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A Review on Loosening of Bolted Joints

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ABSTRACT

In this review on causes and reasons which are responsible for loosening of bolted joints and fasteners has been carried out. Authors have reviewed the various studies carried out by previous researchers in this area of research. Main reasons of loosening are cyclic loading and unloading of threaded components. Many researchers have developed machines for their experimental work. Loosening i.e. unlocking rotation of threaded assembly is caused by the restoring action of an elastic torsion of a bolt shank because of the relative motion at mating surface on threads.

After review of various literature it was concluded in this review that for the loosening of bolted joints the two factors mainly responsible 1) The relative slip between the bolt and nut screw threads, and 2) The relative slip between the nut or bolt surface and the surface of the fastened material.

Key Words Bolt, Loosening of fasteners, Slip, Cyclic loading.

I.INTRODUCTION

A fastener is an Engineering component or device that mechanically joins or affixes two or more objects together. Generally for applying semi permanent joint between any two parts Bolted joints are used. There are two parts in the assembly 1) Bolt and other is 2) Nut. Bolt, can be described as a type of fastener characterized by a helical ridge, known as an external thread or just thread, which are wrapped around a cylinder. Some screw threads are designed to mate with a complementary thread, known as an internal thread, often in the form of a nut or an object that has the internal thread formed into it. Other screw threads are designed to cut a helical groove in a softer material as the screw is inserted. The most common uses of these fasteners are to hold objects together and to position objects. Whereas, a nut can be described as a type of fastener with a threaded hole. Nuts are always used opposite a mating bolt to fasten a pair of parts together. These two parts are kept together by combination of their threads' friction, a slight stretch of the bolt, and compression of the parts.

In many Engineering applications where vibration or rotation may work a nut loose, various locking mechanisms may be employed: such as lock nuts, adhesives, safety pins, lock wire, nylon inserts, or slightly oval-shaped threads. The most common shape is hexagonal, for similar reasons as the bolt head - six sides impart a good granularity of angles for a tool to approach from, but more corners would be vulnerable to being rounded off. Other specialized shapes exist for certain needs, such as wing nuts for finger adjustment and captive nuts for inaccessible areas.

Bolted joints are usually made up of the bolt group which includes head, stud, and nut and the flange top and bottom. Bolted connections are designed to hold two or more parts together to form an assembly. Because of various loading conditions, especially at high loads, bolted connections can loose and separate. To minimize this bad effect, a pretension is applied to the bolt. This will insure that the connection will not get separated, provided the applied load remains less than the pretension.

In most Engineering applications, the lead of a screw thread is so chosen which will impart adequate friction to prevent linear motion being converted to rotary that is so the screw does not slip even when linear force is applied so long as no external rotational force is present. This characteristic is vital in the majority of applications.

II.REVIEW OF WORK CARRIED

It is widely believed that vibration causes bolt loosening. By far the most occurring root cause of loosening is side sliding of the nut or bolt head relative to the fastened joint, resulting in the relative motion occurring within the threads. If this does not occur or can be prevented, then the bolts will not loosen, even if the joint is subjected to severe vibration. By a detailed analysis of the joint it is possible to determine the clamp force required to be provided by the bolts to prevent joint slip.

Study of most Engineering literature will reveal the multitude of many locking mechanisms available for fasteners. For the Designer without any theoretical knowledge of why fasteners self loosen, this represents a hit and trial method. Presented below is key information, for the Designer, on why fasteners self loosen, and, how it can be prevented.

The first study on threaded fastener loosening done by Goodier and Sweeney [1] in 1945 who proposed that in the course of dynamic loading and unloading, initial loosening is caused by loading on the assembled components and tightening caused by unloading, the net effect being a small rotation in the nut but that is not completely true. Junker [2] developed a test and showed that the transverse joint movement can cause loosening; he concluded that transverse vibrations have more adverse effects than axial vibrations.

