NTNU – Trondheim
Norwegian University of
Science and Technology

Effects of Pretension in Bolt for a Slewing Bearing

Md. Jahangir Hossain

Marine Technology
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Supervisor: Bernt Johan Leira, IMT

Norwegian University of Science and Technology
Department of Marine Technology

Acknowledgement

In this Thesis, the effect of bolt pretension in case of three-row slewing bearing used in crane has been performed. This thesis is partial requirement for fulfilling of M.Sc studies at NTNU, Trondheim, Norway and was offered by National Oilwell Varco (NOV) AS, Trondheim, Norway.

The work for this thesis has been completed partly at the department of marine technology, NTNU with supervision of professor Bernt. Johan Leira and partly at the office of NOV, Trohondheim

The practical information required for this project was collected from NOV, Trondheim. I am very much pleased to get such a project and to finish it successfully. During the project, I get continuous guide from professor. I also get help for many times in different form for this project from Robin Brenden, Design Engineer, Structural Calculation Dept., NOV-Trondheim.

For successful completion of this project, I would like to thank Professor Bernt. J. Leira. I would also like to thank Robin Brenden for his kind supports from NOV.

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Trondheim, June 2014　　　　　　*Md. Jahangir Hossain*

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for

Jahangir Hossain

Effects of Pretension in Bolts for a Slew Bearing

Virkning av Forspenning i Bolter for et Dreie-lager

A slew bearing which is part of an offshore crane (and which is applied in order to allow rotation of the crane) is to be considered. This is in principle a roller bearing with a diameter of typically 3 m. It consists of a 3 row roller bearing together with the adjoining crane structure on the lower side and on the upper side. The adjoining structure consists of a cylinder with a heavy flange. The bearing is fixed to the flanges by a number of pre-tensioned bolts. The bolts are pre-tensioned to minimize the stress variations in the bolts, in order to prevent fatigue failure of these components.

The slew bearing consists of three steel rings with roller races and three rows of rollers. A gear race for turning the crane is also an integrated part of one of the rings.

For an offshore crane there is no fixed lifting cycle, each new lift is different from the previous. The load history of the crane will be history of irregular variations. It can be described by probability distributions. Fatigue failure is a result of high load variations and many repetitions. A few high loads will not contribute much. Today bolts are pre-tensioned for the highest expected load. This is probably not necessary. High pre-tension has a cost and unnecessary pre-tension should be avoided.

It is recommended that analysis of the bearing will consist of the following tasks:

1. A description of the slew bearing is to be given. General analytical models for analysis of roller bearings which are available in the literature are to be reviewed and summarized. Relevant limit states for the bearing are to be defined (e.g. yielding/buckling, sufficient pre-tension in the bolts, fatigue, static bearing capacity, ultimate load)

2. An Finite Element Model of the slew bearing assembly is established. The computer program to be applied is decided in agreement with the supervisor. The model should include the following effects: (i) Non-linear elastic properties of the rollers (ii) Clearance between the rollers and the roller races on the rings (intended play in the bearing) (iii)Bolts and bolt pre-tension (iv) Gradual separation of the ring surfaces as the load on the bearing assembly increases.

3. Parametric studies are performed for the established Finite Element Model. The following effects should be investigated: (i) How much will reduced pre-tension influence the fatigue life of the bolts? (ii) What is the influence of low pre-tension on the life of the bearing life ? How will low pre-tension influence the fatigue life of the structural parts ?

4. The effect of plastic material behavior is also to be investigated to the extent that time allows. The ultimate failure load of the slew bearing assembly should then be checked by a calculation based on plastic considerations. A plastic element model of the slew bearing assembly is then established and the relevant loads are incremented until system failure occurs.

The work scope may prove to be larger than initially anticipated. Subject to approval from the supervisor, topics may be deleted from the list above or reduced in extent.

In the thesis the candidate shall present his personal contribution to the resolution of problems within the scope of the thesis work. Theories and conclusions should be based on mathematical derivations and/or logic reasoning identifying the various steps in the deduction.

The candidate should utilize the existing possibilities for obtaining relevant literature.

The thesis should be organized in a rational manner to give a clear exposition of results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.

The thesis shall contain the following elements: A text defining the scope, preface, list of contents, summary, main body of thesis, conclusions with recommendations for further work, list of symbols and acronyms, references and (optional) appendices. All figures, tables and equations shall be numbered.

The supervisor may require that the candidate, in an early stage of the work, presents a written plan for the completion of the work.

The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

The thesis shall be submitted electronically:

- Signed by the candidate
- The text defining the scope included
- Drawings and/or computer prints which cannot be bound should be organised in a separate folder.

Supervisor: Professor Bernt J. Leira Contact person at NOV: Robin Brenden

Deadline: June 11th 2014

Trondheim, January 14th 2013

Bernt J. Leira

Abstract

This thesis is to check to bolt pretension for high duty bolted joint in the slewing ring. The bolted joint in the slewing ring is of special type the loads acts off axis of the bolt. For this kind of bolted joint, there is no direct theory. Most of them are based on experiments and are empirical. Some is also based on standards and experience. In the recent years, some finite element simulation has been done by some researchers.

In this thesis, a finite element model was made using ANSYS WORKBENCH and an analytical formulation was used to find the work load on the bolt and then applied it in the WORKBENCH simulation and the result was satisfactory.

The main task included in this thesis is to investigate the effect on the fatigue life of bolt with reduced pretension. This was also done and the result was satisfactory.

Another task was to investigate the effect of plastic material behavior if time is allowed. This task was not addressed here due to time limitations.

Other software used for this thesis was AUTOCAD INVENTOR. This was used to develop the model and later the model was analyzed in the WORKBENCH.

The loads which act on the slewing bearing in this case comes from load history of the crane. A FORTRAN CODE was written using stiffness method to get loads on the ring from load history.

Few recommendations for future work with this topics has also been attached at the end.

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1 Introduction

1.1 Slewing bearing

The word slew stands for turning or rotating about its own axis without changing the position. A slewing bearing is a bearing which helps to rotate other bodies using its rotation while keeping them in same place. Slew bearing is, in principle, a roller bearing of large dimension with a diameter of up to 13 m (43 ft)[3]

The main use of this kind of slewing bearing ranges from heavy to light industries including offshore, mining, medical, transport, construction, forest industries. To be very specific, it is used in offshore crane, wind turbine, radar dishes, tunnel boring machines and so on heavy machineries.

Figure 1: Slewing bearings in practical examples [4]

It has special structure and can carry combined radial, axial and tilting moment loads simultaneously. It typically supports a heavy but slow oscillating loads. It consist of some steel seat rings with orbit such as upper orbit, nether orbit and radial orbit which accommodate rollers with races and has some rows o rollers. Each rows of rollers take one robit. The specialty of the slewing bearing if compared to other types of bearing is that, it is very thin in section while having large diameter. The slewing ring may have gears in its inner ring (internal gear) or in outer ring (external gear) and sometime without gears.

The main function of these kind of bearings are to connect two adjacent structures allowing themselves to rotate and transmit load between them. The load is mainly carried by the rolling rollers in between the outer and inner ring allowing them to rotate and thus the attached structures to the ring rotate. The attached structure to the ring is kept fixed through bolting joint with pretension bolt

Depending on the application requirements the slewing ring may be of different configurations. The following is some the of configurations[1].

-Single-row ball slewing bearing

-Double-row ball slewing bearing

-Three-row roller slewing bearing

- Cross-roller slewing bearing

Figure 2: Single row ring[1]

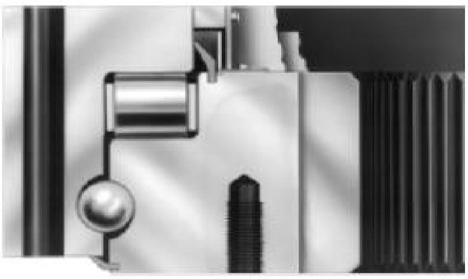


Figure 3: Double row ring[1]

Figure 5: Three row roller ring[1]

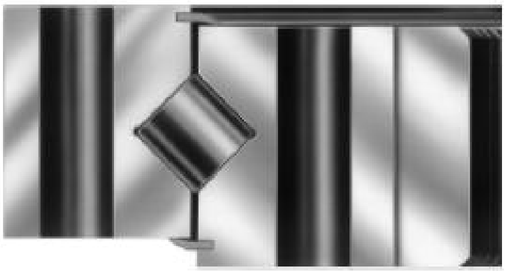


Figure 4: Cross row roller ring[1]

The main features of slewing rings include compact design, light weight, high rigidity, smooth running, very high precision and its reliability in safety.

1.2 Slewing ring for the thesis

The National Oilwell Varco Norway AS (NOV) produces and supplies most of the equipments required for offshore industries. One of the main component of NOV is its crane which uses slewing ring for its operation. The slewing ring used by NOV offshore crane has a typical diameter of around three meter.

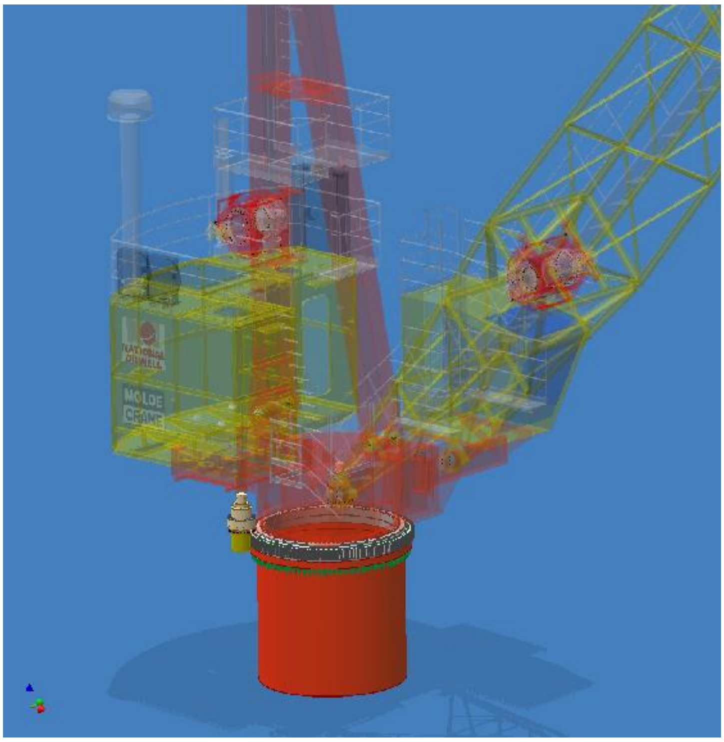


Figure 6: Slewing ring in the crane model

Figure 7: Slewing ring in the crane in practice

In the assembly of slewing bearing for, there is a three row roller bearing together with the adjoining crane structure on the lower side and the upper side. The adjoining structure consists of a cylinder with a heavy flange. The bearing is fixed to the flanges by a number of pre-tensioned bolts.

The Slew bearing for NOV crane consists of three steel rings with roller races and three rows of rollers. A gear race for turning the crane is also in integrated part of one of the rings.

Figure 8: Slewing bearing rings with external gear

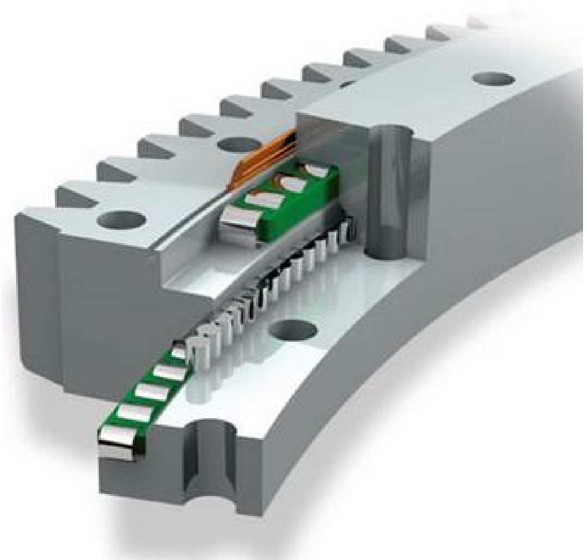


Figure 9: Details of slewing rings in the three-row roller bearings[2]

The main specialty of three-row roller bearing is its three row of rollers. Due to this arrangements, it help for improved load capacity in radial directions. Also due to the middle row which is arranged in the vertical direction, the load capacity in axial direction is improved. The load capacity is mainly borne by these different races and rows of roller. Therefore, for same loading condition, the diameter of this type of bearing can be reduced to compared with other single row bearings and thus the structure associated with it can be compactly assembled resulting in lower requirement of space. Since the offshore crane simultaneously faces axial, radial and overturning moment, this type of three row roller bearing is preferred in this case. This is the type of slewing bearing with load capacity very high.

2 Analysis Methods

For analysis of rolling bearings and its connecting bolt, there is several methods. Here the brief discussion of that methods will be reviewed. Following are the general methods for analysis.

-Experimental Methods

-Dynamic methods

-Numerical Analysis

-Finite element methods

This thesis will mainly deal with finite element methods for analyzing the connecting bolts and associated slewing ring. The other methods will be briefly reviewed.

2.1 Experimental Methods

2.1.1 Definition

One of the experimental method is **Orthogonal Design Method.** This method is mainly based on different factors which will affect the analysis result using orthogonal table. This method is faster, effective [4]

The orthogonal design methods mostly used for analysis are variance and intuitive analysis [5]. This method also can be divided depending on its index number into single index method and multi-index method.

2.1.2 Factors used in orthogonal method

The orthogonal methods first find the factors which may affect the analysis methods. For the bolt connections in slewing ring, the factors which will have effect on the analysis results includes the following but not limited to[6],[7],[8].

- the pretension in the bolt

- friction coefficient between contact surface for bolts and connecting parts

- the rigidity of bearing ring and bolts

- the bush height

- the installation height of ring

- methods for applying pretension in bolts etc

All this factors and other factors may have great influence on the performance of bolt connection and hence the slewing bearings.

2.1.3 Description and brief example of the methods[5]

The factors are considered as an independent variable during analysis. And each factor is divided into several levels. For example, here four factor is considered and divided into levels, and arranged in the following table

Factor name	Factor	Factors level			
		1	2	3	4
A	Pretention in bolt	60% of σ_s	70% of σ_s	80% of σ_s	90% of σ_s
B	Friction Coefficient	0.20	0.30	0.40	0.50
C	Rigidity of Bearing	500 MPa	600 Mpa	700 MPa	750 MPa
D	Rigidity of bolt	750 MPa	800 Mpa	850 Mpa	900 Mpa

Table 1: Factors and level in orthogonal design method

Where σ_s is the rigidity of bolts

Here with the considered four factor, they have been divided into four levels. Then the possible combination of factors with their level is found and for each combination, a test will be done with same boundary condition and environmental conditions. The combination is found using orthogonal matrix. Following is the example of such a orthogonal table. From each set of test, the stress in bolt is checked.

