudes of the loads applied through the loading points are given in Table 17 and Table 18 for each optimization run.

Table 17: The locations of the loading points for winch/actuator loading method

Number of Loading Points	S1 (m)	S2 (m)	S3 (m)	S4 (m)	S5 (m)	S6 (m)	S7 (m)	S8 (m)
5	21.435	34.031	42.731	51.501	60.114	-	-	-
6	18.086	29.959	38.557	46.683	54.300	60.659	-	-
7	18.085	29.010	34.361	35.475	45.313	51.365	60.114	-
8	17.596	26.279	34.259	39.343	42.954	46.955	51.191	60.114

Table 18: The loads applied through the loading points for winch/actuator loading method

Number of Loading Points	S1 (kN)	S2 (kN)	S3 (kN)	S4 (kN)	S5 (kN)	S6 (kN)	S7 (kN)	S8 (kN)
5	74.897	83.073	90.959	100.0	67.861	-	-	-
6	53.375	68.527	76.711	88.297	82.905	46.975	-	-
7	53.375	47.375	16.999	60.399	77.457	93.323	67.861	-
8	42.307	48.507	60.911	22.951	60.853	13.686	99.712	67.861

The bending moment comparison plots of each optimization run are given in Figure 67-70.

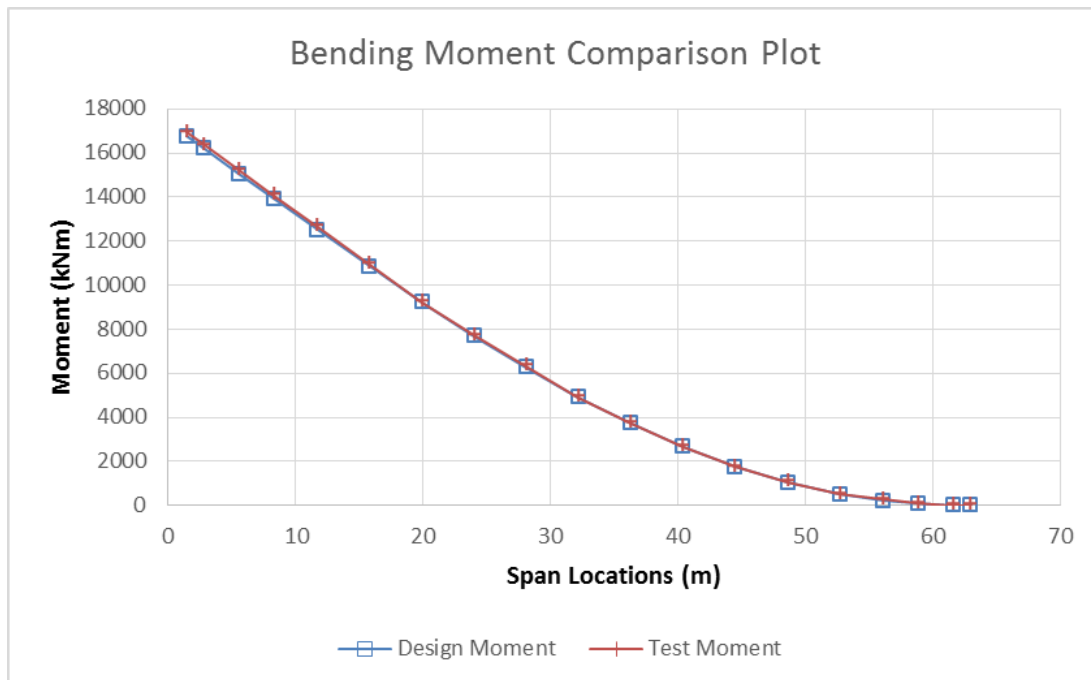


Figure 67: Bending moment comparison plot for 5 loading points

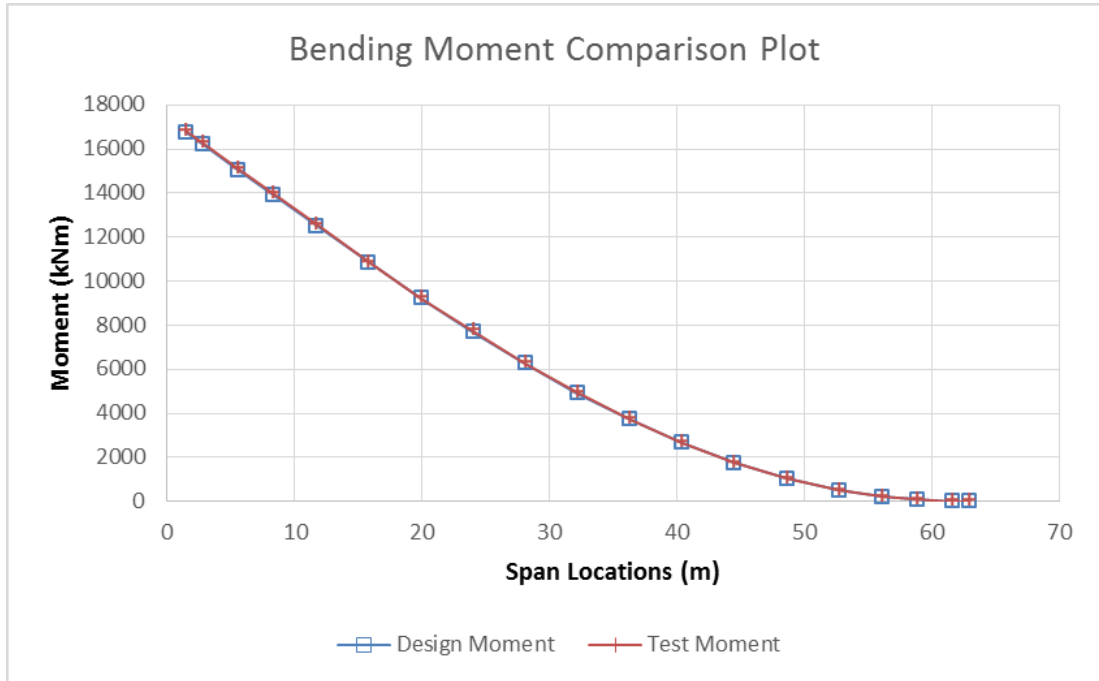


Figure 68: Bending moment comparison plot for 6 loading points

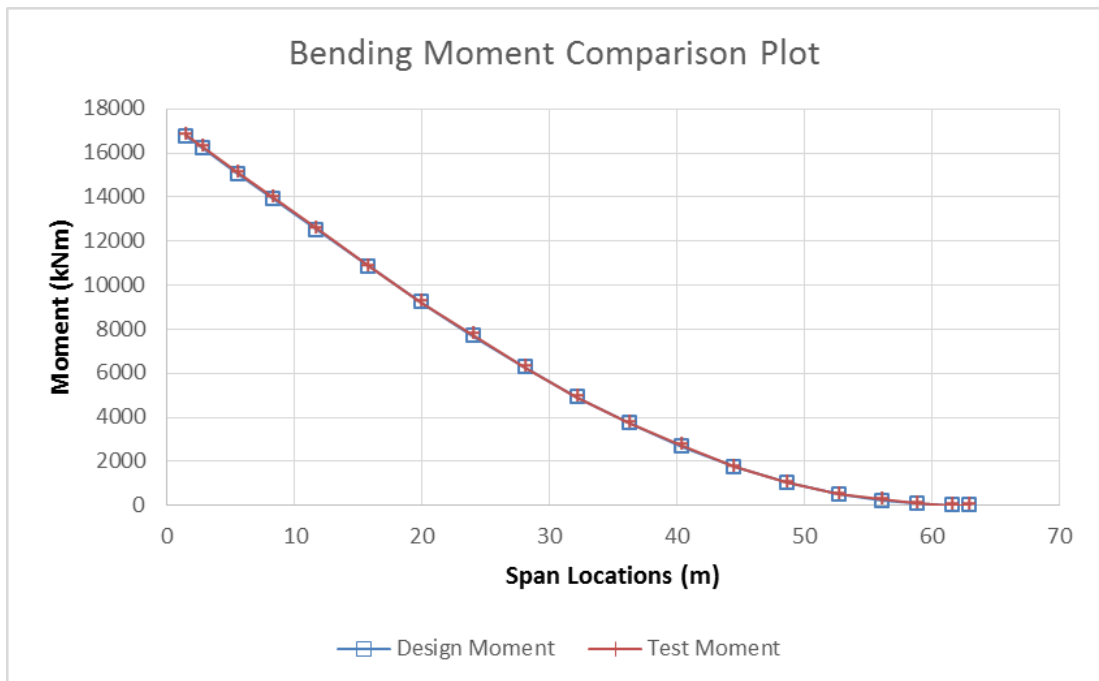


Figure 69: Bending moment comparison plot for 7 loading points

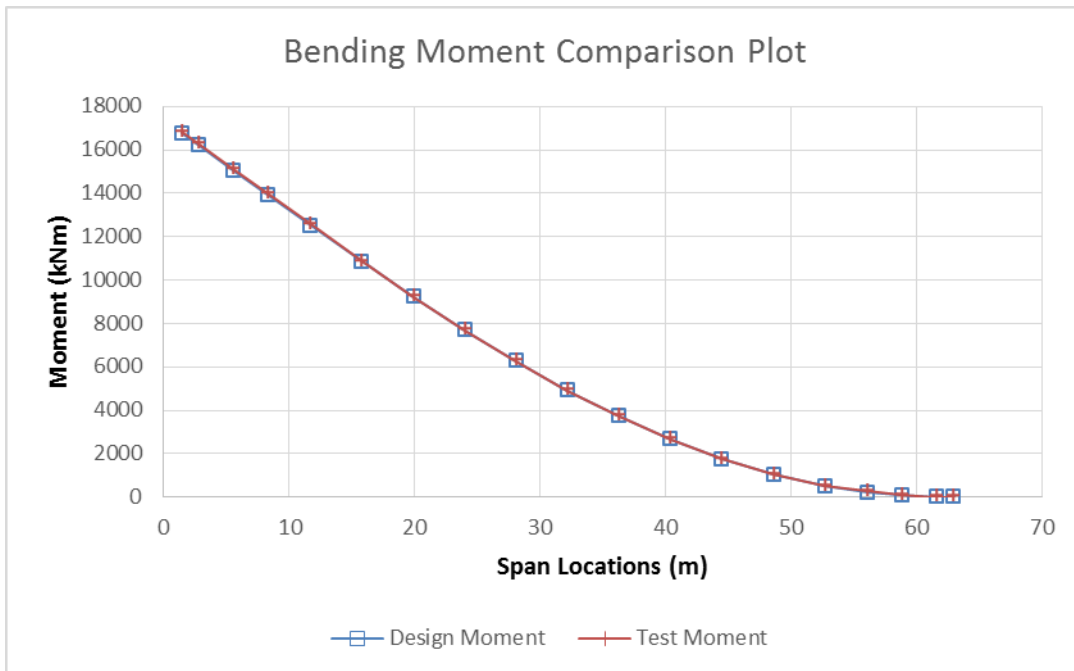


Figure 70: Bending moment comparison plot for 8 loading points

As seen from Figures 67-70, there is almost no difference between different loading configurations in terms of bending moment values. The absolute values of the percentage errors between the test and the design moments at the sections of the blade are given in Table 19 for each loading point configuration.



Table 19: Comparison of the absolute values of the percentage errors between test and design moments at each section

Section (m)	5 Loading Points (%)	6 Loading Points (%)	7 Loading Points (%)	8 Loading Points (%)
63.000	0.000	0.000	0.000	0.000
61.633	100.000	100.000	100.000	100.000
58.900	0.000	0.320	0.000	0.000
56.167	27.612	0.537	27.612	27.612
52.750	0.000	0.056	0.000	0.000
48.650	3.077	0.118	0.000	0.000
44.550	0.000	0.121	0.000	0.000
40.450	0.006	0.041	3.132	0.000
36.350	0.000	0.098	0.000	0.001
32.250	0.000	0.072	0.000	0.000
28.150	1.044	0.000	0.000	0.000
24.050	0.291	0.590	0.590	0.001
19.950	0.000	0.000	0.000	0.000
15.850	0.918	0.001	0.000	0.000
11.750	1.168	0.373	0.372	0.372
8.333	1.126	0.411	0.411	0.411
5.600	1.063	0.402	0.401	0.401
2.867	0.997	0.383	0.382	0.382
1.500	0.964	0.371	0.370	0.370

As seen from Table 19, the number of sections, which have zero error between the test and the design moment values, increases with the increasing number of loading points. The error value at the root section does not change after 6 loading points.

