# THREADED FASTENER LOOSENING DUE TO DYNAMIC SHEAR LOAD

Daniel P. Hess

Department of Mechanical Engineering, University of South Florida,
4202 E. Fowler Avenue, ENB 118, Tampa, FL 33620-5350, USA
hess@eng.usf.edu

**Abstract**
Loosening of threaded fasteners remains a widespread cause of failure in assemblies and structures subjected to dynamic loads. This paper presents results of analyses on failure of threaded fasteners by vibration induced loosening due to dynamic shear loads. Experimental work reveals fastener loosening occurs as a result of complete or localized slip at the thread and head contact surfaces. Finite element model analysis illustrates four different loosening processes that are characterized by either complete or localized slip at the head and thread contacts. The model is found to be capable of adequately modeling factors that influence slip and predicting the different loosening processes. It is found that loosening can occur at relatively low shear loads due to the process of localized slip.

## INTRODUCTION

Threaded fasteners are widely used in machines and structures because of their ability to develop a clamping force and ease of disassembly for maintenance. Research on loosening of threaded fasteners due to vibration spans nearly six decades. The reader is referred to Hess [1] for a comprehensive review of the literature. Early work [2-4] focused on loosening due to dynamic loads acting along the fastener axis (axial loading). However experimental studies in the late 1960's by Junker [5] demonstrated that loosening is more severe when the joint is subjected to dynamic loads perpendicular to the thread axis (shear loading). Loosening under shear loading was attributed to reduction of circumferential holding friction as a result of slip at the fastener surfaces caused by the applied shear load. There have been numerous studies [6-11] to model the loosening phenomenon, however none of these have accounted for the mechanism of localized slip in the loosening process. It was recently shown [12] that a fastener could turn loose under dynamic shear loading as a result of accumulation of localized slip in the form of strain at the fastener contacts surfaces. Adequate modeling of such loosening requires inclusion of fastener geometry, stiffness, as well as contact with friction. A three-dimensional finite element model that includes these features was recently developed [13] and has identified four different loosening processes that cause fasteners to turn loose under shear loading. This paper highlights some of the main features of this previous work involving localized slip.

## LOOSENING PROCESSES

Slip at the contacts under the applied load can be classified as complete slip or localized slip. Complete slip occurs when the entire contact surface (at head or threads) slips, while localized slip occurs when only parts of the contact regions slip. Complete slip requires that the loads acting on the fastener are sufficiently large to overcome friction over the entire contact, while localized slip occurs only in parts of the contact where the friction force has been overcome. Significant loosening occurs only when the entire fastener turns, which requires that the two fastener contact surfaces, i.e., at the head and threads, either undergo complete slip, or localized slip that accumulates over loading cycles. Loosening processes can be divided into four different types depending on the nature of slip at the head and thread contacts. These are characterized by 1) localized head slip with localized thread slip, 2) localized head slip with complete thread slip, 3) complete head slip with localized thread slip, and 4) complete head slip with complete thread slip. The influence of the type of slip on loosening is illustrated in Figure 1, which shows a typical preload versus cycles plot of loosening obtained using a transverse vibration test apparatus [12-13]. The loosening rate shows a drastic increase as soon as head slip changes from localized to complete slip.

Figures 2 shows finite element analysis results of loosening resulting from localized head slip and complete thread slip for a fastener with head and thread contacts lubricated with machine oil and a preload of nearly 11kN. This loosening process is the same as the initial loosening process occurring in Figure 1. Figure 2a shows a hysteresis curve, which is a plot of the shear force acting on the top plate versus its displacement. The slope of the hysteresis curve provides an indication of the joint stiffness in the transverse direction. The reduction in slope of the hysteresis curve is a sign of slip at the contacts. Figure 2b shows the state of the fastener at three points during the cycle. Black regions indicate contact regions that stick, while the gray regions indicate slip. Segments ab and cd in Figure 2a indicate parts of the cycle where the threads undergo complete slip while the head contact undergoes localized slip (see Figure 2bi and 2biii). Both thread and head undergo localized slip during parts of the cycle indicated by the steeper segments bc and da (Figure 2bii). Note that head contact regions that stick during the first half of cyclic loading, slip during the second half (see Figure 2bi and 2biii). This enables the entire head contact to slip over a complete cycle.