Test	A	B	C	D	Test	A	B	C	D
1	1	1	1	1	1	1	4	1	1
2	2	2	2	2	2	2	3	2	2
3	3	3	3	3	3	3	2	3	3
4	4	4	4	4	4	4	1	4	4
5	1	2	1	1	5	1	1	2	1
6	2	3	2	2	6	2	2	3	2
7	3	4	3	3	7	3	3	4	3
8	4	1	4	4	8	4	4	1	4
9	1	3	1	1	9	1	1	3	1
10	2	4	2	2	10	2	2	4	2
11	3	1	3	3	11	3	3	1	3
12	4	2	4	4	12	4	4	2	4

Table 2: Example of Orthogonal design table

The main two indicator in case bolt connection analysis is the maximum stress in bolt and alternating stress. From above test, these two indicator is checked and result is concluded.

2.2 Numerical Methods

The numerical method is based on the stiffness of different associated parts. The equivalent stiffness is for associated part is found then stiffness matrix is formed for the total system. This stiffness matrix is solved for results applying the associated boundary conditions. Here the details will not be discussed but a brief review.

The assumptions for numerical method are followings [3]

- The most loaded part of the ring is considered.
- Extremely rigid mounting
- Only the outer ring is modeled in this method.

Principle behind the numerical model is as follows. Left is the sketch for numerical model and right is portion usually used for finite element methods.

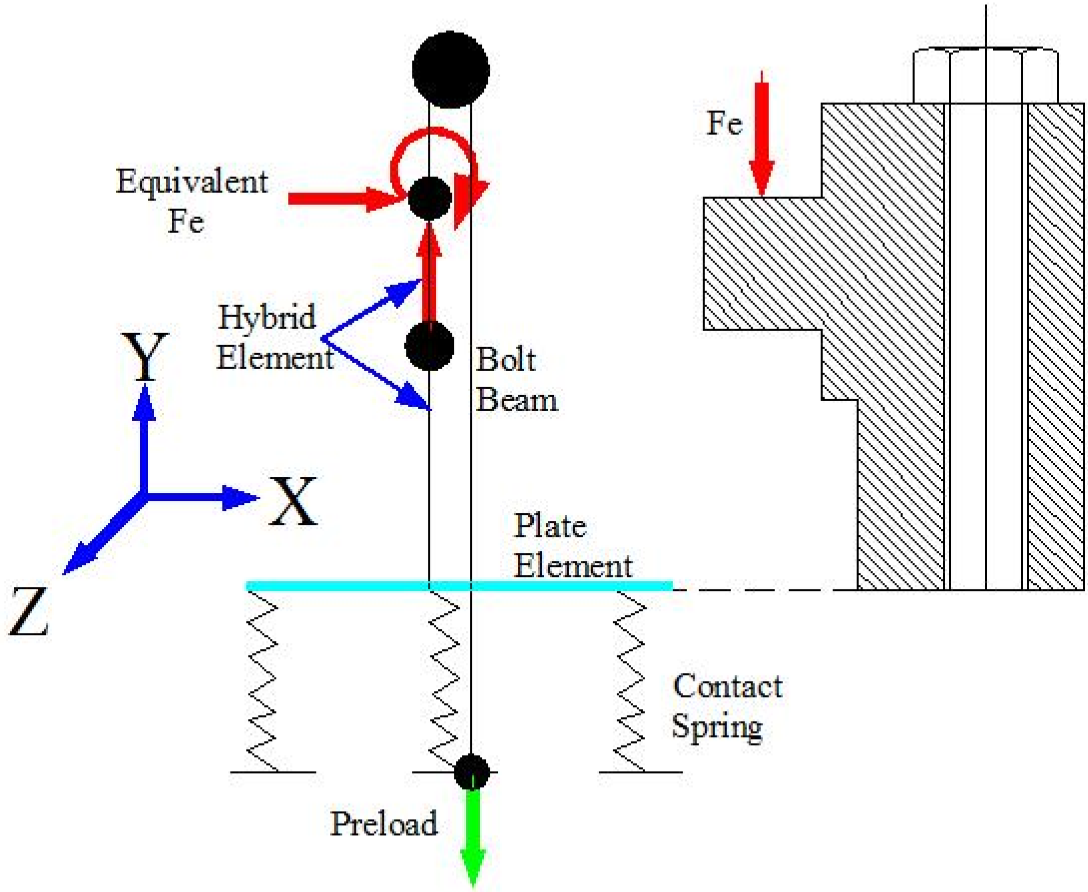


Figure 10: Principle for developing numerical model

The numerical model mainly consist of plate elements, Spring elements, Hybrid elements as shown in above.

Now the axial stiffness of the following part are found [3] and the is used in the analysis for the problem..

- Axial stiffness of the bearing sector
- Hybrid elements stiffness matrix
- Contact Stiffness
- Distribution of axial stiffness.

Finally the system stiffness matrix is formed as similarly for finite element method.

The calculation is done for the tensile force in the bolt and the bending moment in it. It is done based on the displacement in the bolt end and imposing the external force Fe.

To solve the numerical model for above mentioned problem, some computer program such as Fortran, C++ is used.

3 Limit States

3.1 Material Properties

The slewing ring is one of the important parts in the offshore crane structures. The crane performance is dependent on the slewing bearing performance. So the slewing bearing is made up with special consideration and design. These special considerations also requires to look at the material properties of the ring and the connected bolts.

In general the strength of the material is presented by the stress-strain curve. A typical stress-strain relationship is shown in below.

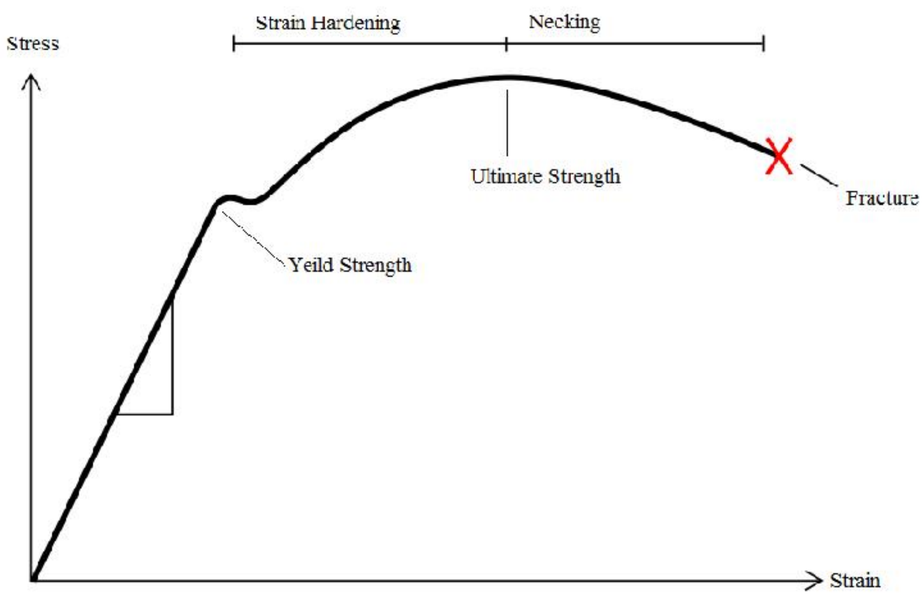


Figure 11: Typical Stress-strain relationship

The material of the slewing bearing elements have high strength. This strength is achieved by special treatment of the steel. Also a very special composition for ring and roller material is followed to achieved this high strength.

Normally the ring is case hardened steel - 50Mn when there is no special requirements. If special required is followed, the ring material is 42CrMo,5CrMnMo[9].

The typical properties and composition of the material for three-row roller slewing bearing ring is given below. This was collected from the technical data sheet for Rothe Erde Larrge Diameter Slewing Bearing [10]. For details composition, has been attached in the appendix.

Inner/Outer ring				
Yeild Point	Tensile Strength	Elongation	Reduction of Area	Impact value
710 N/mm^2	850 N/mm^2	17 %	57 %	42/47

Table 3: Material Properties of Slewing bearing rings

The slewing bearing performance not only depends on its own material properties, it also depends on the fasteners used. For high performance, high duty bolt is required. This bolt is also of special treatment of steel and it has more tensile strength than the slewing ring itself. The bolts used for slewing ring is made of material 34CrNiMo6. The typical properties [11] for this material is as follows.

Fasteners Properties				
Yeild Point	Tensile Strength	Elongation	Hardness	Impact value
940 N/mm^2	1000 N/mm^2	14 %	HB 304	42 J

Table 4: Properties of fasteners used for Slewing ring

The typical size of the bolt ranges from M34 to M49, used in slewing bearing of offshore crane. The strength grade is 10.9.

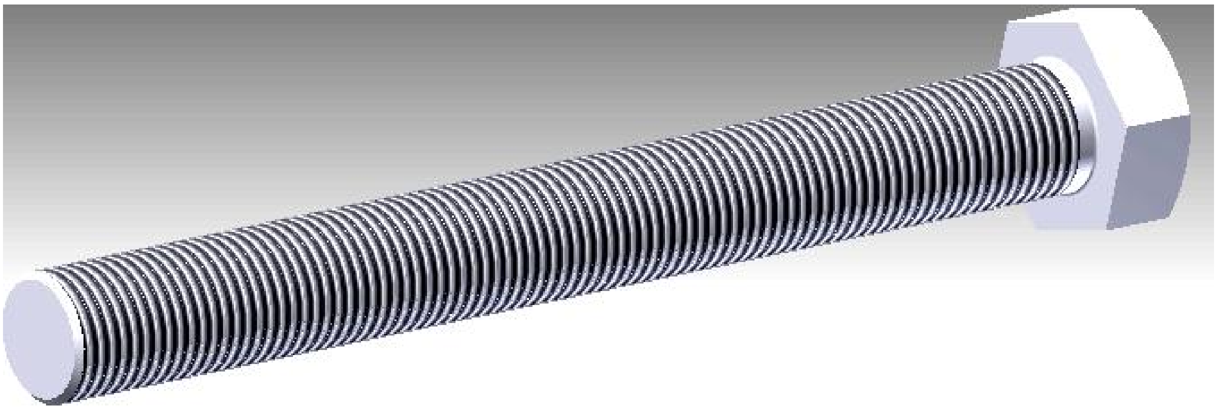


Figure 12: Typical M39 high duty bolt

3.2 Bolt Pretension

3.2.1 Bolt Preload

A critical bolted joint requires lots of consideration. It requires to design the no of bolt to be used, their size, configuration, geometry, placement. Also all the loads that can act on the bolt. One of the major considerations for bolted joint is its preload. How the bolt was made and well designed is not the matter itself, it can't produce the joint sufficient strong and reliable until the preload in the bolt is sufficient.

When there will be a axial tension force in the bolt before applying the external working load, the bolt is called having pretension and the bolted joint is called pre-stressed joint [12].

3.2.2 Minimum requirements for preload

The NASA guideline for bolted joints on space shuttle is as follows [13]

A preloaded joint must meet, as a minimum, the following three basic requirements

1. *The bolt must have adequate strength.*
2. *The joint must demonstrate a separation factor of safety at limit load. This generally means the joint must not separate at the maximum load to be applied to the joint.*
3. *The bolt must have adequate fracture and fatigue life.*

The criteria for checking bolt strength and joint strength differs in the terms of bolt preload. The bolt strength is checked when the maximum preload and maximum external load is applied and at the same time, the joint strength is checked with minimum preload and maximum external applied load[13].

So for a bolted joint, the maximum and minimum preload should be determined.

3.2.3 Preload Measuring Method

There is few methods for measuring the preload in the bolt. These methods are based on experiments and standards.

When the preload is measured by measuring the applied torque in the bolt without reaching it to initial torque yield, the following formula [13]can be used to measure maximum and minimum preload using typical co-efficient.

$$PLD_{max} = (1+\Gamma)T_{max}/[R_t\,(\tan\alpha+\mu_t^{typ/\cos\beta}) + R_e\mu_b^{typ}]+P_{thr}^{pos}$$

$$PLDmin = (1-\Gamma)(Tmin - Tp)/[Rt\,(\tan\alpha+\mu ttyp/\cos\beta) + Re\mu btyp]+Pthrneg- Ploss$$

Where

PLD_{max} = Maximum Preload

PLD_{min}= Minimum Preload

Γ = Preload uncertainties

R_t = Effective radius of thread forces

α = Thread lead angle

β = Thread half angle

T_{max} = Maximum Torque

T_{min} = MinimumTorque

T_p = Prevailing Torque

μ_t^{typ} = Friction of coefficient external to internal thread

μ_b^{typ} = Friction of coefficient nut to joint

P_{thr} = Thermal load postive and negetive

3.2.4 Accuracy of bolt preload tools

The method by which the preload is applied in the bolt does not provide accurate pretension. The estimate of accuracy varies from tools to tools used for preload. Below is a list [14]of accuracy of bolt preload based on application method.

Methods of application	Accuracy percentage
Torque Wrench [No lubrication in bolt]	± 35%
Torque Wrench [Cad-plated bolt]	± 30%
Torque Wrench [Lubricated bolt]	± 25%
Preload Indicating Washer	± 10%
Strain Gages	± 1%
Computer Controlled Wrench (Below Yield)	± 15%
Computer Controlled Wrench (Yield Sensing)	± 8%
Bolt Elongation	± 5%
Ultrasonic Sensing	± 5%

Table 5: Estimate of accuracy for pre-tensioning tools

3.2.5 Static Capacity of Slewing bearing

Static capacity of the slewing bearing varies depending upon it application, size, life etc. The static load is usually found using static limiting load curve. For each bearing there is a limiting load curve and this bearing should be used for the loads or below this loads in the curve. This curve is based on a combination of tilting moment and axial load. If tilting moment is higher then the corresponding axial load will be lower.

The equations used for determining the static capacity curve is given below and few example of static curve is attached in the appendix. For safety reason, the calculated load must be operated by a safety factor and the determined value must be below the static limiting load curve for the selected bearing

The loads in the bearing including the radial load are

F_A = Axial load

F_R = Radial load

M_T = Tilting moment

To apply these loads in a slewing bearing, the loads to be selected in the static limiting load curve will be found out by the following equations [15]. Anyone of the two combination can be used.

Load Combination 1.

$$F'_A = (F_A + 5.046.F_R).f_{stat}$$

$$M'_K = M_K.f_{stat}$$

Load Combination 2.

$$F'_A = (1.225F_A + 2.676.F_R).f_{stat}$$

$$M'_K = 1.225M_K.f_{stat}$$

Few example of limiting loads for different slewing bearing has been shown in the table below[15].

