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Analytical and Numerical Study of Mechanical Behaviour of Bolted Joints –A Review

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Abstract*:* *Any component that is subjected to excessive heat or cold experiences behavioural changes. The nut bolt assembly at the flange joint may not function as planned or may fail under such circumstances. Temperature fluctuations tend to cause the inner and outer threads to react differently, resulting in the pair becoming looser. Flange materials have a propensity to flex, applying unneeded additional stress on the bolt head and nut. Notably, liquid propellant rocket engines display this type of temperature variation. To assess mechanical performance while accounting for different nut factors and flange materials, analytical and numerical approaches are applied.*

Keywords: Engine driven by liquid, static force modelling, and nut-bolt-flange assembly

Nomenclatures

Kg/s –kilogram/second
FEA – Finite element analysis
P – Load
St – Tensile Strength
As – Tensile Stress Area

I. INTRODUCTION

A liquid-propellant rocket or liquid rocket utilizes a rocket engine that uses liquid propellants. Liquids are desirable because they have a reasonably high density and high specific impulse (I^{sp}). This allows the volume of the propellant tanks to be relatively low. It is also possible to use lightweight centrifugal turbopumps to pump the rocket propellant from the tanks into the combustion chamber, which means that the propellants can be kept under low pressure. This permits the use of low-mass propellant tanks that do not need to resist the high pressures needed to store significant amounts of gasses, resulting in a low mass ratio for the rocket.

An inert gas stored in a tank at a high pressure is sometimes used instead of pumps in simpler small engines to force the propellants into the combustion chamber. These engines may have a higher mass ratio, but are usually more reliable, and are therefore used widely in satellites for orbit maintenance.

Liquid rockets can be monopropellant rockets using a single type of propellant, or bipropellant rockets using two types of propellant. Tri propellant rockets using three types of propellant are rare. Some designs are throttleable for variable thrust operation, and some may be restarted after a previous in-space shutdown. Liquid propellants are also used in hybrid rockets, with some of the advantages of a solid rocket.

Liquid Propellant Engine is generally used for propulsion of rockets used for placement of satellites and payloads in the required orbit.

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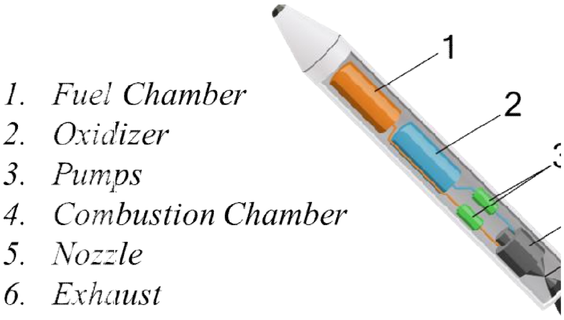


Figure-1 Section of Propulsion Rocket

1.1 Mechanical Properties of Steel fasteners

Most fastener applications are designed to support or transmit some form of externally applied load. If the strength of the fastener is the only concern, there is usually no need to look beyond carbon steel.

Considering the cost of raw materials, non-ferrous metals should be considered only when a special application is required.

Tensile strength is the mechanical property most widely associated with standard threaded fasteners.

Tensile strength is the maximum tension-applied load the fastener can support prior to fracture.

The tensile load a fastener can withstand is determined by the formula P = St x As.

- P= Tensile load– a direct measurement of clamp load (lbs., N)
- St= Tensile strength– a generic measurement of the material's strength (psi, MPa).
- As= Tensile stress area for fastener or area of material (in2, mm2)

In the tension joint, the bolt and clamped components of the joint are designed to transfer the external tension load through the joint by way of the clamped components through the design of a proper balance of joint and bolt stiffness.

The shear joint transfers the applied load in shear on the bolt shank and relies on the shear strength of the bolt. Tension loads on such a joint are only incidental. A preload is still applied but is not as critical as in the case where loads are transmitted through the joint in tension.

The complexity of the simple nut and bolt is frequently underestimated. A fully tightened bolt does not perform like a loose bolt. A fully tightened bolted joint can sustain millions of load cycles without problems, a joint consisting of untightened bolts will frequently fail within a few cycles. The reason for this is the way a bolted joint carries an external load – a fully tightened bolt sustains only a small proportion of any externally applied load.