To demonstrate the performance of the MATLAB test load optimization tool, final objective function values, which are the sum of the absolute values of the percentage errors between test and design moments, are compared with the value of the objective function for the initial point. An initial point is defined for each loading configuration by placing the loading points with equal distances between the upper and lower bounds of the loading points and the applied load values are distributed equally by dividing the design shear force at the root section to the number of loading points. For instance, the initial point for the loading configuration with five points is given in Table 20.

Table 20: Initial point definition for the loading configuration with five points

Loading Point Name	S1	S2	S3	S4	S5
Loading Point (m)	11.75	24.51	37.28	50.04	62.80
Applied Load (N)	83358	83358	83358	83358	83358

For other loading configurations, initial points are generated by using the same methodology and the initial values of the objective functions are obtained. In Table 21, initial values of the objective function are compared to the final values which are obtained at the end of the optimization for each loading configuration.

Table 21: Comparison of the initial and final objective function values for MATLAB tool

Number of Loading Points	Initial Objective Function Value	Final Objective Function Value	Decrease in Objective Function Value (%)
5	1703.3	138.3	91.9
6	1382.4	103.9	92.5
7	1169.5	133.3	88.6
8	1008.6	129.6	87.2

As seen from Table 21, the minimum improvement obtained by the test load optimization tool on the objective function value, which is the sum of the absolute values of the percentage errors between test and design moments, is 87.2% of the initial function value. This result shows that the performance of the test load optimization tool developed by using MATLAB is reasonably well.

## CHAPTER 4

### WHIFFLETREE DESIGN

#### 4.1 Configuration of the Whiffletree

Since the best correlation is obtained for the four-saddle point Whiffletree configuration, by using the optimized saddle locations and the resulting primary load application point, a detailed Whiffletree design can be performed to connect the primary load application point to the saddle locations for this configuration. The configuration of the optimized Whiffletree is shown in Figure 71 with the information about the optimized locations of the saddles, the moment arm values of the spreader bars and the transferred load values.

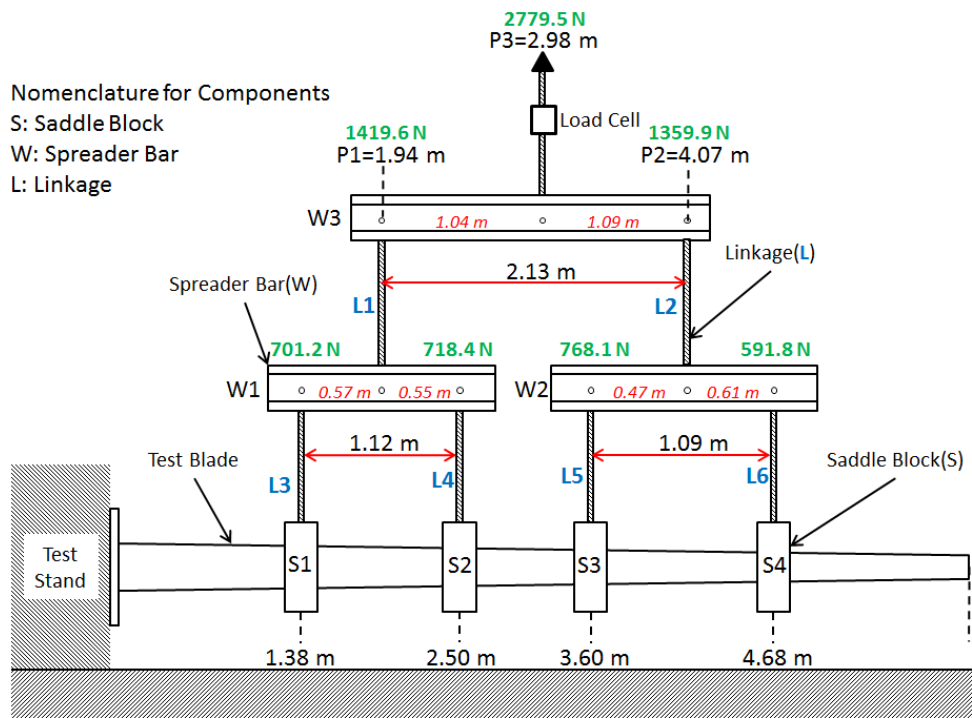


Figure 71: Whiffletree configuration to be designed

For a four-point Whiffletree design, a crane can be used for primary load application. Three spreader bars are used to distribute the crane load to the four saddle blocks attached to the test blade.

#### 4.2 Design of Spreader Bars

As seen from Figure 72, two opposing aluminum C-channels which form an I-beam can be used as spreader bars.