Bearing Type	Moments Range	Axial load range
Single Row Bearing	0 - 200 kNm	0 - 680 kN
Double Row Bearing	0 - 1200 kNm	0 - 3000 kN
Cross roller bearing	0 - 4000 kNm	0 - 5700 kN
Three row roller bearing	0 - 5200 kNm	0 - 8000 kN

Table 6: Statatic load capacity for bearings

The ranges can be above the value mentioned here depending on the size and type of bearing. The above is just for some typical bearing.

4 Bolted joint and preload Mechanism

4.1 Bolted joint

In very general, a bolted joint is made up of a bolt, externally threaded element, and a nut, internally threaded element, and at least two different parts which are separable individually[6],[16].

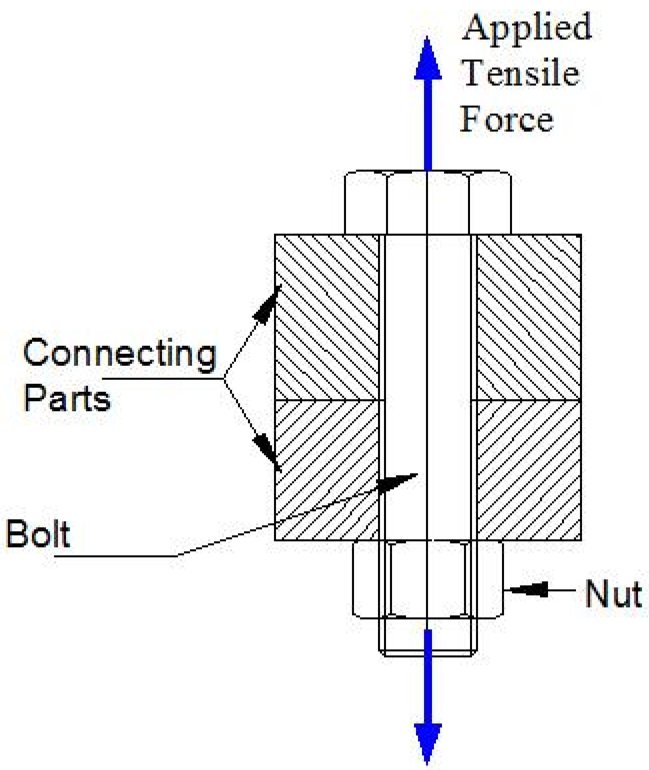


Figure 13: Bolted joint

Now the strength of this bolted joint does not depend only on the fact that how well the bolt was designed and manufactured but also on the facts that understanding the way the threaded bolt sustain load and the great influence of the tightening torque, procedure applied. While a strongly tightened joint can carry full load, a loose bolted joint can fail within few seconds before going in operation.

4.2 Bolted joint mechanism

To illustrate the bolted joint mechanism, the joint diagram is used. It shows the deflection characteristics of the bolt and its connecting parts together in a diagram. It illustrates the how the bolt carry the applied external force and why it does not carry all the applied force.

The basic joint diagram, when a joint is clamped together by tightening the nut is as follows.

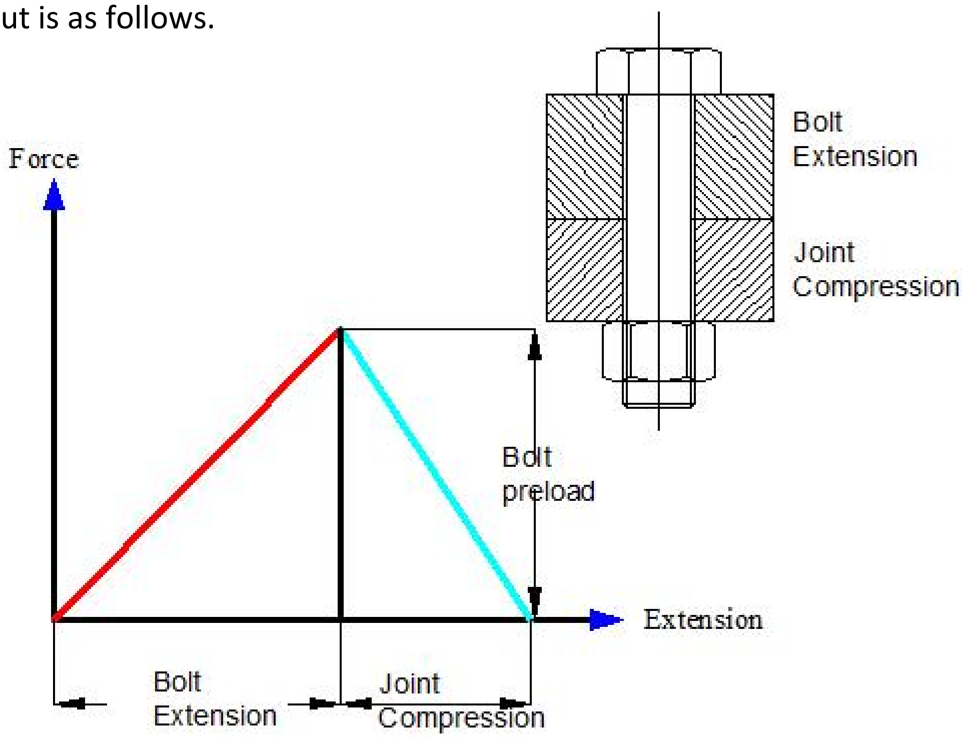


Figure 14: Joint diagram with preload concept

When the nut is tightened against the joint. Since the bolt is extended, the internal force in the bolt will resist this extension and a bolt preload is generated. The result of the preload is the clamp force that causes the joint compression.

4.3 Effects of External forces

When external tensile or compressive force is applied in the joint, the bolt force will increase or decrease resulting in decrease or increase in joint forces respectively. The external force applied will contribute for both in the bolt force and connected parts force and the joint force will change. How the force will changes has been shown in the following diagrams.

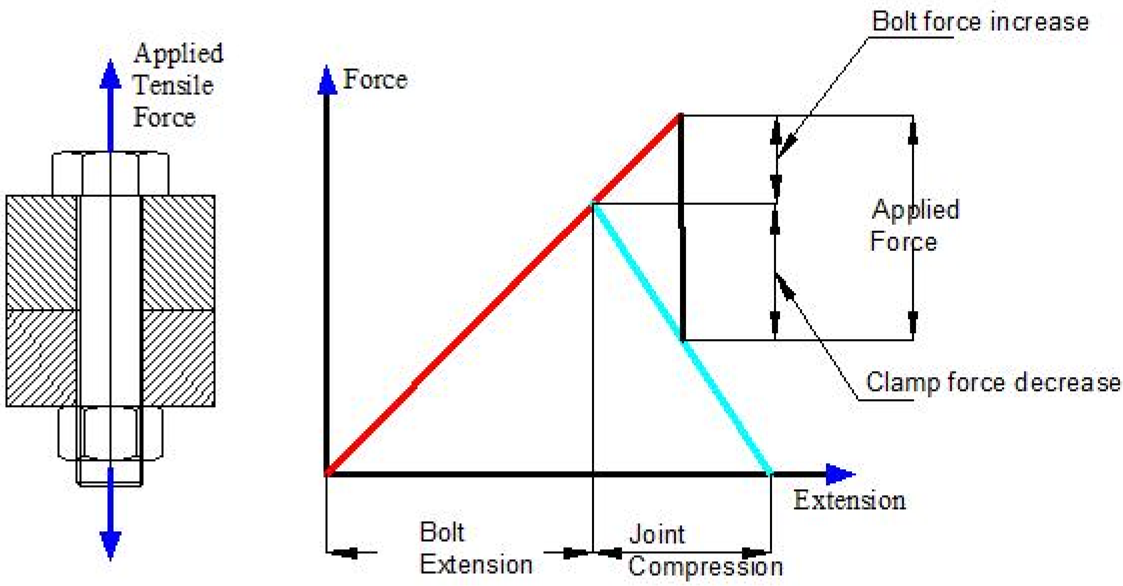


Figure 15: Joint diagram with external tensile force effects

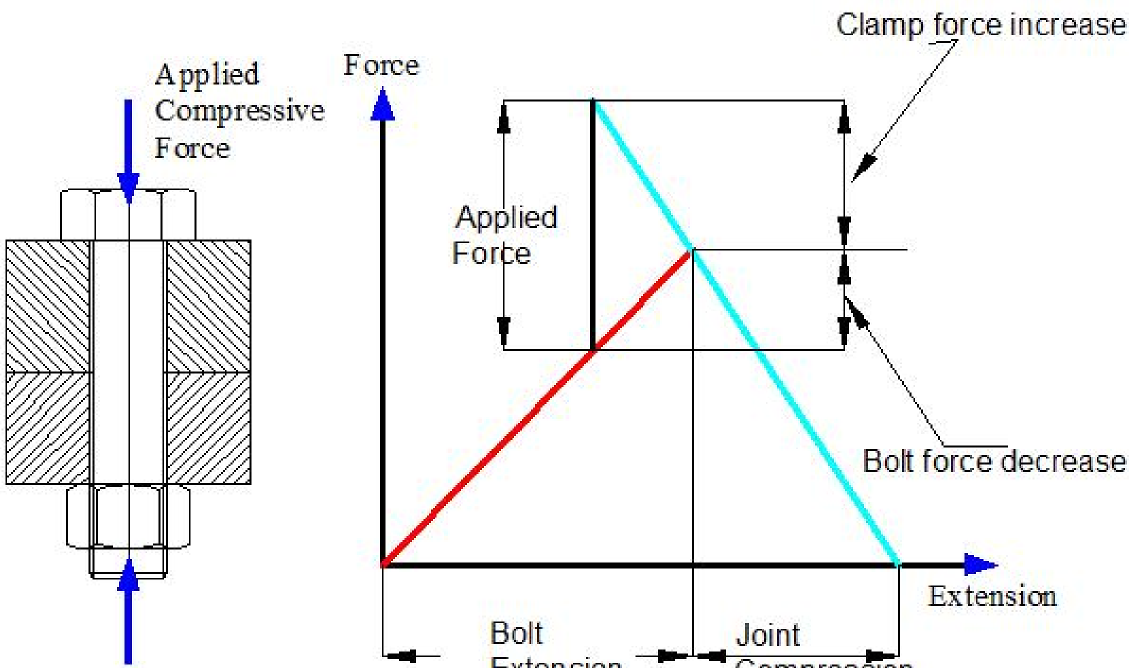


Figure 16: Joint diagram with external compressive force effects

4.4 Effect of Large forces

If the applied force in the joint is large enough and it increases the bolt forces taking the bolt near its yield point or beyond this, the consequences will be a gap in the joint and it has been illustrated with the following diagram as shown. In such cases when bolt forces is equal to its yield point, the join may fail.

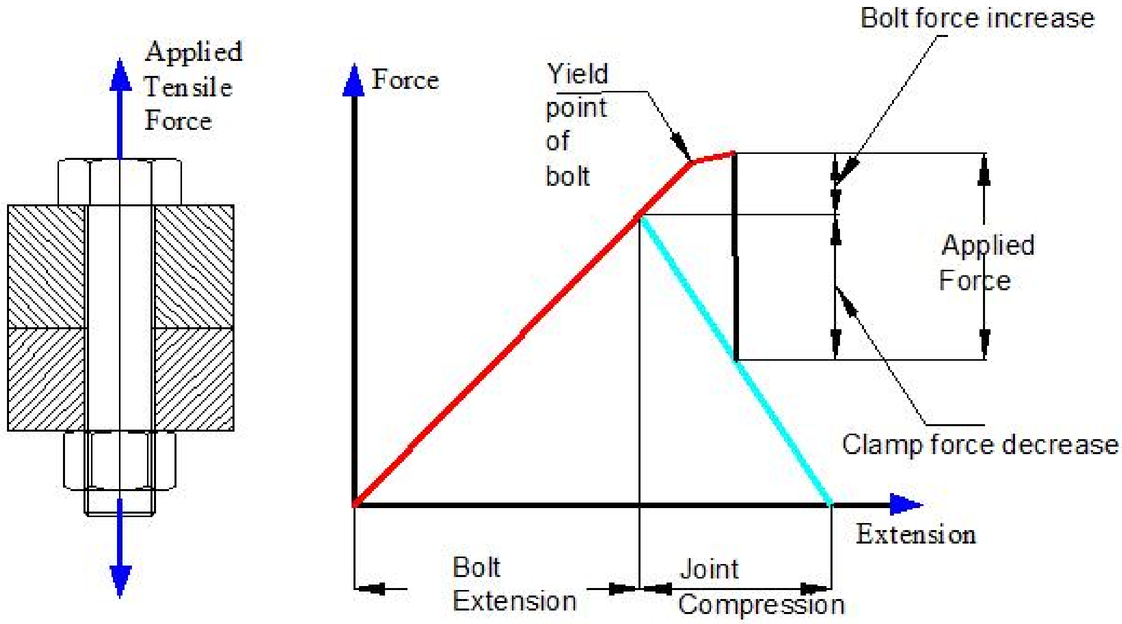


Figure 17: Effect of large tensile forces

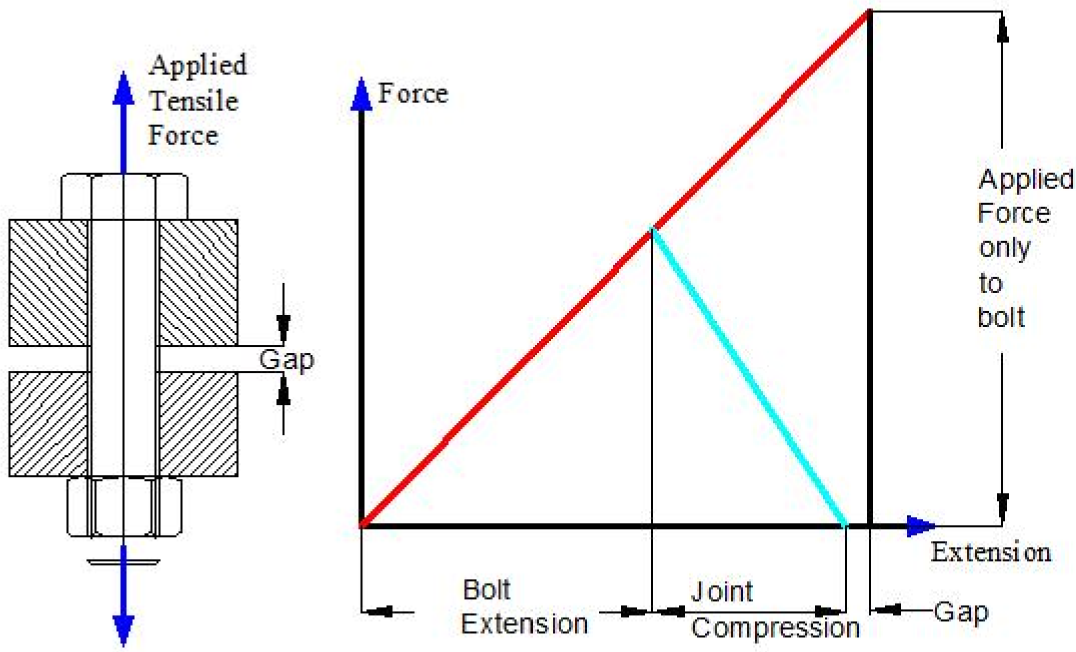


Figure 18: Effect of large forces beyond yeild point

Anymore increase in the applied force beyond the bolt yield point will continuously result to decrease in the clamp force and consequently the clamp force will be zero and further forces will result a gap between the connecting parts. In this case, all the force will be carried out by only bolt. The details has been shown in the following diagram.