Figure 3 illustrates loosening caused by complete head slip and complete thread slip for the thread and head contacts lubricated with machine oil and at a preload of approximately 5.5kN. The hysteresis curve shown in Figure 3a indicates regions with three distinct slopes. Region i reflect parts of the loading where complete thread slip occurs and the head undergoes localized slip (Figure 3bi). At region ii the entire head and thread slip as shown in Figure 3bii. The initial stage of the unloading portion of the cycle is seen to have a higher slope because of localized slip at both the head and the thread (see Figure 3biii). This loosening process corresponds to the loosening occurring at a rapid rate in Figure 1.

Hysteresis curves of the loosening process characterized by complete head slip and localized thread slip are shown in Figure 4 for a fastener with $MoS_2$ grease at the head and dry threads with a preload of about 11.9kN. The hysteresis curve is characterized by two distinct slopes. The stiffer segments indicate parts of loading where the head and thread undergo localized slip (see Figure 4bi). Regions ii and iii reflect parts of the cycle where the entire head slips, while the threads continue to undergo localized slip (see Figure 4bii and 4biii). From Figures 4bii and 4biii it is seen that different parts of the threads stick during different parts of the cycle (note that orientation of the ii is opposite of that of iii).

Figure 5 illustrates the loosening process resulting from localized head and localized thread slip with dry threads and $MoS_2$ grease at the head and at preload of nearly13.2kN. The hysteresis curve shows nearly the same stiffness at all regions with a very slight reduction in the slope as the thread slip region increases. The regions of localized slip (Figure 5b) are seen to vary at different parts of the cycle, however the lower thread contact stick throughout the entire cycle.

The above finite element analysis results illustrate the four possible loosening processes that can occur in a threaded fastener subjected to dynamic shear loads. Of these four processes, only three are widespread in practice. In the typical case of fastener loosening, the initial stage of loosening is characterized by localized slip at both the head and the threads. This progresses to loosening by localized head slip with complete thread slip, and eventually to complete slip at the head and the threads. In some cases, the initial loosening starts with localized head slip and complete thread slip, and progresses to complete slip at the head and the threads. The loosening rate at the initial stages characterized by localized slip is fairly low and increases as the loosening transitions from localized to complete slip (see Figure 1). A contribution of the present work is the identification of loosening caused by localized slip. Loosening at the initial stages resulting from localized slip is critical since it can occur at a significantly lower shear load than that required for complete slip. For example, in the data shown earlier, loosening by localized slip (Figure 2a) occurs when the magnitude of the shear force acting on the joint is approximately 9% of the preload, while loosening by complete slip (Figure 3a) occurs when the shear force is 16% of the preload. In this case, loosening by localized slip occurs at about half of the load required to cause complete slip. Loosening by localized slip is therefore the critical loosening process from a perspective of joint design. Loosening failure in a joint can be avoided by ensuring that the dynamic loads acting on the fastener are lower than the loads required to cause loosening by localized slip.

## COMPARISON WITH EXPERIMENTS

Figure 6 shows hysteresis curves comparing experimental data with FE results for the four different loosening processes.  The FE results agree reasonably well with experimental results as far as displaying the four loosening processes reflected by the slopes of the hysteresis curves.  Figure 6a shows the hysteresis curves for the screw lubricated with oil at the threads and head at preloads of 11kN and 5.5kN.  The hysteresis curves at the higher preload representing loosening by localized head slip and complete thread slip show a very good match.  The comparison of loosening process of complete head and thread slip at the preload of 5.5kN capture the trends, however the net slip occurring during complete head slip is smaller in the FE results than in the experiments.  The amount of slip reflected in the hysteresis curve is a function of the fastener dimensions, and is largely influenced by the clearance between the internal and external threads.  The difference in results is most likely because the thread dimensions utilized for the FE simulations were defined in the middle of the allowable range for Class 2A/2B threads, and the thread dimensions in the test specimens may be slightly different.