Thread engagement is the length or number of threads that are engaged between the screw and the female threads. Screws are designed so that the bolt shank fails before the threads, but for this to hold true, a minimum thread engagement must be used.

$$A_t = \frac{\pi}{4} \cdot (D - 0.938194 \cdot p)^2$$

$$L_e = \frac{2 \cdot A_t}{0.5 \cdot \pi \cdot (D - 0.64952 \cdot p)}$$

Consideration of different factors for designing of Nut Bolt used for Cryo Applications

Some of the consideration for Steel fasteners for the temperature range between -50°C and 150°C

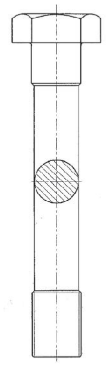
Materials for fasteners: The material that is used is of decisive importance for the quality of the fasteners (screws, nuts, and fittings). If there are any faults in the material used, the fastener made from it can no longer satisfy the requirements made of it. The most important standards for screws and nuts are: • DIN EN ISO 898-1, Mechanical properties of fasteners made of carbon steel and alloy steel, Part 1: Screws • DIN EN 20898 Part 2 (ISO 898 Part 2), Mechanical properties of fasteners, Part 2: Nuts These standards stipulate the material that is to be used, the marking, the properties of the finished parts and their tests and test methods.

Tensile Test: The tensile test is used to determine important parameters for screws such as tensile strength Rm, yield point Re, 0.2% offset yield point Rp0.2, and elongation at fracture A5 (%). A difference is made between "tensile test with turned off specimens" and "tensile test on whole screws".

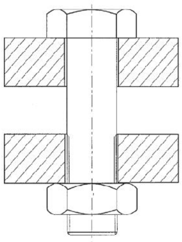
The tensile strength Rm indicates the tensile stress from which the screw may fracture. It results from the maximum force and the corresponding cross-section. With full strength screws the fracture may only occur in the shaft or in the thread, and not in the connection between the head and the shaft.

Tensile strength on fracture in cylindrical shaft (turned off or whole screws): Rm = maximum tensile force/cross-section area = F/So [MPa] Tensile strength on fracture in thread: Rm = maximum tensile force/tension cross-section = F/As [MPa] As tension cross-section

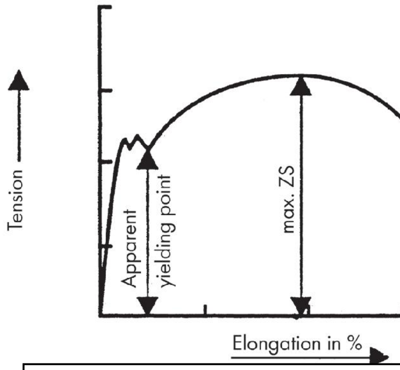
Apparent yielding point Re (MPa): Under DIN EN ISO 898 Part 1 the exact yield point can only be determined on turned off specimens. The yield point is the point to which a material, under tensile load, can be elongated without permanent plastic deformation. It represents the transition from the elastic to the plastic range. Fig. C shows the qualitative curve of a 4.6 screw (ductile steel) in the stress-strain diagram.



Tensile test on a turned-off screw



Tensile test on a whole screw



Stress-strain diagram of a screw with the strength class 4.6 (qualitative)

Properties of screws at increased temperatures: The values shown apply only as an indication for the reduction of the yield points in screws that are tested under increased temperatures. They are not intended for the acceptance test of screws.

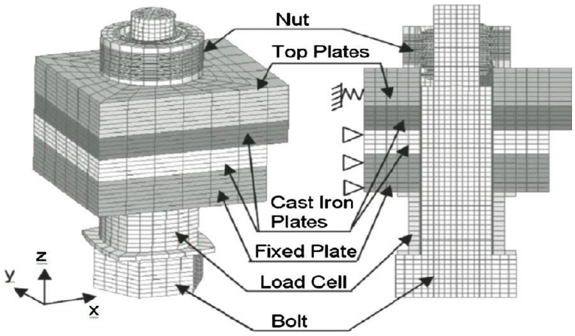
Strength Class	**Temperature**				
	+20°C	**+100°C**	**+200°C**	**+250°C**	**+300°C**
	Lower yield point ReL or 0.2% offset yield point Rp 0.2 MPa				
5.6	**300**	**250**	**210**	**190**	**160**
8.8	**640**	**590**	**540**	**510**	**480**
10.9	**940**	**8755**	**790**	**745**	**705**
12.9	**1100**	**1020**	**925**	**875**	**825**