4.5 Effect of Tightening method

When the joint is tightened, the local pressure in the contact areas of bolt thread, area under bolt head and nut will increase. Due to this local pressure, local plastic deformation causes. This plastic deformation will also affect the joint and the bolt preload. During this process the embedding amount can be shown using following diagram.

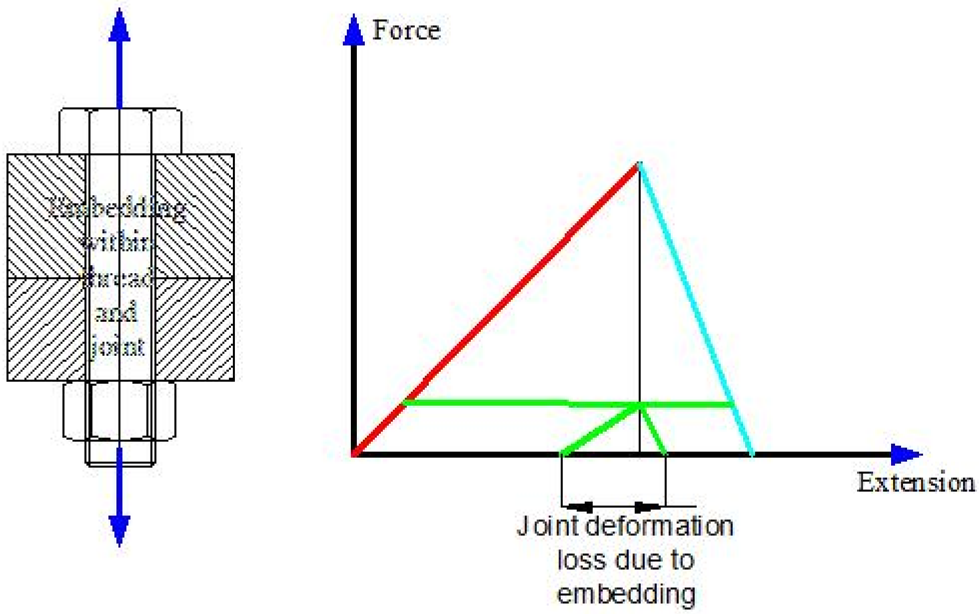


Figure 19: Effect of embedding

There is also a great effect on the bolted joint and the bolt preload from the tightening method used during installation. In the case of slewing bearing, all the bolts are in same size. When several bolts are with same size is tightened with same method, there will be variation in the bolt preload. The effect of tightening method can be shown with following diagram.

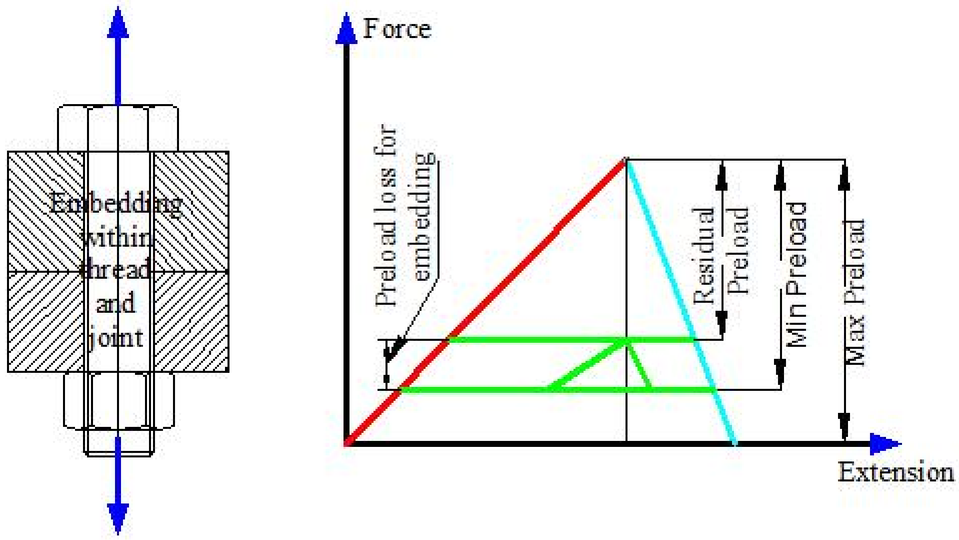


Figure 20: Effect of tightening method

4.6 Joint diagram for bolted joint in slewing ring

The joint diagram for the bolted joint in the slewing ring has been shown in the following figure. Also the illustration has been given in below[12].

In the above figure, the definition of the symbols is as follows.

O_b represents the point where tension and compress in the bolt is zero

O_m represents the pressure and compression between bearing ring and connecting part is zero at this point

O_e represents , at this point , bolt preload F_0 is achieved.

ΔF represents that the increase in the pull of bolt when the external force F is applied.

$\lambda_m - \lambda'_m$ shows the extension of the bolt for the pull increase ΔF

F_1 is the compressive force in the connecting parts due to pull increase ΔF

F_2 is the total tension in the bolt and is expressed as $F_2 = F_0 + \Delta F$

Hence the bolt tension will change from F_0 to F_2 for the work load changes from 0 to F

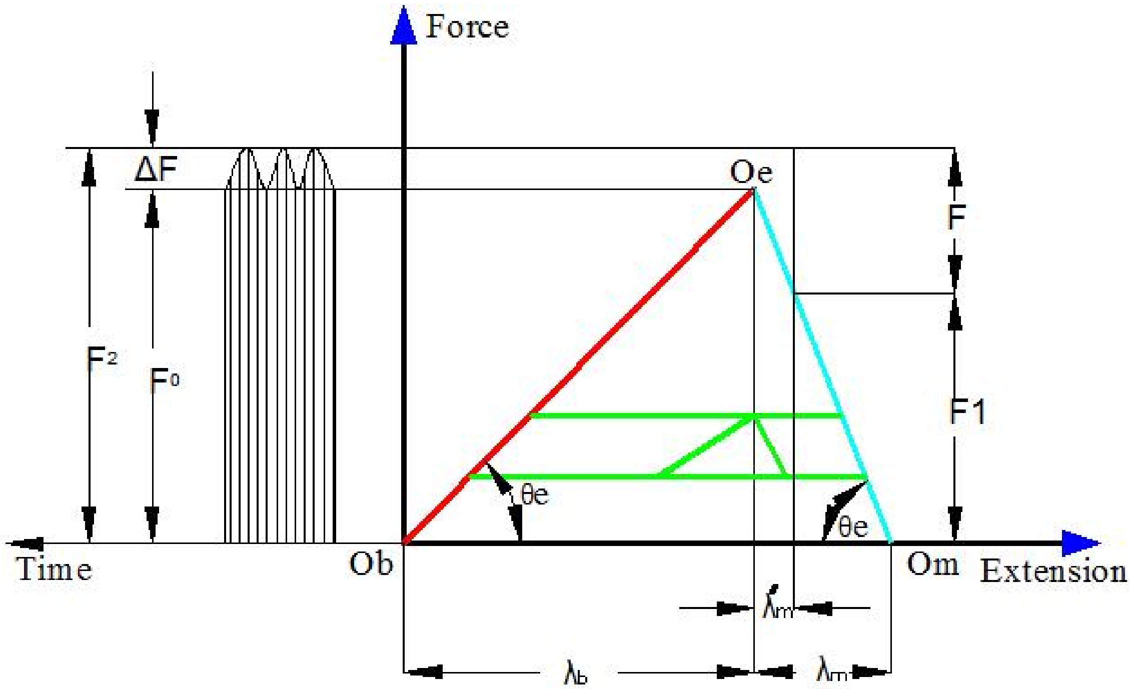


Figure 21: Joint diagram for slewring bolted joint

5 Slew bearing assembly

5.1 Bolt load for slewing ring

In the slewing ring, there is no direct load on the bolt. The load on the bolt come from the loads on the structure with which the slewing ring is attached. What type of load and how it will work on slewing ring or bolt depend on the structure type or machine where the ring is used. The slewing ring for crane mainly bear an overturning moment and a vertical force. These forces acts in the center or around the center of the ring, as shown in the figure, i.e the axis of the connecting bolt for ring and the axis of these forces is not in the same line, they are eccentric. Except these two forces, there is sometime some radial forces in the ring. All this forces will have a great impact on the bolt together with the impact from bolt pretension force. In the following, a description of this forces and how it will affect the bolt load will be discussed.

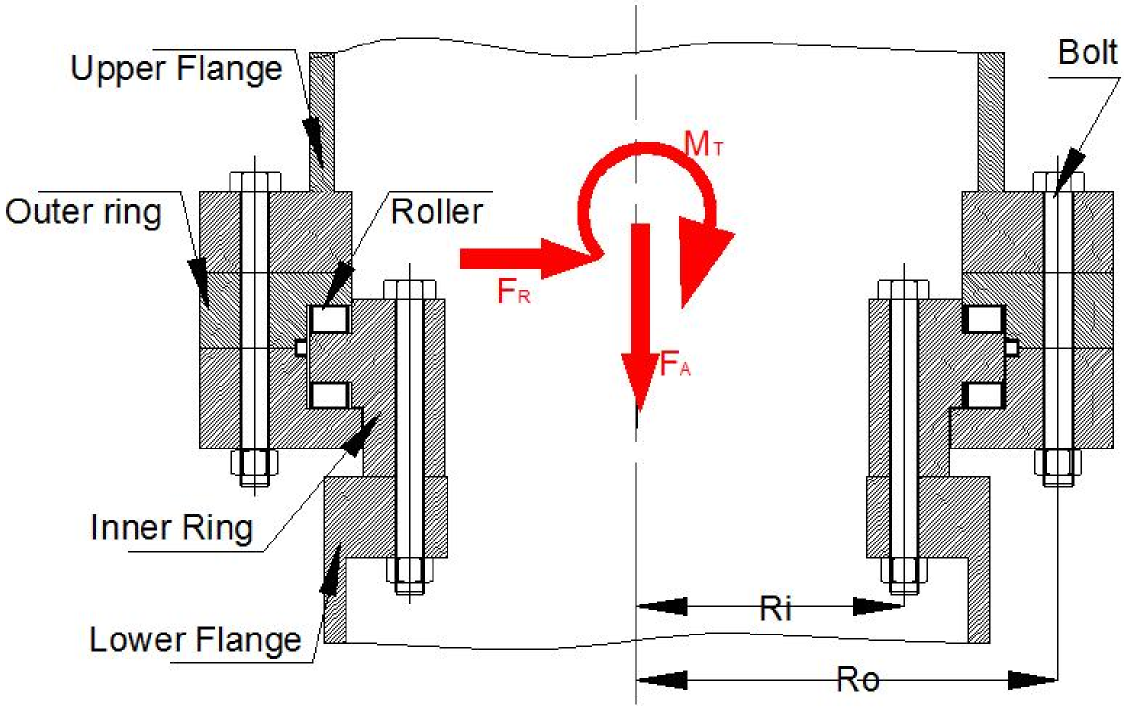


Figure 22: Slewing bearing

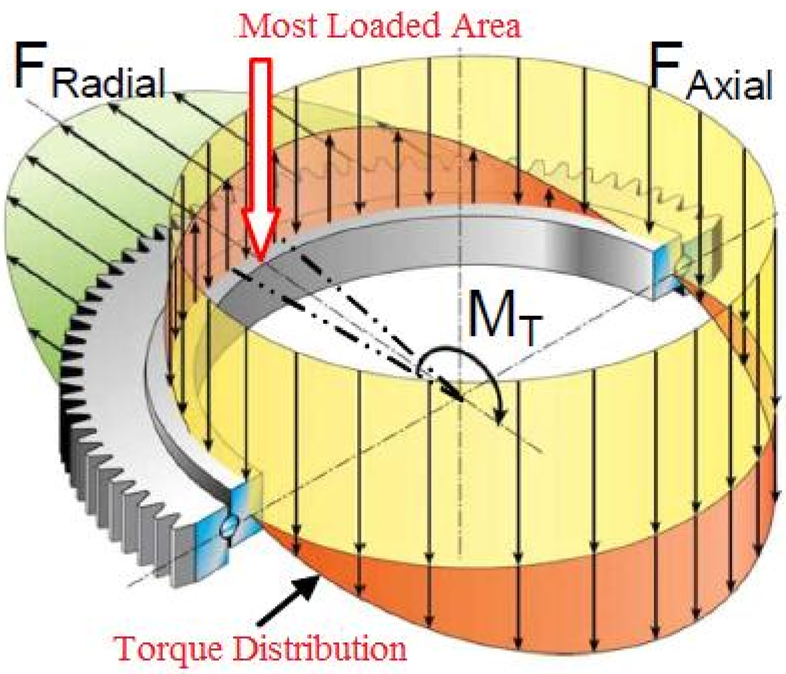


Figure 23: Graphical view of loads on slewing ring[17]

Now the pretension in the bolt is defined as if there is an axial tension force in the bolt stud before applying any kind of external working loads. Let's suppose that

F_M = The pretension force in the bolt

F_A = The external applied force

If the external working load F_A is applied in the pre-stressed bolt in the form of tension force, the tension force in the pre-stressed bolt increases compared to only assembly preload. On the other hand, if the external working load is applied in compressive manner, the tension force will decrease in the pre-stressed bolt compared to only assembly preload. Let's call that

F_S = The force in the bolt.

Then the relationship between the bolt force F_S and the working load F_A , when it acts directly on the on the bolt axis, can be expressed as following.