Kenny and Patterson [3] modified the nut thread form for reducing the stress concentration which occurs during cyclic loading and had described a technique for determining the load distribution experimentally.

The primary cause for loosening is a result of slip between the mating fastener surfaces.[9] In such a system, when sufficient force is applied in the transverse direction, the member not only moves in the transverse direction, but also downwards. In a threaded fastener, the lead of the thread provides the direction for decreased potential energy, while the external loads provide the additional loads required to cause slip.

An experimental study of self-loosening of bolted joints was developed by Jiang et al. they did work on Instron Machine .They showed that the self loosening process of a bolted joint consists of two distinct stages. The early stage occurs when there is no relative rotation between nut and bolt and due to cyclic plastic deformation of the materials. The second stage of self loosening is a result of gradual rotation of nut and characterized by the backing off the nut. The experimental set up was of two plates joined by a nut-bolt were subjected to cyclic transverse shear loading and relative displacement between the plates measured for different preloads.[10]

It is well known that bolted joints are loosened when lateral loads are applied after they are tightened. As the result, the bolt loosening is caused by the shape of the thread that is the wedge inclined to the bolt axis. When lateral loads are applied, the bolt/nut threads slide relatively, which causes the relative nut rotation. When the loads are released, the bolt returns to the normal position keeping the relative slide to the nut. This nut rotation causes a reduction of the bolt tension, too. Although the magnitude of this rotation may be quite small, many times of repetition makes the bolt loosened.[11]

Loosening Rotation is caused by restoring action of an elastic torsion of a bolt shank which is due to relative motion at mating surface on threads[15].

Studying on the loosening mechanism of screwed fasteners revealed that the relative sliding rotation between nut, bolt and components joined is the main reason for loosening:

i) The cause for the sliding and consequent loosening is explained by the fact that the lateral displacement of fastened element makes the bolt inclined, and hence increases the tensile stress coming on to the bolt.

ii) Increase of this tensile stress over a limit initiates slip at the engaged flank surface of the screw thread.

iii) The slip takes place not only in the direction of the flank but also in the direction of the axis of the screw thread due to the presence of lead angle.

iv) Differential thermal effects of clamped materials and fasteners may also induce loosening effect. [16]

The deformation behaviour of bolt-nut joint is depends on the amount of transverse load level applied on the joint. No slip generated at the bolt and nut bearing surface. Then, slip generated at the contact surface between fixed plate and movable plate when W exceeded the frictional force (Where frictional force = number of bolts, n X friction coefficient, μ X initial axial tension, F_b) is given to the joint.

However, when relative displacement, S between upper and lower plate is still small, by the bending deformation of the bolt, sliding at the bolt and nut bearing surface is not generated. Then, load and relative displacement between plates increased and at one stage relative displacement exceeded Delta S, slip is also occurs at the bolt and nut bearing surface. This slip leads to the reverse rotation of the nut and decrease the axial tension. The loosening behaviour of bolt-nut joint shows the same occurrence if the transverse load applied in the opposite direction. When transverse cyclic load applied to the joint, bolt axial tension slowly decreases and at the worst stage, not only loosening occurs but also the fatigue failure of the bolt. So, it is important to evaluate both loosening behaviour and fatigue failure of the bolt-nut joint.[25]