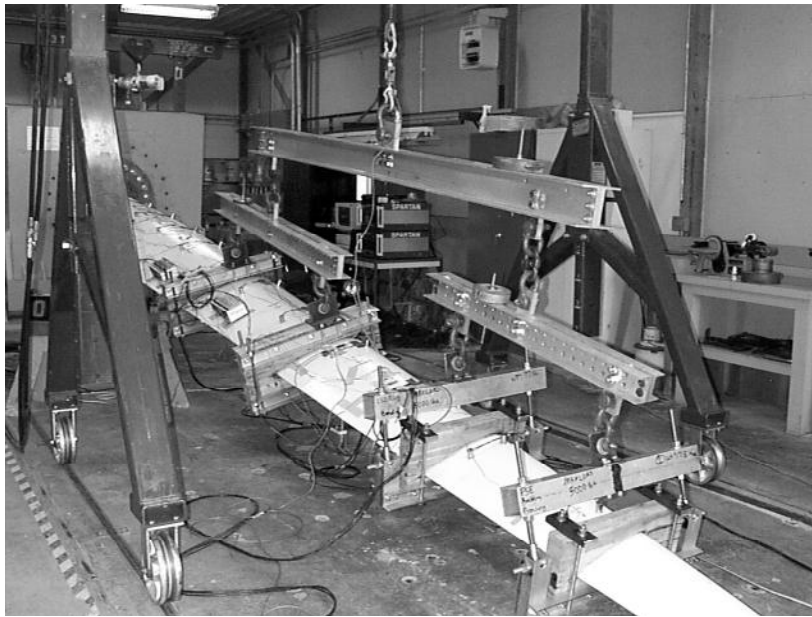


Figure 72: Four saddle point whiffletree design used in ERS-100 blade test [14]

The dimensions of the channel section are determined according to the bending moment applied on the bars which is a measure for required section modulus. The length of the bar is determined according to the moment arm values obtained from the optimization process. According to the optimization results, notations and the dimensions given in Figure 71, the applied maximum moment values can be determined by using the schematic given in Figure 73.

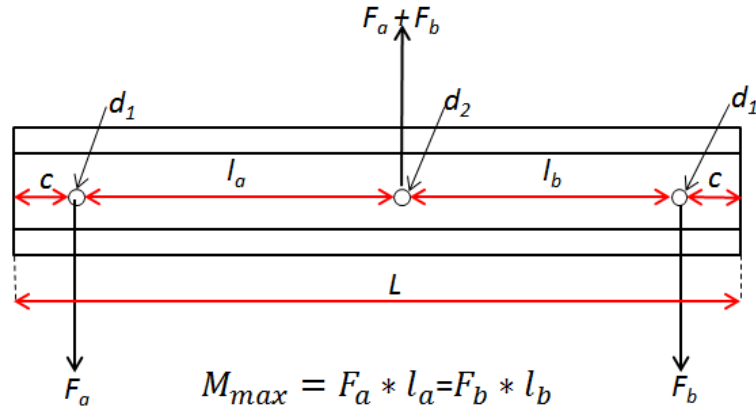


Figure 73: Schematic for moment calculation for spreader bars

where;

$l_a, l_b$ : Moment arm values

$d_1, d_2$ : Hole diameters for the bolt connections

$c$ : Edge distance value which should not be less than  $2.5 \cdot d_1$  [19]

$L$ : Total length of the spreader bar which is  $L = l_a + l_b + 2 \cdot c$

$F_a, F_b$ : Transferred load values

Once the moment value is obtained, the required section modulus value can be determined by using the yield strength value of the C-channel material. The most widely used materials for C-channels are aluminum 6061-T6 and 6063-T52 in the industry, and in the present study, 6061-T6 aluminum is selected for the current design due to its greater strength. The detailed information about the aluminum C-channels, such as standard sizes and sectional properties is obtained from the Aluminum Design Manual 2010 Errata #2 [33]. The required section modulus value can be determined by using Eq. (37).

$$S = \frac{I}{c} = \left( \frac{SF \cdot M}{\sigma_y} \right) / 2 \quad (37)$$

where;

$S$ : Section Modulus

$I$ : Second Moment of Inertia

$\bar{c}$ : Distance from neutral axis to the top or bottom surface of the channel where the bending stress is maximum ( $\bar{c}$  is also the half of the height of the section)

SF: Safety Factor applied to moment value to cover the unexpected loads during the test or the loads when the test continue beyond the design loads up to the failure of the test blade. In the current design, safety factor is taken as 3.0.

M: Applied moment value

$\sigma_y$ : Yield strength of the material which is equal to 241 MPa [34]

It should be noted that since two C-channels are used for the spreader bar, in the calculation of the section modulus; moment value is divided by 2 in Eq. (37). By using the transferred load values obtained from the optimization, the required section modulus values are calculated and according to the required section modulus values, C-channel is selected from the Table 4 of Reference 33. The resulting required section modulus values and the designations of the selected C-channels are given in Table 22.

Table 22: Spreader bar section selection

Spreader Bar Numbering	Required Section Modulus (in <sup>3</sup> )	Selected C-Channel Designation
W1	0.151	CS 2 x 0.577
W2	0.138	CS 2 x 0.577
W3	0.561	CS 2 x 1.07

To find the total length of the spreader bar, “c” value shown in Figure 73 must be known and this value depends on the diameter of the bolts used for the connection of the spreader bar and the linkage. The details of the calculation of the diameter of the bolts are given in the following section. However, to finalize the design of the spreader bars, the diameter value is directly used here which is 5 mm for all connections except for the one between spreader bar “W3” and the linkage used for load cell connection which is 6 mm. As stated in Reference 19, to prevent the friction at the Whiffletree connections during the loading and for the assembly considerations, there should be clearance between the bolt and the hole on the C-channel. For that purpose, the diameter of the hole should be drilled in excess of the bolt diameter. Therefore, for all spreader bars “d1” and “d2” values shown in Figure

73 are chosen as 6 mm except the “d2” value of spreader bar “W3” which is chosen as 7 mm. Since, “d2” value does not affect the “c” value; this value is taken as 15 mm for all spreader bars.

To prevent the rotation of C-channels against each other during loading and to provide the constant gap between channels to prevent friction, they should be fixed by bolt connections with bushings between the channels. The location and number of those connections can vary according to the section properties of the channel and the length of the spreader bar. For the current design, four bolts are placed at the locations shown in Figure 74. The exact values of the locations are given in Table 23 which has all the required information for the spreader bar design.

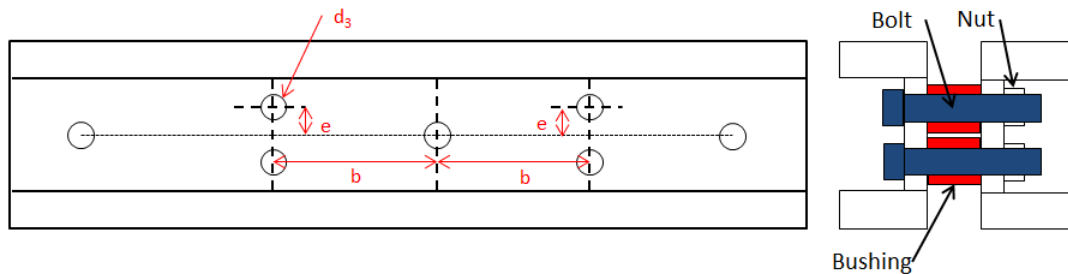


Figure 74: Approximate locations for bolt connections on the c-channels to prevent rotation

Finally, for the manufacture of the designed spreader bars, the required dimension information should be prepared in the form of a table which is given in Table 23 by using the notations given in Figure 73 and Figure 74.

Table 23: Required dimensions for the spreader bar design for manufacturing purposes

No:	C-Channel Designation	$l_a$ (mm)	$l_b$ (mm)	$c$ (mm)	$L$ (mm)	$d_1$ (mm)	$d_2$ (mm)	$b$ (mm)	$e$ (mm)	$d_3$ (mm)
W1	CS 2x0.577	570	550	15	1150	6	6	250	15	6
W2	CS 2x0.577	470	610	15	1110	6	6	250	15	6
W3	CS 2x1.07	1040	1090	15	2160	6	7	500	15	6

### 4.3 Design of Linkages

The linkages between spreader bars and saddles should be designed such that the transferred load at the connection points should be in the direction of the crane loading direction, and only the loads should be transferred through the connection points. In other words, there should not be moment transfer at the connection points which results in loads transverse to the crane loading direction. In such a case, load distribution might turn out to be different from the optimized load distribution. To satisfy this requirement, ball joints should be used at the connection points. Therefore, rod ends with spherical bearings installed inside are used at the connection points. Rod ends are connected via a threaded rod for the design of linkages. Schematic for this rod design is given in Figure 75.

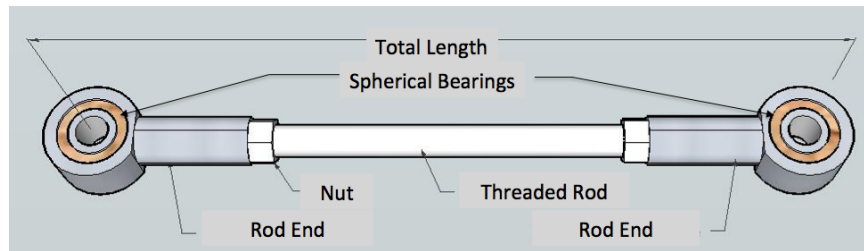


Figure 75: Schematic for the connection rod design

Rod ends used in the design should be selected according to the transferred load through the rod. For the current design, the maximum transferred load value is 1419.6 N which is through the linkage “L1” as shown in Figure 71. The connection between “W3” and the load cell is not taken into consideration here, since that connection has a different design which is detailed later. Again, when the safety factor of 3.0 is applied to the maximum load value, an allowable load value of 4258.8 N is required for the rod end. There are different suppliers for rod ends in the industry and all the required information such as dimensions, material and allowable load values can be obtained from the supplier website or product catalogues. For the current design, the rod end is selected from the supplier website [35]. The minimum allowable static load value listed in the website is 5300 N which satisfies the current design requirement. Detailed specifications about the rod end are given in Figure 76.