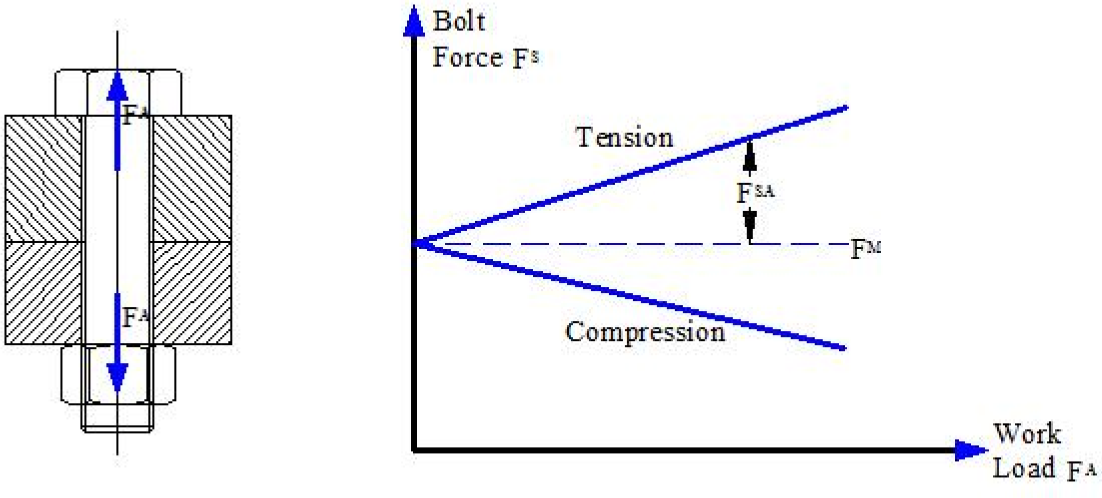


Figure 24: Bolt force and work load relationship

Now let's calculate the additional force in the stud due to application of this external force. Here it is assumed that the relationship between the applied force and bolt force is linear [18]. Let's suppose that

F_{SA} = The additional force in the bolt stud

Then $F_{SA} = \phi . F_A$

$$= n.\frac{\delta_p}{\delta_p+\delta_s}.\ F_A \qquad (1)$$

Where ϕ = Relative elasticity

n = Load introduction factor

δ_p = Stiffness of the connecting part

δ_s = Stiffness of the connecting bolt

Applying all this factors and known values, the bolt additional force F_{SA} can be determined and hence the bolt force F_S

$$F_S = F_M \pm F_{SA} \qquad (2)$$

The sign depends on whether the additional bolt force is tensile or compressive.

Now the fact is that the bolt stiffness can easily be determined using well established analytical methods [18]. Also using some numerical analysis, the bolt stiffness can be calculated taking into account the various geometrical parameters such as bolt thread, it's heat and nut, material properties and it's frictional properties [6]. But the stiffness of the connecting part or structure is not so easy to determine, especially when the structure have more complex geometry. The methods to determine member stiffness mainly uses effective volume of the structure which is subjected to compressive or tensile stress. And these method is verified using finite element method [3].

However it is very difficult to apply this quantitative method for the bolt strength calculation in slewing ring. The other reasons are also described in the following. [7]

1. This analytical model is mainly suitable for single bolted joint where the center of the clamping position and the center of applied external force should coincide. Sometime only small eccentricity is allowed. But in case of slewing ring, the bolt axis and the applied force has far eccentricity and the complex cross section o the slewing ring will produce complex deformation.

2. Equation (1) uses load introduction factor n. For some very simple geometrical configuration and loading condition, this load factor is available. But for the complex geometry and loading condition including the example of slewing ring, there is no suitable load introduction factor. As a result, the outcome from this method will have significant error in determination of bolt load for slewing ring.

3. When there is eccentricity among clamping position and applied working load, partial opening happens in the bolted joint in tensile side. The above formula is does not consider any opening in the pre-stressed bolted joint. This partial opening is one of the reason or non-linear dependence between working load and bolt load.

4. In the case of slewing ring, there is over turning moment and for this the bolt can be loaded in a different way. So the determination of working load for slewing ring require extra attention. The above formula can't help to determine the working load F_A for the slewing ring.

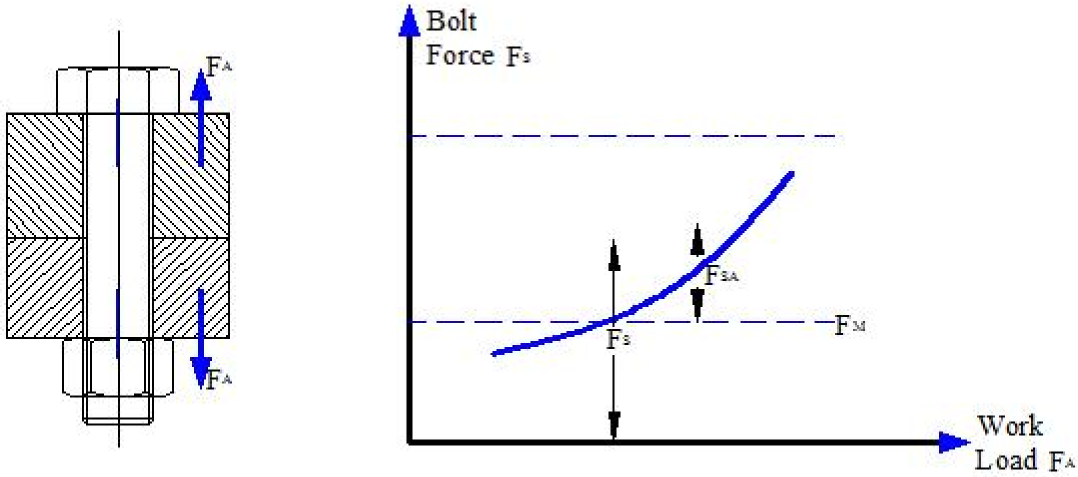


Figure 25: Partial opening in the slewing ring

So to find a possible suitable solution which can be applied for pre-stressed bolted connection in such type of slewing ring, a numerical method was developed. This method mainly uses a particular finite element which is a combination of several simple finite elements and allow the simulation of bearing and bolt contacts and bending in the bolt. It is also possible to take into account the partial opening ,the eccentricity effect using this these finite element.

5.2 Calculation Model for work load in the bolt in slewing ring

Now the entire problem need to be modeled to calculate the work load. There two basic ways to model.

First method is to model the entire ring with it's connecting superstructure and all other belongings. Where the geometric imperfections of the ring need to be considered this method can be applied. Also when the substructure is complex and does not have constant elasticity i.e the elasticity varies along the circumference of the ring, this method is beneficial. This method produce more accurate results for the working load in the bolt and uses the elasticity of belonging structures in the direction of bolt axis [19], [20].

Second method is , when the bolts are equally spaced around the circumference of the ring, the belonging support can be considered as rigid and has no hard-spot, modeling of most loaded section of the ring. The main disadvantage of this method is, it overestimates the loading in most loaded section because it can't take into consideration the redistribution of the stress when stressed center deviate from bolt axis [21]. When this method is used, the following formula is used for determination of working load $F_A$on the analyzed portion of the bolted joint[6].

$$F_E = \frac{1}{\cos\beta}\left(\frac{F_A}{Z} + \mathcal{E}\frac{2M_T}{\pi R} sin\frac{\pi}{Z}\right) \qquad (3)$$

Where β = Angle between the working load and axis of bearing

Z = Number of equally spaced bolts in the ring circumference

R = Pitch circle radius of load introduction

M_T = Overturning moment

$\mathcal{E}$ = ±1 depending on the direction of working load

5.3 Finite element model of the ring

5.3.1 Assumptions

The fundamental assumptions for finite element modeling has been described below[22].

1. All the components of bolt were not modeled explicitly in the finite element model. For example the nuts, washers was not modeled.
2. Material properties for one single part were assumed to be homogenous neglecting the HAZ effect.

3. Modeling was done using two different mesh size. Fine mesh near the joint and analysis portion and rest is coarse mesh.

The main advantage during the modeling of the slew ring is it's geometric symmetry and equally spaced bolts around it's circumference. Due to this geometric symmetry, only the most stressed portion of the ring bolt joint has been used in the model. The model was built in Autodesk Inventor modeling software and analyzed in the ANSYS Workbench Software. The model used for analysis includes all the components of slew ring assembly which will have effect on results. The components include inner ring, outer ring, bolt head, stud and flanges.

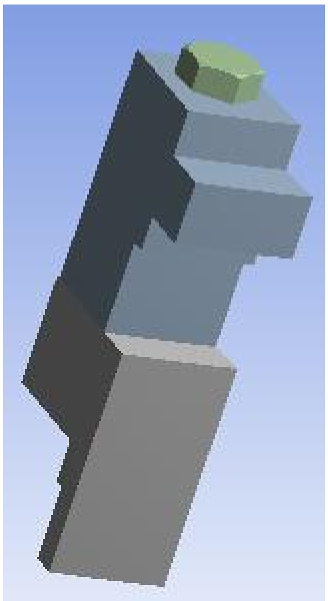


Figure 26: Components in the model

Now depending on the desired result and its accuracy, the modeling of bolt in finite element software including ANSYS can be done in various way. It can be modeled as an one dimensional beam element, as a solid body or in combination of both. Different research paper [23], [24] has shown that if the bolt is modeled as a solid body, an acceptable result can be gained without detail modeling the bolt thread, nut and bolt head details. So here the bolt has been modeled as a solid body including its head, stud and nut.

Another advantage of the finite element software is its build in options for applying bolt preload in the model. Using this options, automatic bolt pretension simulation can be done and the subsequent consequence of externally applied load can be realistically simulated. The working load was applied as a uniform pressure on the race way of the slewing ring under different angle.

During the analysis, to get precise result, all the normal and radial contacts among components were considered and coefficient of traction was introduced. The following contacts were considered

- Contacts between bolt head and ring
- ring and flange (To take into the effect of partial opening)
- nut and the flange
- bolt stud and ring (Radial contacts)

In ANSYS analysis, linear elastic material was used and the following properties for different component has been applied. These properties were collected from practical slew ring assembly used in the crane for NOV AS.

The boundary condition used in the analysis assume that the bottom flange has fixed support. And for meshing in the model , the element size is approximately 1 mm and is type solid element.

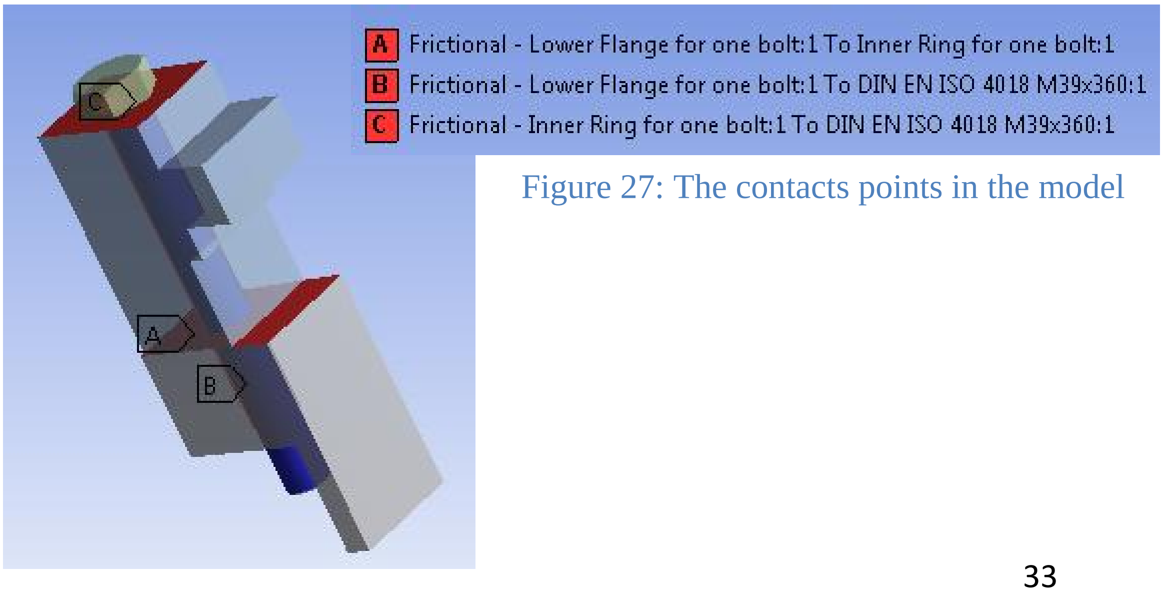


Figure 27: The contacts points in the model

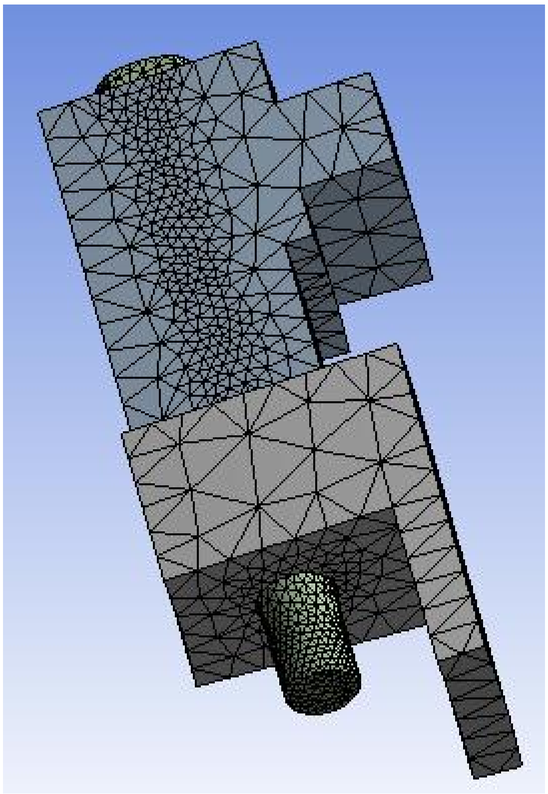


Figure 28: The mesh in the model

Notes: There was two different size mesh in the model, the bolt and its near region has fine mesh while the rest has coarse model.

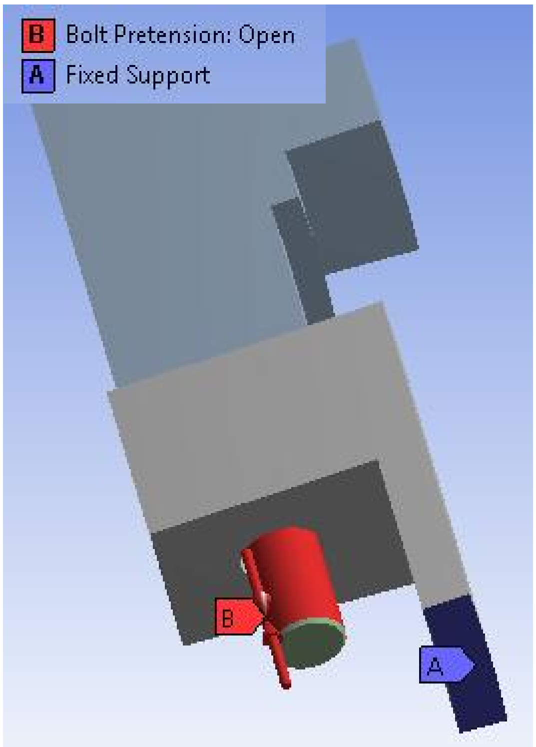


Figure 29: The boundary condition.