Ramey and Jenkins [4] did their study on the Structural Test Division of MSFC. The objective of their study was to identify the main design parameters contributing to the loosening of bolts due to vibration and to identify their relative importance and degree of contribution to bolt loosening. Vibration testing was conducted on a shake table with a controlled-random input. Test specimens which contained one test bolt were vibrated for a fixed amount of time and a percentage of pre-load loss was measured. Each specimen tested implemented some combination of eleven design parameters as dictated by the design of experiment methodology employed. The design parameters were: bolt size, lubrication on bolt, hole tolerance, initial pre-load, nut locking device, grip length, thread pitch, lubrication between mating materials, class of fit, joint configuration, and mass of configuration. These parameters were chosen for this experiment because they are believed to be the design parameters having the greatest impact on bolt loosening. The results of the investigation indicated that nut locking devices, joint configuration, fastener size, and mass of configuration were significant in bolt loosening due to vibration. The results of this test can be utilized for future research the complex problem of bolt loosening due to vibration. A study on high strength fastened joints using direct tension indicators [5] were done to know the transverse vibration loosening characteristics, the outcome was that with direct tension indicators loosening was less. A linear three-dimensional finite element analysis was performed by Srinivasan and Lehnhoff [6] on bolted pressure vessel joints to determine maximum stresses and stress concentration factors in the bolt head fillet. Their objective was to show the stress concentration factor. The models consisted of a segment of the flanges containing one bolt, using cyclic symmetry boundary conditions. The flanges were each 20 mm in thickness with 901.7 mm inner diameter. The outer flange diameter was varied from 1021 to 1041 mm in steps of 5 mm. The bolt circle diameter was varied from 960.2 to 980.2 mm in steps of 5 mm. The bolts used were 16-mm-dia metric bolts with standard head and nut thickness. This study showed that the traditional stress concentration factor might not be sufficient in the design of eccentric bolted joints, such as pressure vessel flanges.

Pai and Hess [7] carried out extensive experiments on a simple nut and bolt assembly and also developed a three dimension finite element model to study details of four different loosening processes, characterized by complete or localized slip at the head and thread contact. They discussed the primary contact factor for loosening, and found that slip can occur at lower shear force then loosening caused by complete slip, and therefore critical in joint design. Pai and Hess [8] also done study on loosening of threaded fasteners subjected to dynamic shear loads. The fundamental analysis of loosening was that a fastener can loosen at lower loads than previously expected, due to localized slip at the contact surfaces. Four different loosening processes of a screw under different conditions of slip at the head and thread contact regions are identified. Experiments were done and results illustrating these loosening processes were presented. In addition, the minimum dynamic shear force required to initiate loosening determined experimentally. The analysis presented in their paper illuminates the various causes of slip under shear loading.

Pai and Hess [9] has developed a non-linear three-dimensional finite element model that includes friction and contact was developed using the commercially available software, ANSYS, to determine the loads acting on the fastener in a compound cantilever beam subjected to a concentrated load at the end.

An experimental study of self-loosening of bolted joints was developed by Jiang et al. they did work on Instron Machine [10].They showed that the self loosening process of a bolted joint consists of two distinct stages. The early stage occurs when there is no relative rotation between nut and bolt and due to cyclic plastic deformation of the materials. The second stage of self loosening is a result of gradual rotation of nut and characterized by the backing off the nut. The experimental set up was of two plates joined by a nut-bolt were subjected to cyclic transverse shear loading and relative displacement between the plates measured for different preloads. They observed that there exist an endurance limit below which self-loosening would not persist and large preload resulted in a large endurance limit. But fatigue failure possibility of bolt increases at large preload, they suggested that the use of regular nut is better than the use of flanged nut. They used M12X1.75 nut bolts for their experiment. Studies on the other type of nut bolts are remaining to be done.

Shoji and Sawa [11]. Several finite element analysis were performed and noticed that bolts are loosened or nut rotates, when the lateral loads are applied, based on this result, the mechanism of bolt loosening investigated. It was examined that loosening of bolt resists when double nut procedure is used. Chen et al. [12] studied the failure of threaded fasteners due to vibration; the main objective of their work was to study the loosening tendency of a threaded fastener. They developed the looseness model, static and dynamic threaded fastener models are derived to find the static and dynamic interior forces respectively. Secondly, for investigating the bolt loosening behavior, the effects of thread lead angle, initial preload, vibration frequency, and the nature of material on the bolt looseness, the threaded fastener looseness model is constructed by combining the above models with a Karnopp frictional model. The proposed approach not only analyzed both the static and the dynamic behaviors of the bolt as well as well as the bolt loosening but also detected whether the bolt is within the elastic range or not.