Sr No	**Name of the Investigator**	**Focus of the research work**	**Key findings/ Results**
1	Lucy Bulla*, Eric J. Palmiereb, Richard P. Thackrayb, Ian W. Burgessc, Buick Davisonc	Tensile Behaviour of Galvanised Grade 8.8 Bolt Assemblies in Fire	At ambient temperature the failure mode of bolt assemblies is dependent on the microstructure. However, at elevated temperatures, when ductility is more critical, all assemblies failed through thread stripping. Thread clearance was not found to influence the failure

			mode or ultimate capacity in this. case: further research is clearly required to determine why all assemblies failed in this way.
2	W. Brown, T.-Y. Lim	Factors Affecting Nut Factors for PVP Bolted Joint Assembly	It has been highlighted that manufacturing tolerances have a significant influence on the Nut factor, and thus the integrity of a bolted joint. Small defects on the nuts and bolts resulted in a 30% increase in Nut Factor. Additions should be made to the ASTM A193 and ASTM A194 standards for bolt and nut material.
3	Yancheng Cai, Ben Young n	Bearing factors of cold-formed stainless steel double shear bolted connections at elevated temperatures	A non-linear finite element model has been developed and put to the test against the data for cold-formed stainless steel double shear bolted connections at high temperatures. In this work, the bearing strengths obtained from the finite element analysis are utilised to calculate the corresponding plastic strain in the bolt hole.
4	Mohamed A. Shaheen a, Andrew S.J. Foster a,∗, Lee S. Cunningham a, Sheida Afshan b	Behaviour of stainless and high strength steel bolt assemblies at elevated temperatures—A review	The behavior of high strength and stainless-steel bolt assemblies at elevated temperatures has been reviewed and presented. Whilst the behavior and strength of these bolt assemblies at ambient temperatures now constitute a substantial body of research with most key parameters and phenomena identified and understood, this study has shown that insufficient work has been conducted to develop reliable design guidance at elevated temperatures. The absence of consistent testing procedures for bolt assemblies at elevated temperatures, combined with the significant differences noted in the test parameters used by differentresearchers has resulted in a high degree of scatter in the experimental results and correspondingly, the strength reduction factors.

Self-Loosening of bolt due to temperature variation or exposure to cyclic temperature change

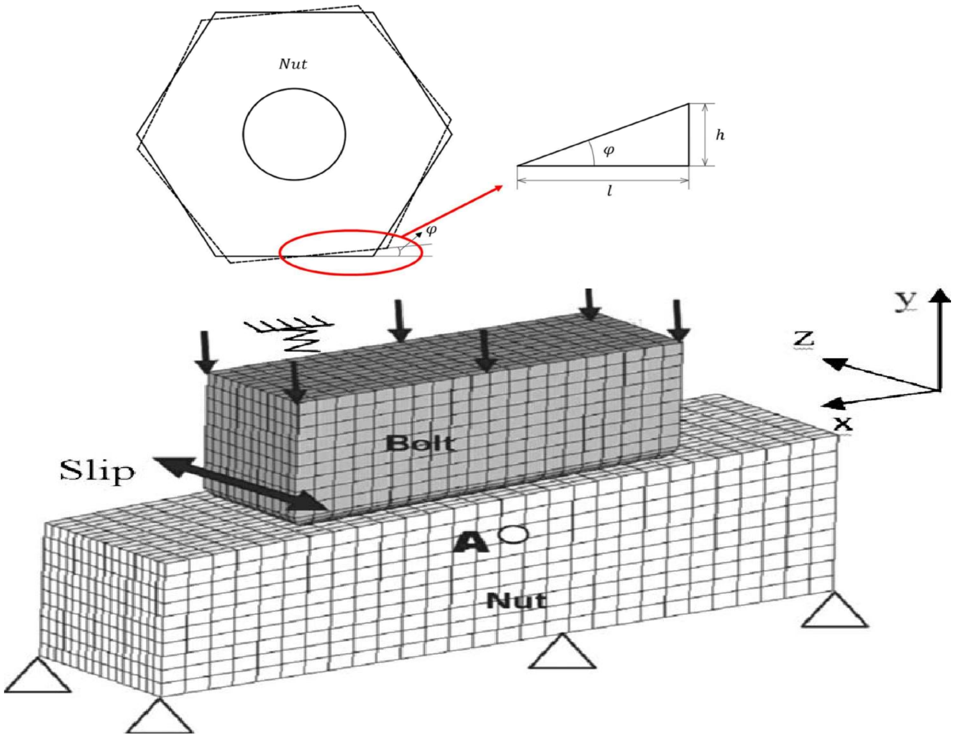
Self-loosening is the gradual loss of the clamping force in the bolted connections under cyclic external loading, especially transverse loading. Bolt loosening is a major form of failure in machines and structures. Great efforts have been made to understand the self-loosening phenomenon through experimental investigations. Due to the complex geometry involved in a threaded joint, it is difficult to directly measure the local deformation and possible microslip occurring inside a bolted joint. Little information regarding the mechanisms was explored through experimental investigations for the bolt loosening. The exploration of the mechanisms of bolt loosening may rely on a theoretical and/or numerical analysis. Attempts have been made to describe the self-loosening process with vibration theories.More recently, the finite element (FE) methods were used to model bolted joints under dynamic loading.