6 Practical Example:

A practical slewing bearing was analyzed according to the finite element model as described above. This slewing ring was used one of the offshore crane made by NOV AS. The slewing bearing was a three-row roller bearing, both the outer and inner ring and its connecting bolts were taken into considerations. The geometrical properties is as follows.

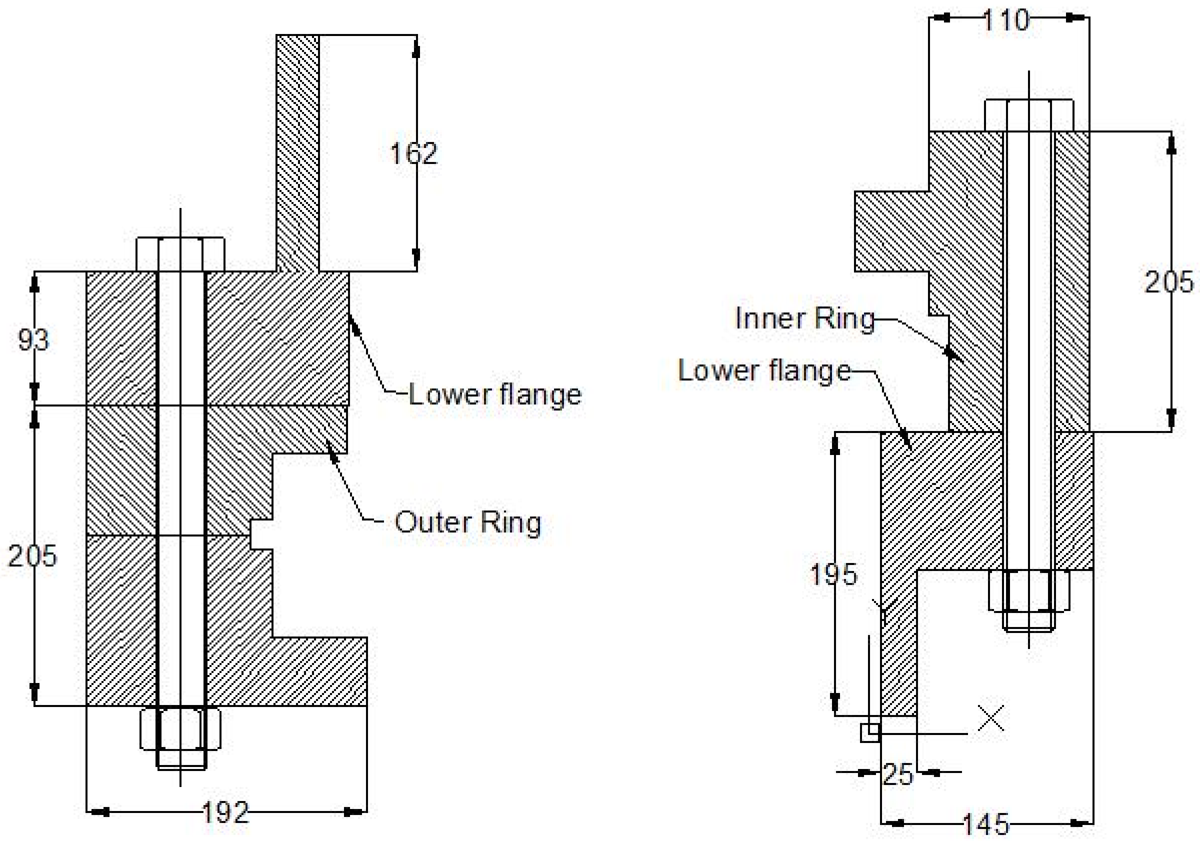


Figure 30: Geometrical properties for the slewing ring used (dimension is mm)

Parameter	Outer ring	Inner ring
Diameter of bolt hole	42mm	42 mm
Diameter of bolt circle	2548mm	2263mm
No of bolts	96	96
Bolt length	360mm	360 mm

Table 7: Geometrical properties of bearing ring

The material properties for the bearing elements and the bolts is as follows

Name	Yeild Strength	Ultimate Strength	Young Modulus
Inner Ring	710 Mpa	850 Mpa	207 Gpa
Outer Ring	710 Mpa	850 Mpa	207 Gpa
Bolt	940 Mpa	1000 Mpa	207 Gpa
Flange	320 Mpa	460 Mpa	207 Gpa

Table 8: Material properties for the bearing elements

The external applied load on the bolt was determined from the above described formula and has been shown in below.

The overturning moment used for the calculation is M_T = 3000 kNm, the axial force is 1500 kN. These values are taken based on the critical value for this type of bearing from the manufacturers catalog[1].

Now the corresponding bolted force for overturning moment is

$$= \left(\frac{2M_T}{\pi R} sin\frac{\pi}{Z}\right) = \frac{2x3000}{3.1416x1.22} sin\frac{180}{96} = 51.22 \text{ kN}$$

The corresponding force for axial force is

$$= \frac{F_A}{Z} = \frac{1500}{96} = 15.625 \text{ kN}$$

Then the total force is equal to

= 51.22 + 15.62 = 66.84 kN

Here the analysis is mainly done in three steps

- Applying only the preload in the bolts
- Applying the external load in the tensile direction together with preload in bolts
- Applying the external load in the compressive direction together with preload

Now by applying this external force together with the bolt pretension force, the stress in the bolt along its length will be observed both for inner and outer ring. The stress observation was made in three ways.

1. Applying only the pretension
2. Applying the pretension together with external force in extension direction
3. Applying the pretension together with external force in the compression direction.