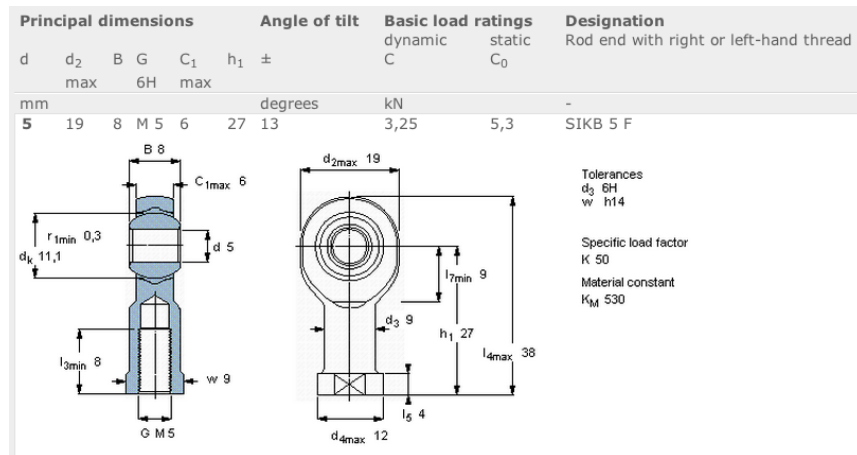


Figure 76: Product specifications for the selected rod end [35]

Since the transferred load values are smaller for other linkages, same connection rod design can be used for the all other linkages. The thread size of the threaded rod and the nut shown in Figure 75 is selected as M5 (Metric 5) and the material of the threaded rod and nut should be selected according to the applied stresses on the threads due to the transferred load multiplied with safety factor. Eq. (38) is used for the determination of the required strength of the threaded rod material by using the tensile stress area value in Table 8-1 of Reference 36.

$$S_{required} = \frac{SF * F_{applied}}{A_t} = \frac{3 * 1419.6}{14.2} = 299.915 \text{ MPa} \quad (38)$$

where;

$S_{required}$ : Required strength value

SF: Safety factor

$F_{applied}$ : Transferred load

$A_t$ : Tensile stress area

Since the required strength of the threaded rod material is 299.915 MPa, low or medium carbon material with property class 4.8, which has minimum proof strength of 310 MPa, is selected according to the material specifications given in Table 8-6 of Reference 36. For the selection of the nut material, proof stress values given in “ISO-898-2” standard [37] are used. According to “ISO-898-2”, the nut material with property class “04”, which has minimum proof strength of 380 MPa, is selected for the design of the connection.

For the connection of spreader bars and rod ends, a bolt-nut joint can be used as shown in Figure 77. To prevent the friction during the loading, there should be a gap between the components. Since, the thickness of the rod end is 8 mm, the gap between the C-channels is selected as 10 mm.

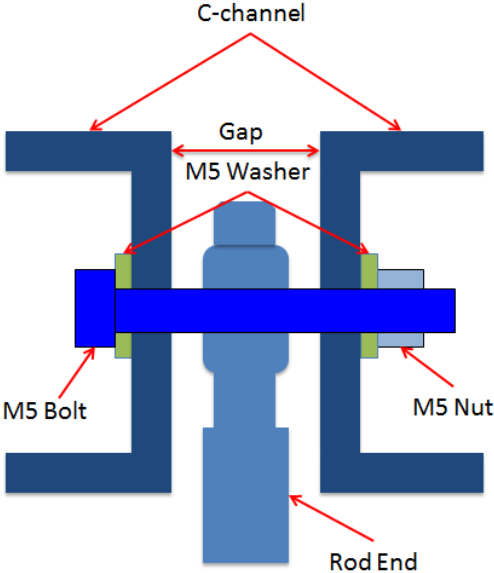


Figure 77: Typical bolt-nut connection for the rod end installation between the c-channels

For the selection of the material of the bolts used, bending and shear failure checks should be performed. The required shear strength of the bolt is determined according to the Eq. (39) given in Reference 18.

$$S_{required, shear} = \frac{SF * (F_{applied}/2)}{A_{shear}} = \frac{3 * (1419.6/2)}{19.63} = 108.48 \text{ MPa} \quad (39)$$

where;

$S_{required, shear}$ : Required shear strength value

SF: Safety factor

$F_{applied}$ : Transferred load

$A_{shear}$ : Cross-sectional area of the bolt

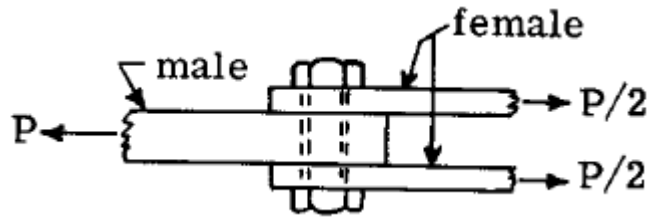


Figure 78: Load distribution on the bolt for shear strength calculation [18]

As seen from Figure 78, the transferred load is resisted by the two sections of the bolt. Therefore, in the shear strength calculation, transferred load value is divided by two. To determine the required strength of the bolt for bending resistance, Eq. (40), which is given in Reference 18, is used.

$$S_{required,bending} = \frac{SF * (F_{applied}/2) * b * (D/2)}{I_{bolt}} = 895.36 \text{ MPa} \quad (40)$$

$$b = \frac{t_1}{2} + \frac{t_2}{4} + g$$

where;

$S_{required,bending}$ : Required bending strength value

SF: Safety factor

$F_{applied}$ : Transferred load

$I_{bolt}$ : Second moment of inertia of the bolt

b: Moment arm

D: Diameter of the bolt

$t_1$ : Thickness of the c-channel

$t_2$ : Thickness of the rod-end

g: gap between rod-end and c-channel

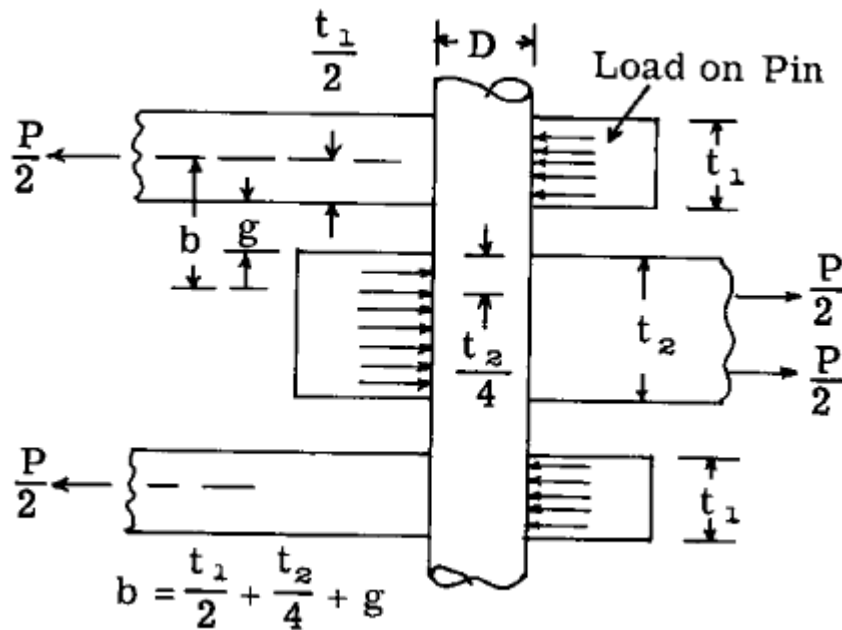


Figure 79: Notations used in the calculation of the required bending strength [18]

According to the required strength values, quenched and tempered alloy steel material with property class of 12.9 is selected for the M5 bolt, which is used in the connection. The material properties of the selected bolt can be obtained from Table 8.6 of Reference 36. For the total length of the connection rods, there are several constraints such as the overhead clearance of the crane, if a crane is used for the loading, or the minimum distance between top and bottom spreader bars according to the expected relative deformation of the saddle points which results in rotation of the bars. In addition, instead of using rod ends installed on the connection rods for the linkage design, shackles attached to chains could also be used as shown in Figure 80. It should be noted that with the use of shackles ball joint connection requirement is also satisfied in this type of design. However, the usage of this alternative design method is less reliable since there could be jamming problems at the connection points between the shackle and the bolts under the applied loading. Also, the loss in the applied loading is higher for the alternative design due to the higher friction between shackle and connection bolts.