Ibrahim and Pettit [13] reviewed and provided an overview of the problems pertaining to structural dynamics with bolted joints. They see problems are complex in nature because every joint involves different sources of uncertainty and non-smooth non-linear characteristics Under environmental dynamic loading, the joint preload experiences some relaxation that results in time variation of the structure’s dynamic properties.

Ganeshmurthy S. [14] conducted an experimental procedure and test set up was proposed to investigate the effect of under head contact radius, thread pitch, surface coating, and fastener head versus nut side tightening on the static and kinetic frictional torque components. Investigated effect of tightening speed, coating, effect of repeated tightening and loosening.

A study of self loosening of bolted joint was done by Kasei [15], when very small slippages occur repeatedly at bearing surfaces under transverse loads. He did some sample tests on setup and checked the loosening performance to show relative displacement between bolts and nut’s threads drive. He performed experiments for M10 X 1.25 nut bolt. He inspected the anti-loosening performance of nut-bolt joint. The conclusion was when a high anti-loosening performance is required, a firm obstruction of the slippages at the mating surface on threads must be ensured. To study the anti-loosening phenomenon of the threaded fasteners, a testing rig has been designed and fabricated by Saha et al. [16] where the clamping force can be continuously recorded under the application of accelerated known frequency vibration between two plates of nuts and bolt, the results obtained on the anti-loosening property of a number of threaded fasteners are presented, discussed and the effective one is found out. They concluded the nylon inserted nuts imparting higher frictional grip when fitted with standard metric bolt, the conventional BSW fasteners have shown lesser tendency to loosen.

J.A. Sanclemente and D.P. Hess[17] presented results from an experimental investigation of mechanical loosening in bolted joints due to cyclic transverse loads. They studied influence on the resistance to loosening of basic parameters such as preload, fastener material elastic modulus, nominal diameter; thread pitch, hole fit and lubrication. Sixty-four tests have been performed as part of a nested-factorial design in which the nominal diameter is the nesting factor of preload, thread pitch and hole fit. They found that the preload and the fastener elasticity are the most influencing parameters for loosening. A statistical model developed that predicts the level of loosening reached by a threaded fastener under defined conditions. The analysis shows that optimum conditions to avoid fastener loosening are high preload, low modulus of elasticity, large diameter, lubrication, tight fit and fine threads.

The mechanisms of loosening resistance components are investigated by Izumi and Sakai [18] and Izumi S et al. [19] with the three-dimensional finite element method. The results of the double nut tightening method, spring washers, and conical spring washers were shown. Their work focused on the comparison among the components based on the results. They found that double nut shows significant resistance of loosening if properly tightened. Spring washers show negative loosening resistance.

The loosening of screw fasteners is caused by two factors mainly. One is the relative slip between the bolt and nut screw threads, and the other is the relative slip between the nut or bolt surface and the surface of the fastened material. In their work Mahato and Das [20] the anti loosening ability of various 3/8 BSW locking screw fasteners with nylon nut, flat washer, nylon washer, serrated washer and spring washer are tested under accelerated vibrating conditions. The experiment has been carried out in an indigenously made testing machine. The initial clamping force given has been around 0.82 ton. Under vibrating condition, the loss of tightening force has been measured at regular intervals to adjudge the loosening of threaded fastener. From the results, it is observed that only small improvement has been obtained using flat washer over conventional nut. Outside serrated, spring and nylon washers show marginal anti-loosening ability. Nylon nut was seen to have better resistance to loosening than the other popularly known anti-loosening fastening elements tested, and hence, may be quite effective to use in vibrating conditions. However, other popularly known anti-loosening nuts or washers are found not to be that effective.