The result found has been show here in the following graph

6.1 Outer Ring Bolt

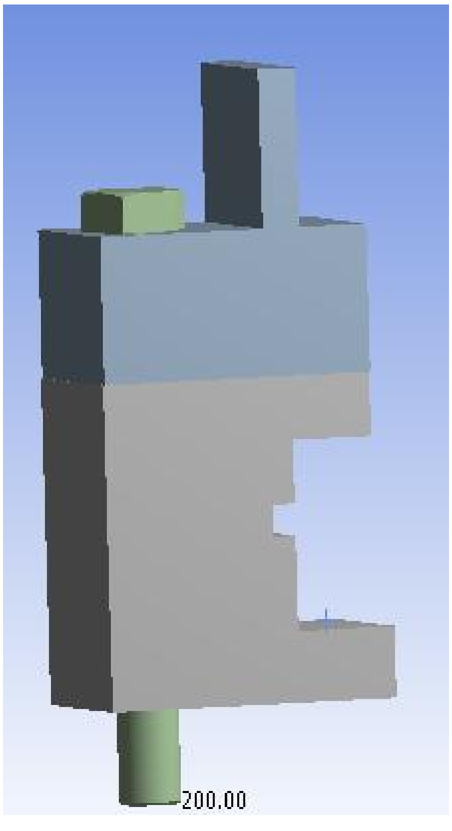


Figure 31: Outer ring model

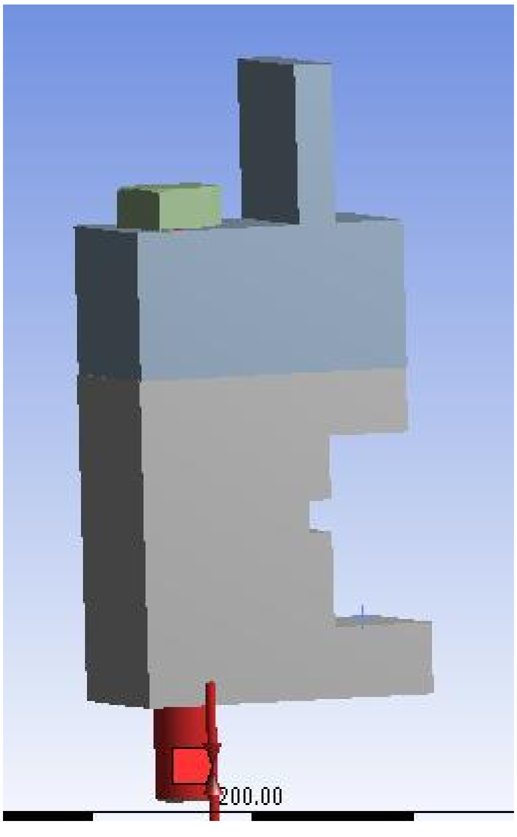


Figure 32: Outer bolt with pretension

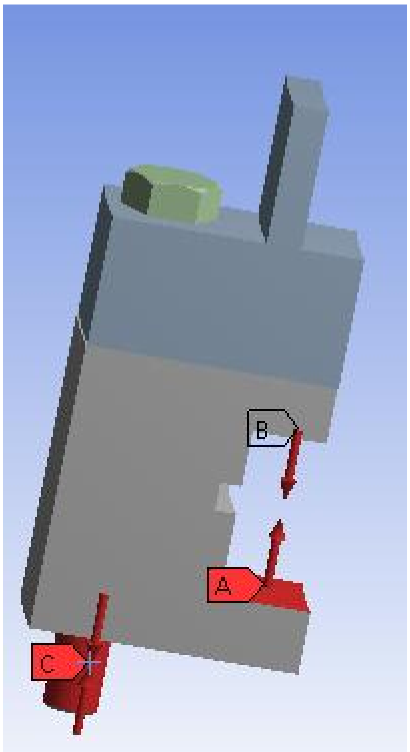


Figure 34: Outer bolt with pretension and compressive load

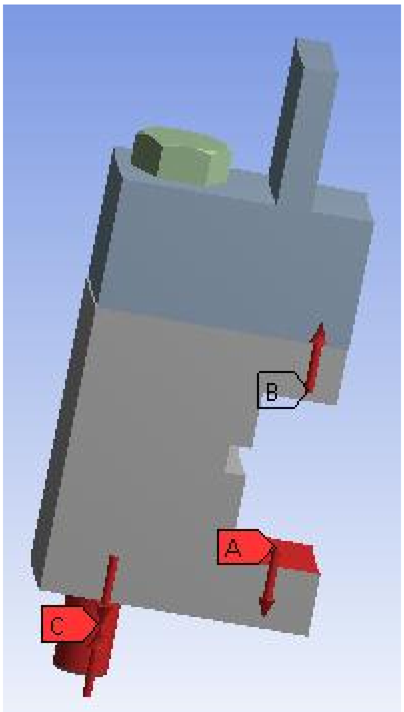


Figure 33: Outer bolt with pretension and tensile load

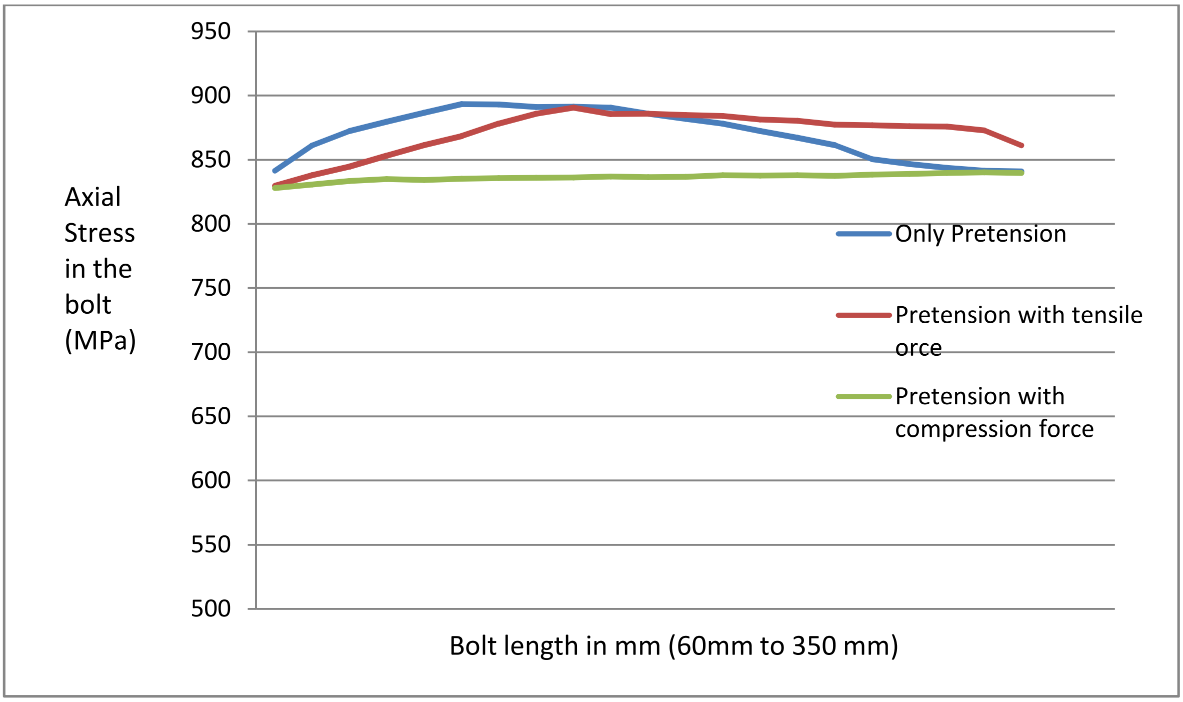


Figure 35: Stress in the outer bolt with 90% pretension and external force

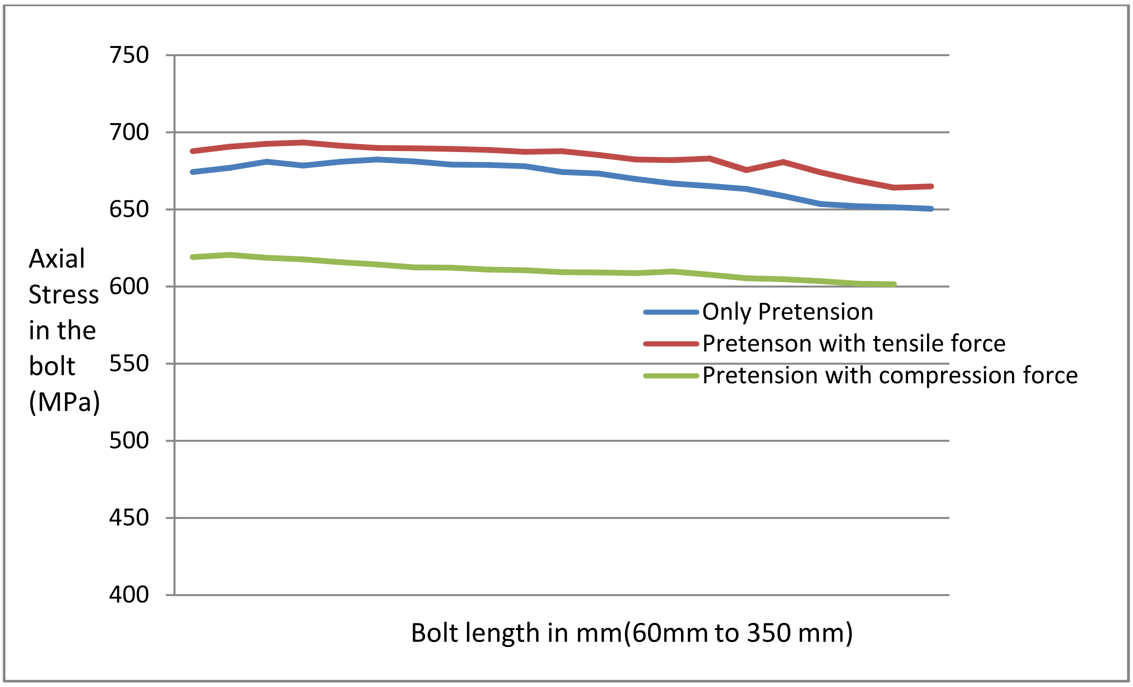


Figure 36: Stress in the outer bolt with 70% pretension and external force

6.2 Inner Ring Bolt

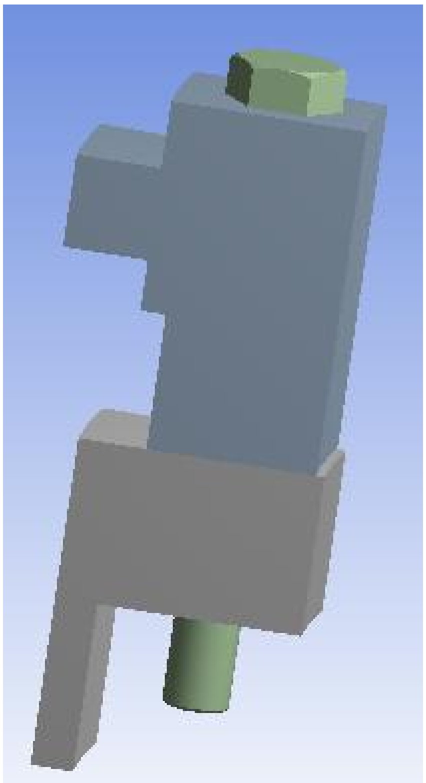


Figure 38: Inner ring model

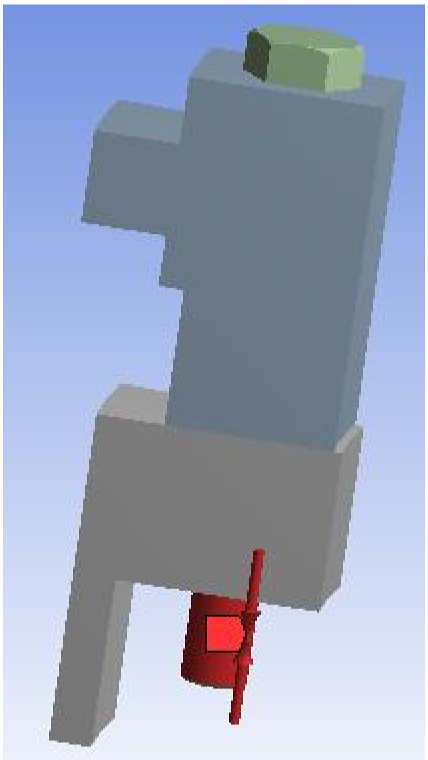


Figure 37: Pretension in inner bolt

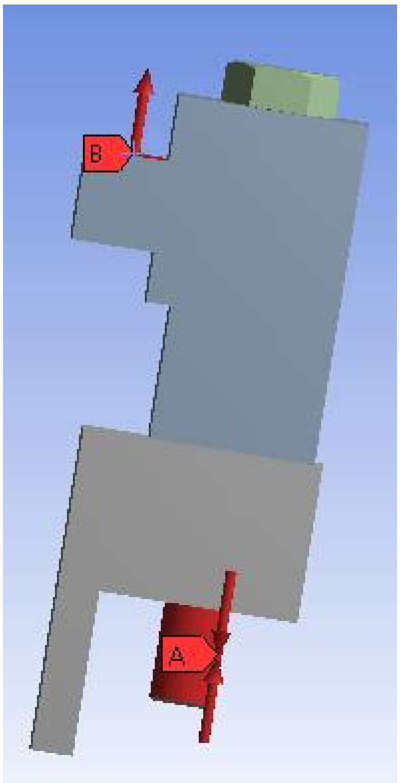


Figure 39: Inner bolt with pretension and tensile load

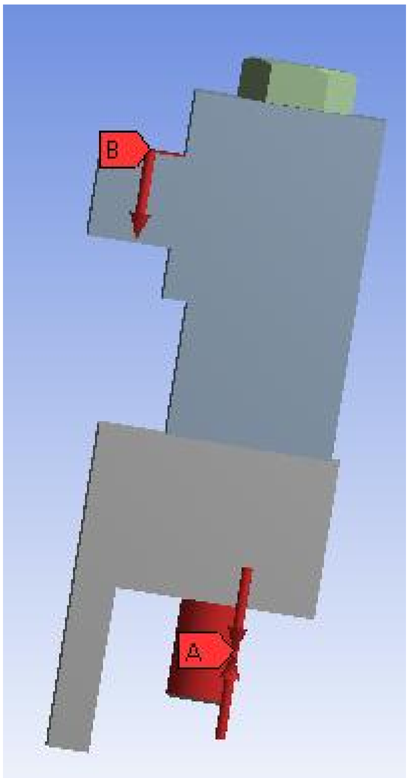


Figure 40: Inner bolt with pretension and compressive load

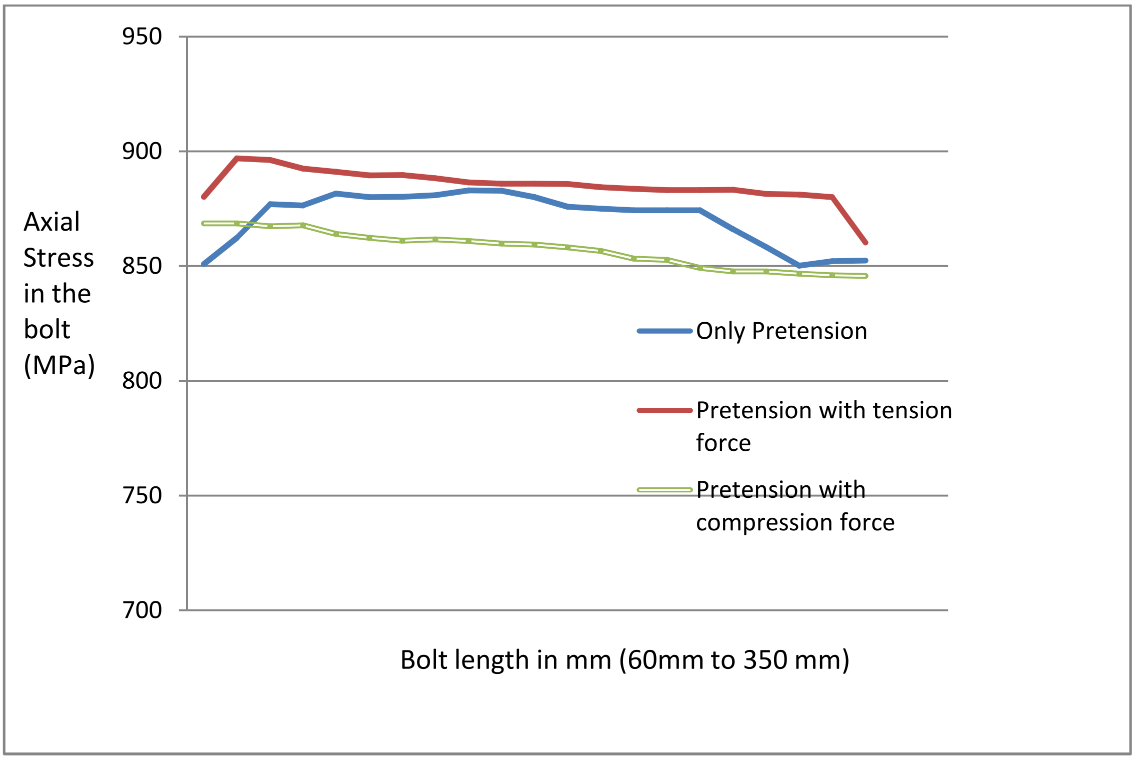


Figure 41: Stress in the inner bolt with 90% pretension and external force

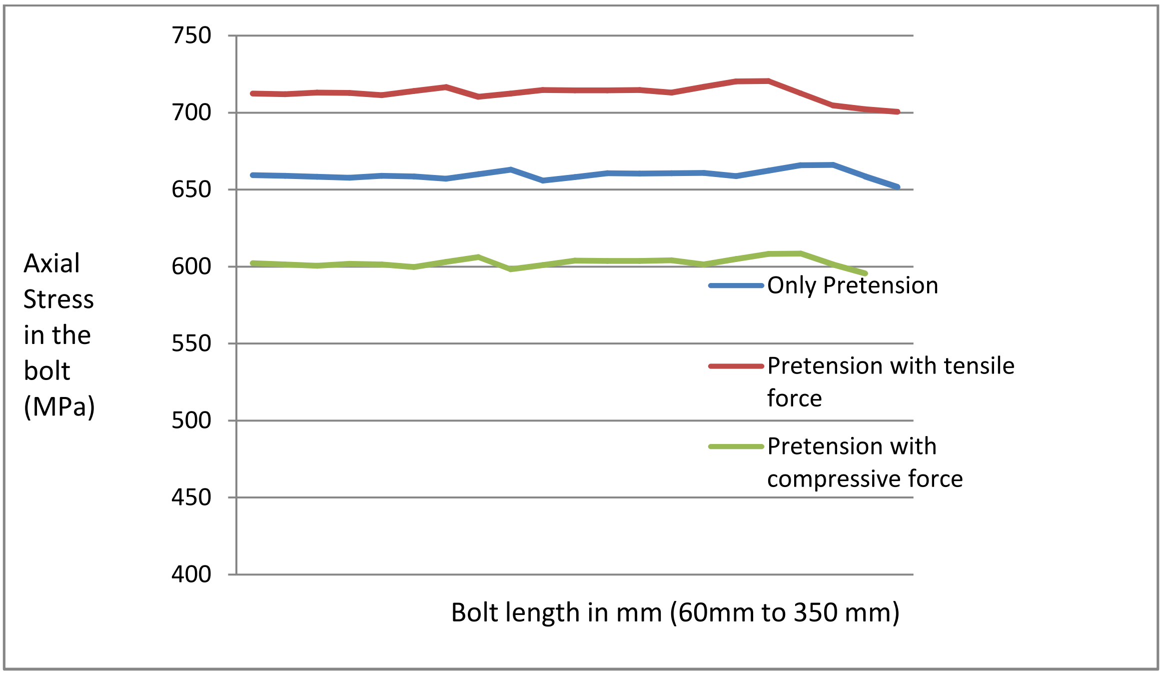


Figure 42: : Stress in the inner bolt with 70% pretension and external force

In this simulation, two different preload was analyzed.

1. 90% of Tensile strength of bolt (846 MPa)
2. 70% of Tensile strength of bolt (660Mpa)

Based on the results from ANSYS WORKBENCH, the graph was plotted.

6.3 Fatigue

The fatigue in the bolt is controlled by the alternating stress in the bolt[18]. Alternating stress is the difference between the maximum and minimum stress in the bolt.

Alternating stress $\sigma_a = \dfrac{\sigma_{max} - \sigma_{min}}{2}$

Where σ_{max} = maximum stress

σ_{min} = minimum stress

The maximum and the minimum stress can be directly read from the graph and hence the alternating stress.

Alternating stress in Outer bolt at 90% Pretension

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} = \frac{840 - 890}{2} = 25 \text{ Mpa}$$

Alternating stress in inner bolt at 90% Pretension

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} = \frac{842 - 898}{2} = 28 \text{ Mpa}$$

Alternating stress in Outer bolt at 70% Pretension

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} = \frac{615 - 680}{2} = 32.5 \text{ Mpa}$$

Alternating stress in inner bolt at 70% Pretension

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} = \frac{598 - 710}{2} = 56 \text{ Mpa}$$

Now the fatigue limit according to VDI 2230 [18] for M39 bolt is as follows. In the analysis M39 bolt was used.

$$\sigma_{ASV} = 0.85\left(\frac{150}{d} + 45\right)$$

$$= 0.85\left(\frac{150}{39} + 45\right)$$

$$= 41.51 \text{ Mpa}$$

The fatigue limit must be smaller than the fatigue limit of the bolt in complete life (i. e it should be less than 2.10^{6} cycles of alternating stress). Above formula represent the alternating stress limit for fatigue of bolt.

Now from the above graph it can be seen that the maximum stress in the bolt is always smaller than its yield point.

From the calculation it can also be seen that the alternating stress is within the limit range according to VDI 2230 [18] except one case i.e alternating stress in the inner bolt at 70% pretension.

7 Conclusion

This thesis dealt with the effect of bolt pretension in the slewing ring bolted joint and the work was done using ANSYS WORKBENCH simulation. The result got from the simulation was satisfactory.

From the analysis we get both the basic strength requirement for the bolt, that are the working stress or the axial stress and alternating stress in the bolt.

The external work load applied to bolted joint was calculated from the basic conventional model for pre-tightening bolted joint which is based on standard. Here the sources of error may lay here.

Also the material properties at the heat affected zone (HAZ) due to welding in the flanges is different from the rest but in the model it was assumed to be same everywhere in particular elements, so here is another sources or error.

Also the results depend on many factors such as the type of supports, here it is assumed to fixed support, the height of bush, nut factor, frictional coefficient (here used $\mu = 0.2$), here also lays some sources of error.

The main highlights from the result is that at the higher pretension, the alternating stress is less which means that the fatigue is less and survivability is more.

8 Recommendations

Work load was determined based on conventional method, which uses so-called load factor i.e it gives an amount of load which is transmitted to the bolt from external load. The load factor depend on the location where the external forces has applied and distribution of member stiffness[25], except for some very basic geometry the load factor does not give accurate result.

So further attention should be paid to determine the external working load on the bolt.

Also the geometry of the body and contacts should into consideration with great care because it can changes the result greatly.

Meshing and mesh size plays a great effect in the result, so some considerations should be allowed in this case.

If the boundary condition applied during the analysis is not correct, the result may differ greatly.