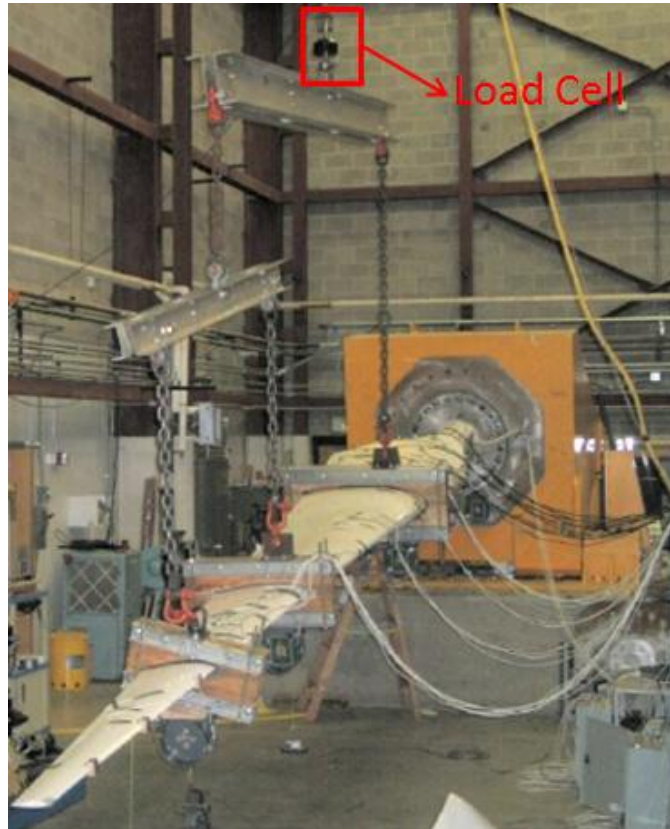


Figure 80: The alternative design for linkage [10]

A load cell should be installed between the crane and the top spreader bar as shown in Figure 80 to read and control the load during the test. For the spreader bar connection, a rod end may be used with higher allowable load capacity than the ones used for other connections due to the increase in the transferred load at that point. For crane connection, a shackle installed to a male fitting should be used. Detailed design for the connection between top spreader bar and the crane can be seen in Figure 81.

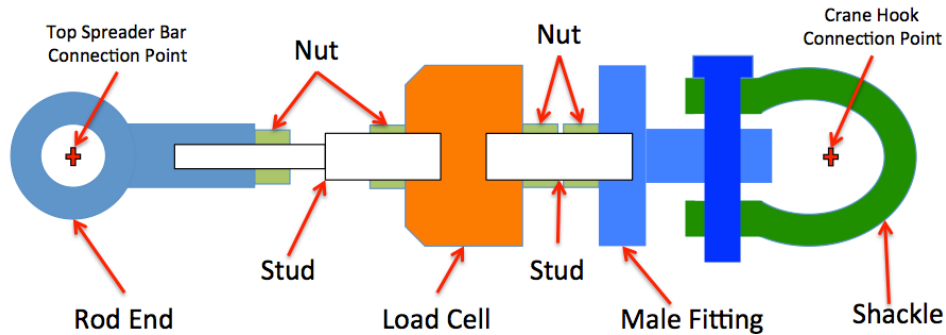


Figure 81: Schematic for the design of the connection between the crane and the top spreader bar

The allowable load value of the rod end used in the connection should be higher than 7386.9 N which is the primary load value multiplied with a safety factor of 3.0. By using the required load value, the rod end can be selected accordingly from the supplier website [35]. For the current design, “SI 6 C” type rod end should be selected which has 8150 N static allowable load value. For the current load application, a load cell with a capacity of 5 kN can be used in the connection because the value of the primary load to be applied is about 2.8 kN, which is in the limits of the load cell capacity. All the necessary information regarding the load capacity and installation can be obtained from a manufacturer website or product catalogue. Since there are various types of load cells used in the industry, a specific selection is not performed in this thesis. The stud and male fitting thread sizes should be designed according to the rod end and load cell installation drawings, and the material properties of the stud and male fitting should be selected according to the applied load through the crane. Instead of using a male fitting, an eyebolt or a rod end could be installed on the load cell for the shackle installation and the selection should be done according to the allowable load values, the thread size information given in load cell installation drawing and the bolt diameter of the selected shackle. For the shackle selection, the dimensions of the crane hook and the working load limit values should be considered, and the hole diameter of the male fitting-shackle connection should be designed according to the selected shackle.

#### 4.4 Design of Saddles

Saddles which are used to introduce test loads to the test blade can be manufactured from laminated wood [38]. Laminated wood blocks should be cut into two pieces from the center by opening the shape of the airfoil at the span location which comes out as the result of the test load optimization. Figure 82 shows typical laminated wood blocks that are used in the saddle locations.

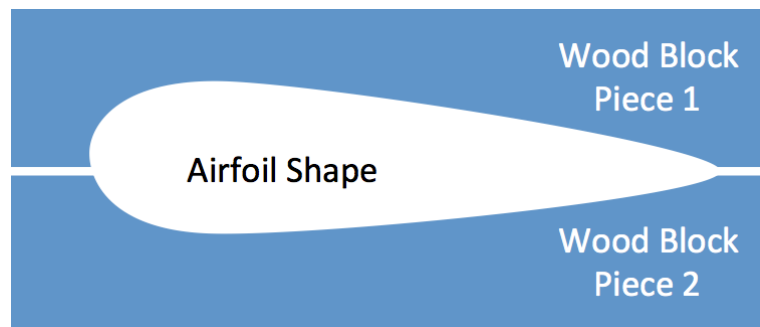


Figure 82: Wood blocks used for the saddle design

The airfoil profiles should be cut with some oversize from the laminated wood block, and the space between saddle and blade may be filled with two-part polyurethane mixture or thin layer of rubber may be placed between saddle and blade to distribute the load on blade surface area evenly and allow the flexibility in the blade-saddle interface. The chance that the saddles would slide outboard the blade during test loading can be reduced by the use of the polyurethane mixture [38]. However, if the blade will be used after the test for any purpose, rubber method should be used to prevent the damage on the blade while detaching the saddles from the blade. The width of the wooden block that determines the surface area between the saddle and the test blade should be decided according to the strength of the structure at the saddle location that should not result local failure due to concentrated loading. Since there is no specific information about the strength of the blade, the detailed saddle design is not given in the present study. However, the conceptual design is detailed as much as possible. The two wooden blocks should be connected to each other as seen in Figure 72 and Figure 80 by using threaded rods through the C-channels installed on the wood blocks. The design for the connection of wood blocks is demonstrated in Figure 83. The length of the wooden blocks should be larger than

the airfoil chord length at the saddle location for the installation of threaded rods and the height of the wooden blocks should allow the installation of C-channels.

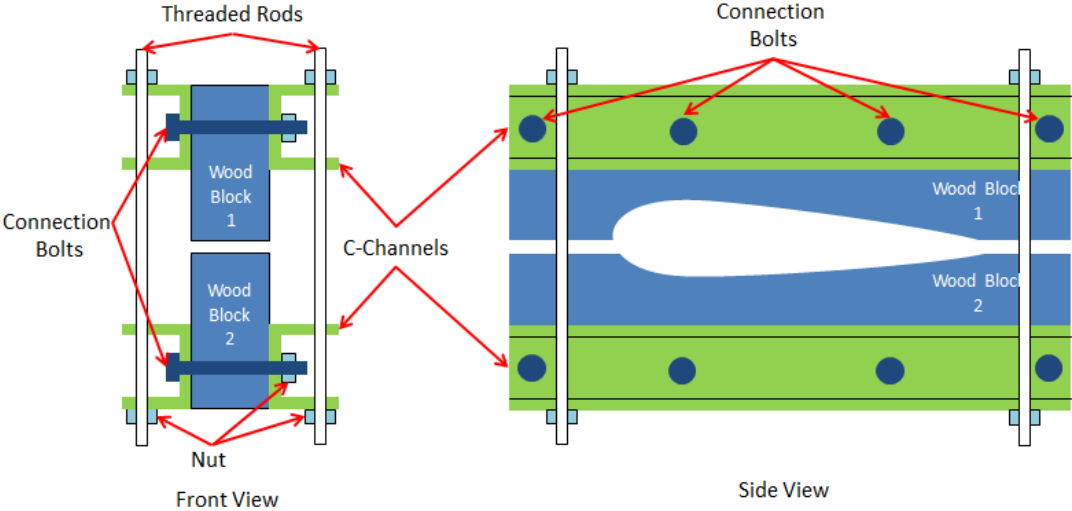


Figure 83: Schematic for saddle design-1

Before connecting the upper and lower wood blocks, the preload value to be applied on threaded rods should be determined. If the value of the test load applied through the saddle is small, the preload value may have an adverse effect on the test loading. Therefore, the torque value used for the threaded rod connection should be selected carefully with the test requester or the manufacturer. As seen from Figure 83, there are two C-channels attached to each wood block via bolt-nut connections. The material and sectional properties of the C-channels can be selected according to the dimensions of the wood block used. In addition, the bending moment on the C-channel flanges due to the compression loads applied by the threaded rods shown in Figure 83 and the bolts used for the installation of the fitting shown in Figure 84 should be considered for sizing of the C-channels. The C-channel section, “CS 2x0.577”, used in the spreader bar design and the threaded rod used for linkage rod design can also be used for the saddle design. The length of the C-channels should be the same with the length of the wooden blocks. The installation of the fitting used for the connection of the saddle and spreader bars is shown in Figure 84.