Yamamoto and Kasei [1] developed quantitative models based on a two-stage theory for the nut to slide along the thread of the bolt due to the internal clamping force and the external loading on the bolted joints. However, no quantitative results were provided for the verification of the models. Following Junker's basic assumptions [2], Sakai [3] proceeded to conduct a theoretical analysis, trying to derive the conditions necessary for a bolt to loosen by self-rotation. It was concluded that unless the friction coefficient was less than 0.03, the bolt would not rotate loosely. Zadok's and Yu [4,5] conducted a series of studies on self-loosening of bolted joints. It was found that it was difficult to stop the preload from releasing if there was a transverse movement between the clamped portions. Using a mathematical model of dynamic self-loosening, the link between the transverse force, Q, and the transverse displacement was established. The necessary transverse force was found. This Q value revealed a necessary condition for the transverse motion to occur. Consequently, a threshold below which self-loosening would never occur was set. The critical force can be raised by increasing preload, thread-to-surface friction, and nut-bearing surface friction.

Self-Loosening Mechanisms

Two major factors were identified that determine State II self-loosening. They are the variation of the contact pressure in the engaged threads with the external load and the microslip occurring between the contact surfaces of the engaged threads.



Sr No	Name of the Investigator	Focus of the research work	Key findings/ Results
1	Oybek Maripjon Ugli Eraliev1 , Yi-He Zhang2 , Kwang-Hee Lee2 and Chul-Hee Lee2	Experimental investigation on self-loosening of a bolted joint under cyclical temperature changes	Self-loosening of the bolted joint under cyclical temperature changes is investigated experimentally. The results show that the bolt can face more loosening in the first cycle of temperature changes than that of the rest of the cycles. The loosening amount of the bolt preload changes proportionally to the increment of temperature changes. From the results, loosening of the bolted joint under cyclical temperature

			changes can be considered as early-stage self-loosening.
2	Ming Zhang, Yanyao Jiang	Finite Element Modeling of Self-Loosening of Bolted Joints	The three-dimensional finite element model captures the essentialcharacteristics of the experimentally observed StageII self-loosening behavior of a bolted joint subjected to transverse loading.
3	Oybek Eraliev, Kwang-Hee Lee and Chul-Hee Lee	Self-Loosening of a 3D-Printed Bolt by Using Three Different Materials under Cyclical Temperature Changes	In this paper, self-loosening of 3D-printed bolts using three different materials, namely: ABS-2, PLA, and glass under cyclical temperature changes were investigated experimentally. Under high temperature changes, PLA and glass bolts reached the maximum amount of loosening in the first cycle of temperature changes and did not loosen anymore.
4	Shikun Lu1,*, Dengxin Hua*, Yan Li1, Fang yuan Cui1, Pengyang Li	Load and Stress Distribution of Thread Pair and Analysis of Influence Factors	According to the data, the bolt often sustains damage before the nut does in a pair of threads engaged with each other since the bolt's root stress is higher. The magnitude of the bolt's axial load has minimal bearing on the threads' load % in the elastic range. Each circle's load increases by the same amount as the axial load of the boltproportion and the share of each circle's burden remains mostly identical.
5	Shiyuan Hou, Ridong Liao, and Jishan Li	A Mathematical Model for Temperature InducedLoosening due to Radial Expansion of Rectangle Thread BoltedJoints	If the thermal expansions of the bolt and joint do not line up with the cyclically changing temperature, expansion-induced radial shear stress can decrease the friction torques and eventually lead to the loosening of bolted joints. The amount of temperature fluctuation that might cause slippage in the first segment of temperature change for bolt joints with specific structural specifications is directly inversely proportional to preload. At least twice as much of a change in temperature is required to cause lasting loosening.

II. CHALLENGES AND RECOMMENDATIONS

Internal torque and load are setup when nut bolt assembly is pre-tensioned and exposed to cyclic temperature change. Deformation or failure of the bolt results from internal load and stress setting. Nut bolt assemblies often experience compressive stress when they are subjected to cryo liquids like LOX, LN2, and LOH. Additionally, because of cyclic temperature variations, cyclic stresses are also created.

The following difficulties are encountered while developing a nut-bolt assembly:

1. Selecting the assembly's nut factor and material.
2. The bolt should have a pretension load applied to it, and failure from a temperature differential should not occur.
3. For the storage and transfer lines, use SS304 material to prevent corrosion at low temperatures.

III. CONCLUSION

The effectiveness of such a junction depends on the tension created considering the nut factor and various flange materials. It should be able to withstand cyclic loads to enhance the strength and flexibility of the joint at various temperature ranges. Because they are suitable for use at cryogenic temperatures, SS304 and SS304L can be utilised for this purpose. Materials exposed to cryogenic temperatures should have low thermal conductivity, low thermal expansion coefficient, and resistance to oxidation.

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