Appendix A: Symbols

Symbol	Description	Unit
ΔF	Increase in pull of bolt	kN
μ	Friction Coefficient	
μ_b^{typ}	Friction co-efficient nut to joint	
μ_t^{typ}	Friction co-efficient external to internal thread	
E	Young Modulus	
F_1	Compressive force in connecting parts	kN
F_2	Total tension in bolt	kN
F_A	Axial load	kN
F'_A	Axial load in limit static curve	kN
F_E	Working load	kN
F_M	Pretension in bolt	kN
F_R	Radial load	kN
F_S	Forces in bolt	kN
F_{SA}	Additional force in bolt	kN
f_{stat}	Safety factor used in limit static curve	
M'_K	Tilting moment in limit static curve	kNm
M_T	Tilting moment	kNm
n	Load factor	
PLD_{max}	Maximum preload	N
PLD_{min}	Minimum preload	N
P_{thr}	Thermal load	
R	Pitch circle radius of load	m
T_{max}	Maximum torque	Nm
T_{min}	Minimum torque	Nm
T_p	Prevailing torque	Nm

Z	No of bolts	
α	Thread lead angle	Degree
β	Thread half angle	Degree
δ_p	Stiffness of the connecting part	
δ_p	Stiffness of the connecting bolt	
λ_m	Extension of bolt	mm
σ_a	Alteranting stress	MPa
σ_s	Yeild limit state	MPa
ϕ	Relative Elasticity	
Γ	Preload uncertainties	

Appendix B: Abbreviations

34CrNiMo6	Steel classification, used to manufacture slewing bearing
42CrMo	Steel classification, used to manufacture slewing bearing
50 Mn	Steel classification. case hardened steel
5CrMnMo	Steel classification, used to manufacture slewing bearing
Cross roller bearing	Slewing bearing that has cross row of rolling elements
DNV	Det Norske Veritas
Double row bearing	Slewing bearing that has two row of rolling elements
Grade 10.9	It's a standard for bolt strength, there is different grade
HAZ	Heat affected zone
Mounting Hole	Hole in the slewing bearing for mounting
NOV	National Oilwell Varco
Orbit	The path on which a row of roller sit
Races	The path on which the rollers sit

Roller	The main elements in slewing bearing which helps to rotate her
Single row bearing	Slewing bearing that has only one row of rolling elements
Slewing Bearing	A bearing which help to rotate and transmit load between structures keeping them in place
Three-row roller bearing	Slewing bearing that has three row of rolling elements
VDI - 2230	Standard guide for bolted joint

Appendix C: Numerical Results

Axial stress in outer bolt with 90% preload (MPa)

Preload	Preload and tension	Preload and copression
841.23	829.59	827.85
860.99	837.86	830.53
872.19	844.53	833.26
879.58	853.19	834.79
886.42	861.25	834.06
893.38	868.36	835.1
893.07	878.07	835.55
891.09	885.65	835.91
891.21	890.57	836.04
890.41	885.41	836.79
885.7	885.87	836.47
881.86	884.73	836.59
878.07	883.98	837.89
872.4	881.28	837.49
866.95	880.3	837.83
861.24	877.35	837.48
850.33	876.69	838.39
846.61	876.04	838.81
843.72	875.87	839.67
841.46	872.7	839.98
840.94	861.07	839.67

Axial stress in outer bolt with 70% preload (MPa)

Preload	Preload and tension	Preload and copression
674.44	687.87	619.09
677.06	690.74	620.51
680.95	692.62	618.62
678.46	693.48	617.68
680.94	691.26	615.72
682.4	690	614.28
681.09	689.75	612.48
679.08	689.34	612.38
678.92	688.6	611
678.04	687.39	610.54
674.44	687.79	609.39
673.27	685.31	609.11
669.84	682.51	608.65
666.89	681.95	609.88
665.12	683.14	607.81
663.32	675.58	605.41
658.73	680.86	604.73
653.61	674.04	603.48
652.12	668.65	601.89
651.43	664.27	601.42
650.49	665	

Axial stress in inner bolt with 90% preload

Preload	Preload and tension	Preload and copression
850.83	880.11	868.64
862.27	896.89	868.52
876.92	896.21	867.39
876.35	892.51	867.78
881.52	890.99	863.94
880	889.47	862.34
880.18	889.71	861.02
880.91	888.26	861.62
882.94	886.46	860.84
882.78	885.95	859.79
880.02	885.93	859.41
875.86	885.68	858.09
875.06	884.29	856.57
874.27	883.71	853.23
874.27	883.03	852.66
874.27	883.08	849.16
866.02	883.23	847.69
858.19	881.41	847.67
850.16	881.13	846.67
852.06	880.04	845.98
852.41	860.26	845.67

Axial stress in inner bolt with 70% preload (MPa)

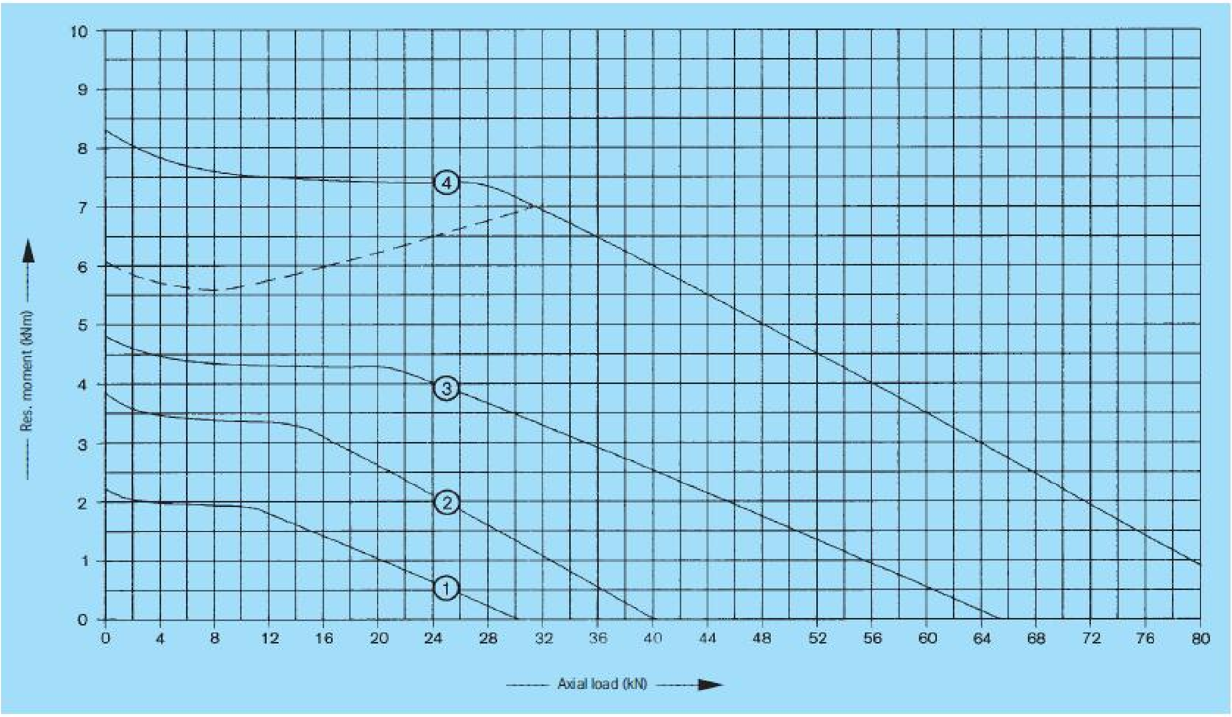
Preload	Preload and tension	Preload and copression
659.42	712.37	602.19
658.91	712.03	601.42
658.37	713.08	600.63
657.81	712.74	601.91
658.98	711.37	601.44
658.57	714.08	599.69
657.01	716.56	603.16
660.1	710.26	606.28
662.9	712.46	598.29
655.76	714.65	601.06
658.24	714.41	603.83
660.72	714.48	603.6
660.49	714.75	603.76
660.6	713.04	604.16
660.93	716.65	601.51
658.76	720.21	604.89
662.26	720.48	608.25
665.73	712.63	608.39
665.94	704.75	601.43
658.53	702.21	595.56
651.64	700.57	

Appendix D:

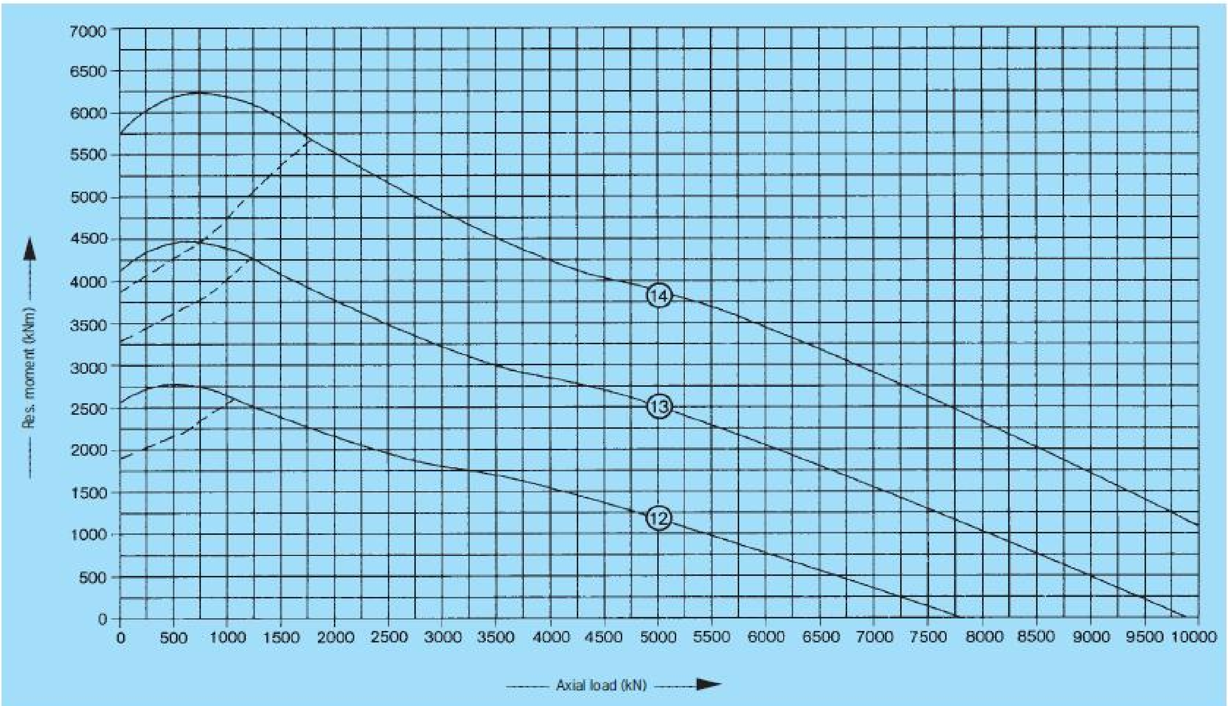
Sample limit static curve for slewing bearing [1]

Static limiting load curves —— Raceway – – – Bolts

For loads exceeding the limiting bolt load curve ④, the number of fastening bolts must be doubled.



Static limiting load curves —— Raceway – – – Bolts



References

1. Erde, R., *Rothe Erde Slewing Bearings [http://www.thyssenkrupp-rotheerde.com/download/info/GWL_EN_13.08_V05W.pdf]*.

2. *http://www.google.no/imgres?imgurl=http%3A%2F%2Fwww.ah-slewingring.com%2Fproducts%2F7-3-4.jpg&imgrefurl=http%3A%2F%2Fwww.ah-slewingring.com%2F1-3-roller-slewing-bearing.html&h=469&w=600&tbnid=tC_VW64XX3KREM%3A&zoom=1&docid=GZbBrgKvn3hE7M&ei=gemQU9T1NeyQ4gTL9ICgBQ&tbm=isch&ved=0CDoQMygNMA0&iact=rc&uact=3&dur=2008&page=1&start=0&ndsp=17.*

3. Vadean, A., D. Leray, and J. Guillot, *Bolted joints for very large bearings—numerical model development.* Finite Elements in Analysis and Design, 2006. **42**(4): p. 298-313.

4. www.rollix.com.

5. Qiu, M., et al., *A finite-element analysis of the connecting bolts of slewing bearings based on the orthogonal method.* Journal of Mechanical Science and Technology, 2012. **26**(3): p. 883-887.

6. Chaib, Z., A. Daidié, and D. Leray, *Screw behavior in large diameter slewing bearing assemblies: numerical and experimental analyses.* International Journal on Interactive Design and Manufacturing (IJIDeM), 2007. **1**(1): p. 21-31.

7. Göncz, P.G., S. , *CALCULATION MODEL FOR PRE-STRESSED BOLTED JOINTS OF SLEW BEARING.* 2009.

8. chaib, Z.D.A.G.J., *Study of a bolted and screwed joint of a slewing bearings.* 2005: p. 1-16.

9. *RTR bearing [http://www.rtr-bearing.com/english/Product_Detail.asp?ID=92].*

10. *Technical Data Sheet - Rothe Erde Large Diameter Slewing Bearing.*

11. *Data Sheet - Dokka Fasteners.*

12. Li, W.X.H.L.Y.X.J., *Strength Analysis for Pre-stressed Bolted Joints of Turnable Bearings.* 2011.

13. *CRITERIA FOR PRELOADED BOLTS - National Aeronautics and Space Administration [NASA].*

14. Baca, K.H.B.C.M.S.D.A., *Guideline for Bolted Joint Design and Analysis - Version 1.0.* 2008.

15. *Rothe Erde Catalog [http://www.thyssenkrupp-rotheerde.com/gb/TG/Statische_Tragfaehigkeit.shtm].*

16. Leray, D.d., Alain; Combes,Bertrand;, *Rapid simulation of preloaded bolted assemblies for slewing bearings.* 2001.

17. Chaib, Z., *ÉTUDE DU COMPORTEMENT DES FIXATIONS PAR VIS DES COURONNES DE GUIDAGE DE GRAND DIAMETRE : ELABORATION D'UN OUTIL DE DIMENSIONNEMENT* February 2008.

18. *VDI - 2230 Systematic Calculation of High Duty Bolted Joints*

19. Zupan, S.P., I; Lukancic, B;, *An Imporved method for operating bolt load calculation of bolted joints.* 2001: p. 61-75.

20. Smolnicki, T., D. Derlukiewicz, and M. Stanco, *Evaluation of load distribution in the superstructure rotation joint of single-bucket caterpillar excavators-Automation in Construction 17.* 2008: p. 218-223.

21. Li, Y.Y., Y.C. Li, and Y. Chen, *Three rows of Turnable Bearing for the oil rig component design.* 2009: p. 9-12.

22. Raju;, N.F.K.D.R.P.I.S., *Simulating Structural Response of a Preloaded Bolted Joint.*

23. Schaumann.p;, *Global structural behaviour of Ring Flange Joints.* 2002: p. 1-9.
24. Williams, J., et al., *Analysis of extremely loaded bolted joints: Analytical, computational and experimental study.* 2009.

25. Zang;, O. and J.Poirer;, *New analytical model of bolted joints.* 2004.