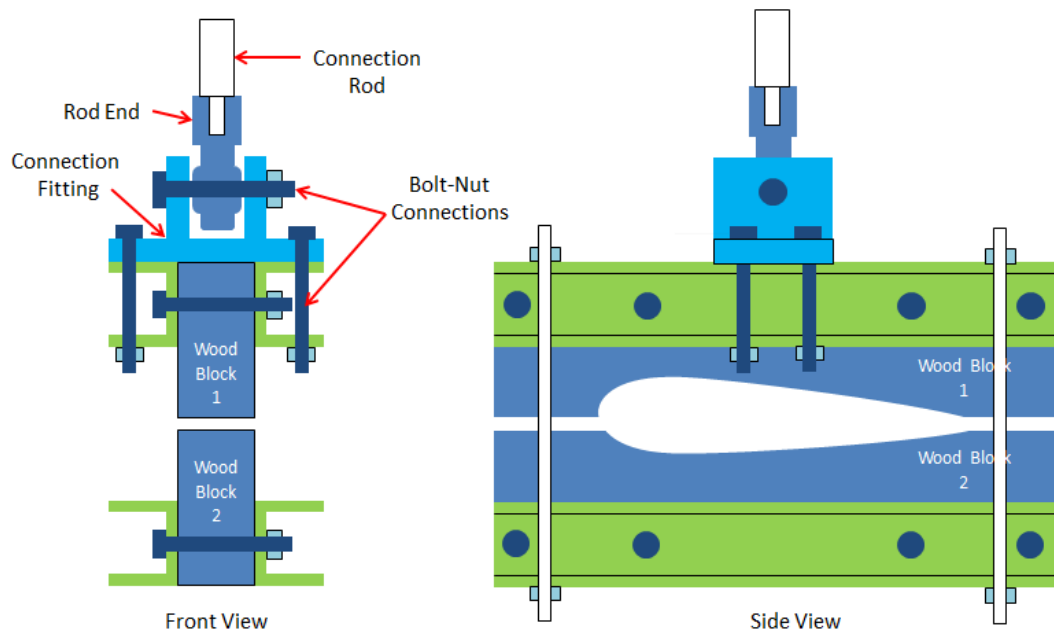
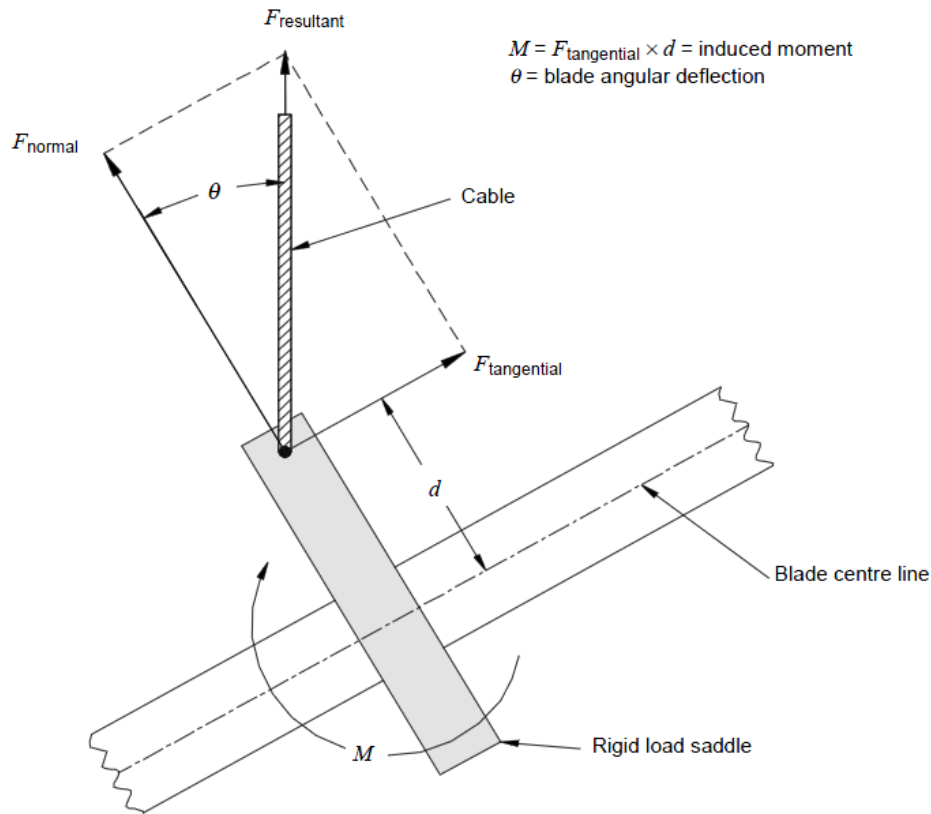


Figure 84: Schematic for saddle design-2

A female fitting is attached to the upper wooden block by using four bolts as shown in Figure 84 for the rod end connection. The sizing and material properties of the fitting should be determined according to the detailed analysis considering the applied saddle load. The most important part of the installation is the chord wise location of the fitting such that the axis of the connection rod should coincide with the location on the airfoil chord where the design loads are calculated.

If the expected blade deflections are very high at the locations where saddles are attached, rigid saddle designs as detailed above can result errors in the desired loading due to loading angle changes. As shown in Figure 85, there is an angle between the saddle and the load direction when the blade deflection is large.



IEC 430/01

Figure 85: Force couple introduced bending moment during static testing [12]

Due to the load angle change, as seen in Figure 85, a force couple is created by the blade reaction force which can prevent the intended moment distribution over the blade [12]. For the current design, to minimize this effect, a different design concept is applied to the last two saddle points. As mentioned in Reference 14, the load can be applied at or near the blade chord line by using a pivoting mechanism. The pivoting saddle design can reduce the introduced bending moment due the large deflections of the blade during the static testing. A comparison of the two different saddle designs is shown in Figure 86.

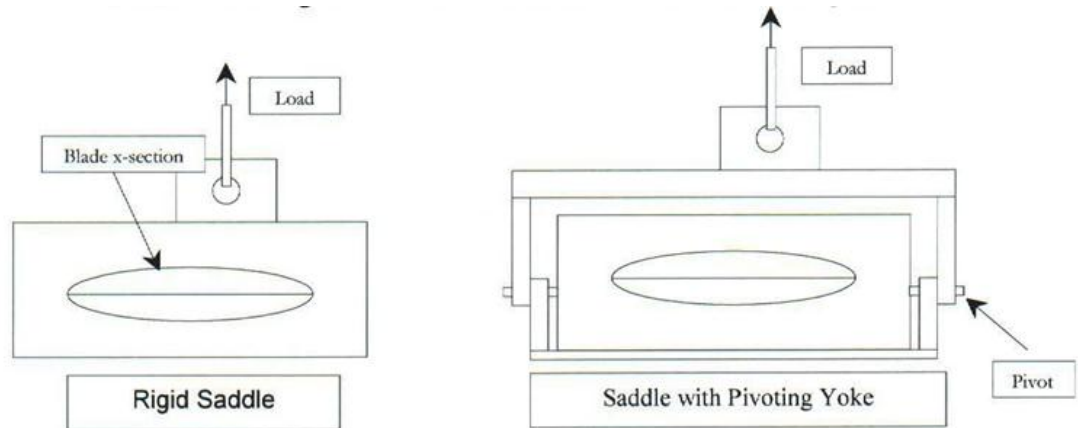


Figure 86: Comparison of different saddle designs [38]

To perform the pivoting saddle design, following modifications should be applied to the rigid saddle design. Firstly, C-channels attached to the upper wooden block should be removed and aluminum plates should be used to attach upper and lower wooden blocks. Also, the length of the C-channels attached to the lower wooden block should be increased to attach the aluminum block for the pivoting pin installation as seen in Figure 87.