R. Friede & J. Lang [21] has taken especially the case in the field of bolts for steel structures with diameters of 16 to 36 mm, where the number of results is low. At risk for self loosening are steel structures under cyclic loads, such as cranes, mast constructions, smokestacks and bridges. To protect connections against the self loosening several anti loosening devices were on the market. Recent results showed that unfortunately almost all of them were malfunctioning. Due to that in 2003 all German regulations for these elements were withdrawn. At the moment a research project is running at the Technische Universität Darmstadt, Germany, to analyze the mechanism of self loosening. The aim is to find a constructive way to protect a bolted connection from self loosening. Therefore several tests to identify the important parameters were performed, especially the variation of the clamping length. Within the paper the results of the project so far were presented.

Kathryn J. Belisle [22] has done study on complete single bolted joint model incorporating the wheel rim flange and the two main loads seen at the bolted joints; bolt preload and the external load created by tire pressure on the wheel rim. A 2x3 full factorial DOE was used to establish the joint's response to various potential load combinations assuming two levels of preload and three levels of external load. The model was analyzed both experimentally and in finite element form. The strain results around the mating face radius were compared between the two analyses. Several parameters were identified that could affect the correlation between the results. The finite element model was modified to incorporate each of these factors and the new results were compared against the original finite element results and the experimental data. The best correlation was found when the finite element model preload was adjusted such that the mating face radius strains under only preload matched those of the experimental results.

The goal of thesis of Kathryn J. Belisle was to establish a correlation between experimental and finite element strains in key areas of an aircraft wheel bolted joint. The critical location in fatigue is the rounded interface between the bolt-hole and mating face of the joint, called the mating face radius. A previous study considered this area of a bolted joint but only under the influence of bolt preload. The study presented here considered both preload and an external bending moment. [22]

The study was done by Kadam and Joshi [23] on a bolted joint to determine the factors influencing the resistance of the bolted joint against vibration loosening. The results of their analysis using Taguchi method have been correlated using the reliability approach.

Eccles et al. [24] studied the loosening characteristics of prevailing torque nuts. They used a modified Junker test machine that allows the application of axial loading to a joint while experiencing transverse displacement. Tests have been completed using an intermittent as well as a constant axial load. Loading in both modes has been demonstrated to result in the complete detachment of this nut type. Based on this investigation, if the magnitude of the axial loading exceeds the residual preload in the bolt retained from sustaining transverse movement alone, the all-metal type of prevailing torque nut can completely detach. Applications that involve shear and axial loading being simultaneously applied to a joint are numerous in engineering. Axial loading applied while transverse joint slip is occurring also affects the loosening characteristics of standard plain nuts.

Based on the work of Junkers and other researchers, it is known that self-loosening of threaded fasteners can be prevented if sufficient preload is generated so that friction grip between the joint plates prevents the occurrence of transverse movement. In applications in which overload conditions can occasionally cause transverse joint movement, prevailing torque fasteners are frequently used in the belief that although partial loosening may occur, the nut will not become detached from the bolt. [24].

Dravid et al[26] proposed a test set up to study the effect of loading on loosening of the bolted joint.

Hattori et al. [26] investigated the loosening and sliding behavior of nut bolt fastener under transverse loading conditions. They showed that loosening behavior of nut bolt joint shows the same occurrence if the transverse load applied in the opposite direction and when transverse cyclic load applied to the joint, bolt axial tension slowly decreases and at the worst stage not only loosening occurs but bolt fails in fatigue also. Medium carbon steel plates were used by them for fastened components and ordinary bolts of carbon steel, M6, M10, M16 were used for fastening. They showed that the outcome of the result can be used for CAE design tool for machine structure. Fatigue testing machine with hydraulic pump were used in order to generate transverse cyclic loading. Bolt nut joint with sensor and to measure fastening and bending stress a strain gauge mounted on bolt neck is used.

III.CONCLUSION

Bolted joints transfer the given load from one part of the joined structure to the another joined part through bolt and this bolt failure. Failure can be minimised by washers many researcher works on this practice to improve the strength, reliability & efficiency by carrying out different experimental set up and studies. Still there is a lot of scope in this field for new work to be done in coming time.

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