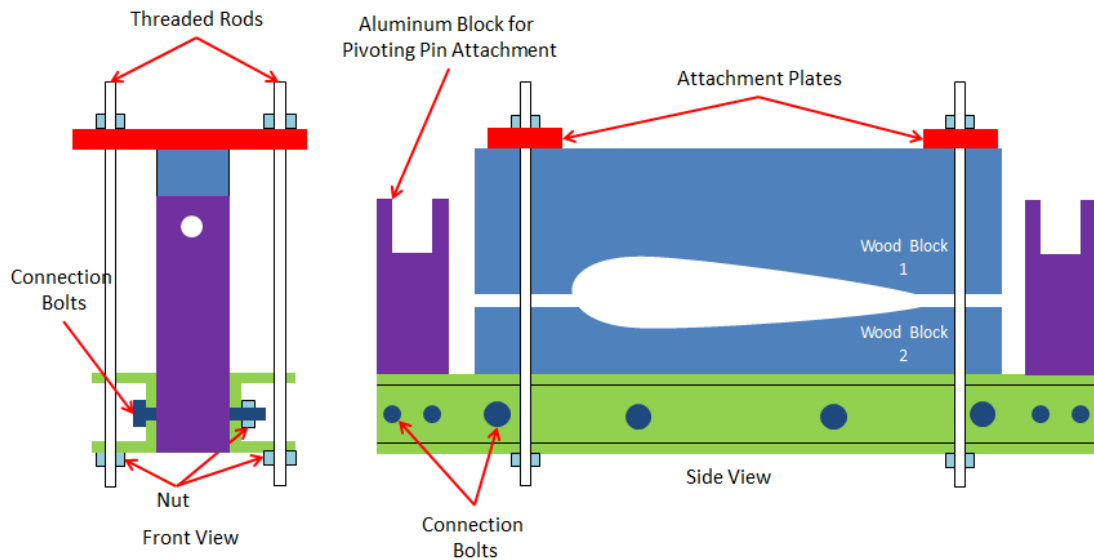


Figure 87: Schematic for the pivoting saddle design-1

For the upper part of the saddle, a square tube section can be used. This square section tube should be installed to the lower saddle assembly through the pivoting

pin connection by using threaded rods which have rod ends with spherical bearings inside to prevent friction at the pivot connection. Detailed installation schematic is shown in Figure 88.

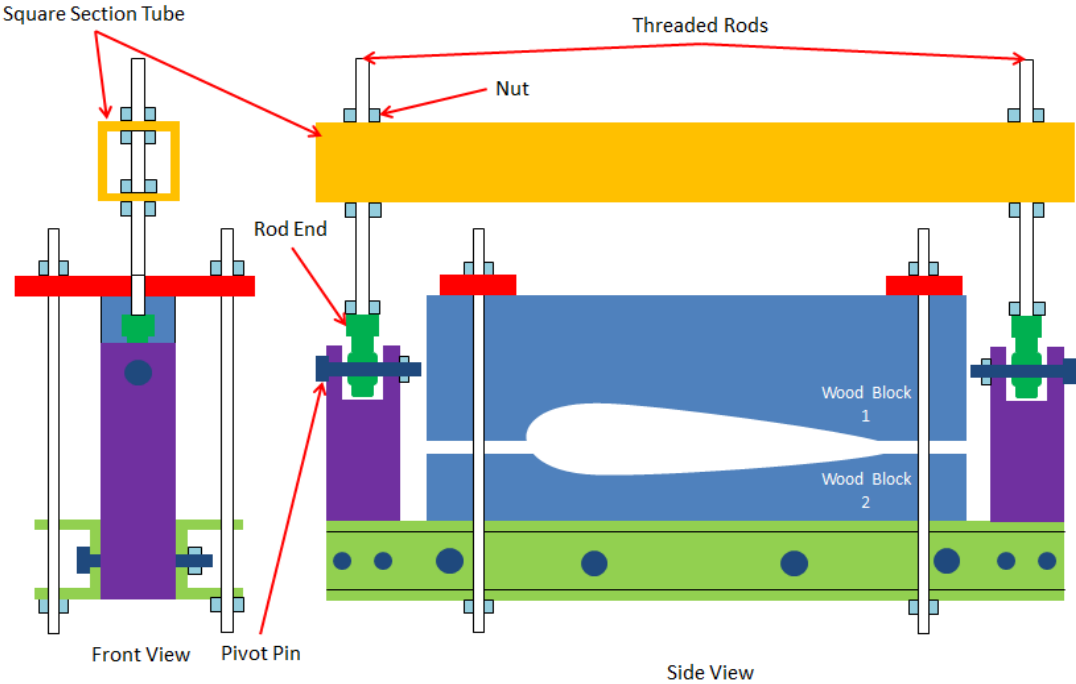


Figure 88: Schematic for pivoting the saddle design-2

Finally, the female fitting is attached to the square section tube by using four bolts for load introduction to the saddle. Detailed installation schematic is shown in Figure 89.

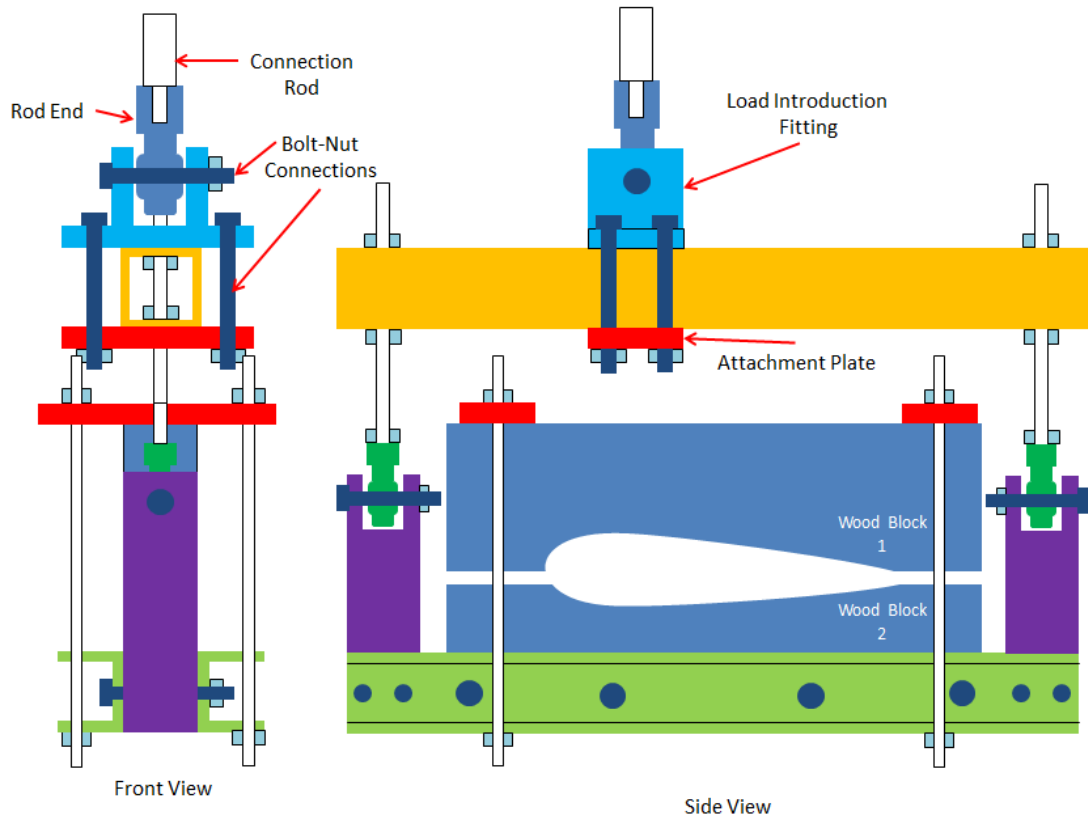


Figure 89: Schematic for the pivoting saddle design-3

The sizing checks should be performed for the additional components of the pivoting saddle design according to the loads transferred loads through the pivoting points.

#### 4.5 Ballast Weight Application

The Whiffletree assembly should be balanced statically by attaching ballast weights to spreader bars according to the weight of the components used in the design. Bending moments in the blade caused by the Whiffletree components can be eliminated by this method [38]. The usage of ballast weights can be seen in Figure 90.

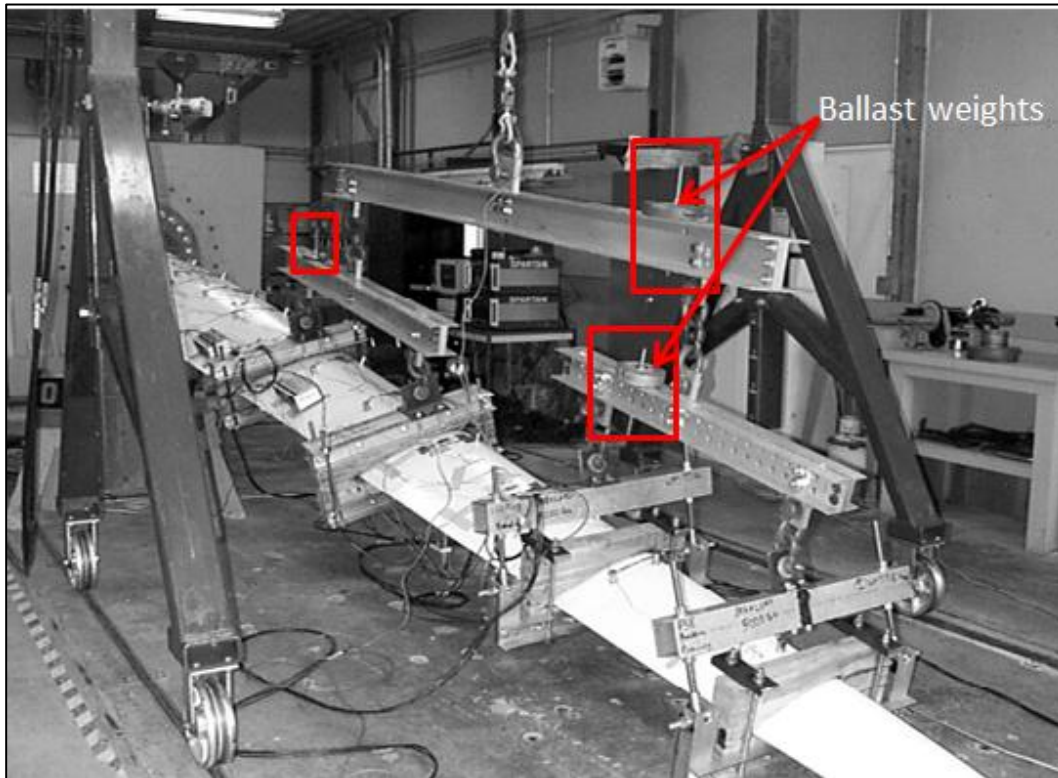


Figure 90: Ballast weights attached to the spreader bars [14]

The amount of the ballast weight can be obtained by a simple moment calculation for the connection point at the middle of the spreader bar by using the weight information of the components in the system. An example calculation is shown below in Figure 91 for the top spreader bar.

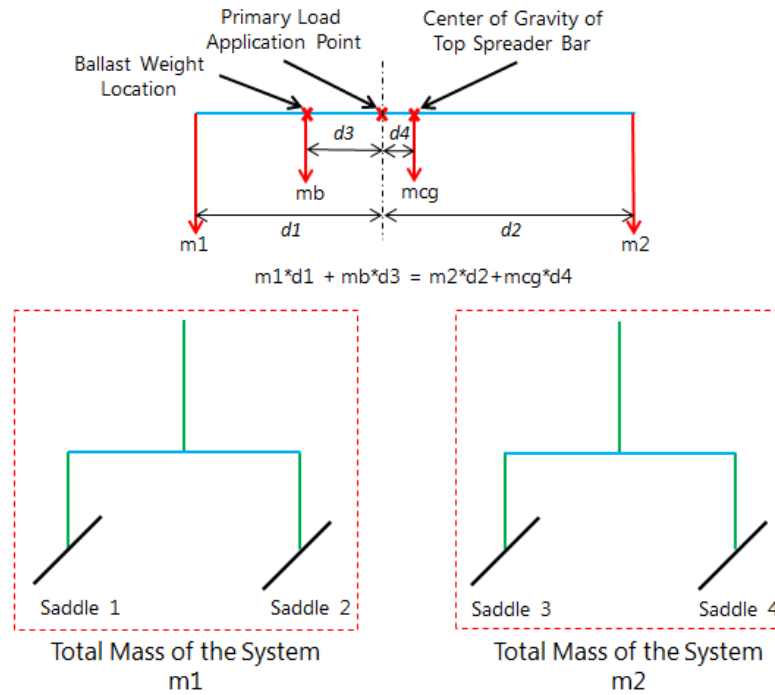


Figure 91: Example calculation for the ballast weight application

Since the amount of the ballast weight at hand is known, the location of the ballast weight can be found easily. It should be noted that, the total weight of the loading system including the ballast weights should be added to the primary load value as tare load to counter-balance the loading system. The additional loading of the weight of the loading system on the test specimen is prevented by this way.





## CHAPTER 5

### CONCLUSION

#### 5.1 Summaries and Conclusions

In this thesis, first brief information about the static blade testing is given. In addition, different test loading methods are outlined and the whiffletree system is introduced. Then, the basic parameters of the UAE wind turbine blade, which is the reference blade selected for the design load calculation, are given. These parameters are used in the design load calculation, and design load calculation is performed for the selected power production design condition. Different design conditions can also be selected when necessary to see the extreme conditions such as parking and the gust loadings. Since the main scope of the thesis is not to perform a complete design of a wind turbine blade, simplified design loads calculated are considered to be sufficient in demonstrating the calculation of the optimum discrete test loads that give the closest bending moment as the distributed load. The methodology, which is used for the calculation of the simplified design loads, is outlined.

After the design loads are calculated, test load generation is performed by using the optimization capability of the solver add-in of MS EXCEL software and the developed MATLAB test load optimization tool for Whiffletree configurations which have different number of saddle points. Sum of the absolute values of the percentage errors between the test and the design moment distribution over the blade span is used as objective function to minimize. Saddle locations and the saddle loads are found as a result of the optimization. Different objective functions can also be defined if required. A set of constraints is defined for optimization. Those constraints can be changed according to the requirements defined by the test requester or the manufacturer.

Firstly, the optimization is performed by using MS EXCEL Solver add-in tool. It should be noted that the MS EXCEL sheet, which is used for design load calculation, is also used for the optimization purpose. Therefore, the design loads calculated for the selected load case can be directly used as the input for the optimization. The parts of the MS EXCEL sheet are introduced to demonstrate the methodology used in the MS EXCEL Solver add-in tool for the optimization of the Whiffletree configurations. Separate MS EXCEL sheets are prepared for each of the Whiffletree configurations optimized in the thesis. The results of the optimization, which are obtained by the MS EXCEL Solver add-in tool, for different Whiffletree configurations are compared and the resulting moment distribution is found to be almost the same with the design loading for the four-saddle point Whiffletree configuration. However, there are differences between the test and the design loadings for the shear force distribution. Shear force distribution looks like the staircase as expected. Because, continuous design load can only be approximated by a staircase shear force distribution due to the application of discrete external test loads through the saddle points. If the requirement for the error between the test and the design moment distributions is not strict very much, the other whiffletree configurations with less number of saddle points can be used for the test loading. It should be noted that the assembly time is shorter and the cost of the system is less if the number of saddle points is less, because there are few connections and components used in the system.

The optimization process which includes the preparation of separate MS EXCEL sheets and selecting the variables and constraints for the Solver add-in tool is a complicated process. Therefore, to simplify and generalize the test load optimization process, a tool with a simple user interface is prepared with MATLAB. In addition to the optimization of the Whiffletree systems, the developed MATLAB tool has the capability of the optimization of the loading systems with any number of loading devices, such as actuators and winches. The results of the optimization for different Whiffletree configurations are compared with the results obtained by the MS EXCEL Solver add-in tool. It is observed that the results obtained by the developed

MATLAB tool are same with the results obtained by the MS EXCEL Solver add-in tool except for the Whiffletree with two saddle points. The test moment distributions, which are obtained by each tool for the Whiffletree with two saddle points, about the root and tip of the blade are almost same. However, there is a slight difference in moment distributions between the saddle points.

To demonstrate the extra option in the developed MATLAB tool for the optimization of the loading systems with any number of loading devices, NREL's offshore 5-MW baseline wind turbine blade, which is 61.5 m long, is selected. The simplified design loads for rated wind speed operation condition are calculated for the selected blade by using the same methodology outlined for UAE research wind turbine blade. The test load optimization is performed for the number of loading points from 5 to 8 and the results obtained for each optimization run are compared. It is observed that there is almost no difference between different loading configurations in terms of bending moment values. In addition, the number of sections, which have zero error between the test and the design moment values, increases with the increasing number of loading points. The error value at the root section does not change after 6 loading points.

The design of the Whiffletree that is used for the connection of the saddle points and the primary load application point is performed by using the results of the optimization for the four saddle point whiffletree configuration. The conceptual design of the components of the Whiffletree system is detailed as much as possible. However, the detailed sizing is not performed for some of the component because of the missing strength information of the blade which is used as the reference blade for the Whiffletree optimization.

## **5.2 Future Work**

The main focus of this thesis is the static testing of the wind turbine blades only. As a future work, research on fatigue testing methods for wind turbine blades can be conducted. Currently, there are different fatigue testing methods which are open for improvement. MATLAB tool developed for the static test load optimization can be updated such that fatigue test load generation capability can be added to the

developed test load optimization tool. After the establishment of the blade test facility in METU Center for Wind Energy, static and fatigue tests of blades can be conducted. Besides the test execution, studies can be conducted for the verification of the applied test load by the load measurements at the reaction wall where the blade is attached. In addition, by means of the digital image correlation system, full field deformation measurements can be performed on the different locations of the blade and these measurements can be compared with the strain gage readings. Such measurements are very important in finite element model updating studies. It should be noted that performing a wind turbine blade test is not an easy task. Besides the complications in the load introduction, deformation measurements in static and fatigue loading also need special care. In the future, main focus has to be to develop a blade test facility which has the capability of static and fatigue testing of wind turbine blades. Such a facility is not only important from research point of view but such a facility can also serve to the industry. The test load optimization tool that is developed as part of this thesis can be used very effectively in the blade test facility to determine the optimum load introduction points and load values that simulate the bending moment created by the actual distributed loading acting on the wind turbine blade which may be calculated from any design load case that is specified in the relevant standards such as IEC-61400-1 or IEC-61400-2 [39].

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