The hysteresis curves shown in Figure 6b show loosening by complete head slip and localized thread slip for a screw with $MoS_2$ grease at head and dry threads at 11.9kN preload.  The FE result is seen to capture the experimental data quite well, and as with the previous case the slip is slightly smaller.  A similar trend is observed for loosening caused by localized thread and head slip shown in Figure 6c for the same lubrication condition at 13.2kN preload.

In all four cases, especially in Figures 6b and 6c, the FE results are seen to be slightly stiffer than the experimental data.  This is because the FE model includes six threads before the first engaged thread instead of twelve threads found in the test specimens.  The additional threads in the screws used in the experiments contribute to the lower bending stiffness observed in the experimental data.  A FE model with twelve exposed threads could not be used because of the significant additional computational cost.  The influence of this omission is clearly not very significant as indicated by the reasonably good comparisons between the results.

In all the cases presented in this work, the fastener preload has been fairly low so has to minimize the influence of localized thread yielding, which is likely to influence the thread load distribution.  Inclusion of thread yielding in the FE model requires a denser mesh to ensure accurate determination of stresses.  This was not attempted at this stage of the study due to the extremely high computational cost.  The effect of thread yielding on loosening will be addressed in future work.          .

## CONCLUSIONS

The experimental measurements and finite element model results presented illustrate four different loosening processes and the presence of both localized and complete head and thread slip.  The finite element results capture the essential features displayed by the experimental data. The model includes the primary factors that cause loosening, and provides a powerful tool for evaluation of the details of fastener loosening. The loosening process caused by localized slip can occur at significantly lower shear force than loosening caused by complete slip, and therefore is critical in joint design.

## REFERENCES

1. D. Hess, "Vibration- and shock- induced loosening," *Handbook of Bolts and Bolted Joints* (Bickford JH, Nasser S, editors). New York: Marcel Dekker, 757-824 (1998)
2. J. Goodier, R. Sweeney, "Loosening by vibration of threaded fastenings," Mechanical Engineering, **67**, 798-802 (1945)
3. J. Sauer, D. Lemmon, E. Lynn, "Bolts: How to prevent their loosening," Machine Design, **22**, 133-139 (1950)
4. S. Gambrell, "Why bolts loosen," Machine Design," **40**, 163-167 (1968)
5. G. Junker, "New criteria for self-loosening of fasteners under vibration," SAE Transactions, **78**, 314-335 (1969)
6. T. Sakai, "Investigations of bolt loosening mechanisms (1st Report, On bolts of transversely loaded joints)," Bulletin of JSME, **21**, 1385-1390 (1978)
7. A. Yamamoto, S. Kasei, "A solution for self-loosening mechanism of threaded fasteners under transverse vibration," Bulletin Japan Society of Precision Engineering,**18**, 261-266 (1984)
8. O. Vinogradov, X. Huang, "On a high frequency mechanism of self-loosening of fasteners," Proceedings of 12th ASME Conference on Mechanical Vibration and Noise, Montreal, Quebec, 131-137 (1989)
9. A. Daabin, Y. Chow, "A theoretical model to study thread loosening," Mechanism and Machine Theory," **27**, 69-74 (1992)
10. R. Zadoks, X. Yu, "An investigation of the self-loosening behavior of bolts under transverse vibration," Journal of Sound and Vibration, **208**,189-209 (1997)
11. S. Kasei, H. Matsuoka, "Considerations of thread loosening by transverse impacts," ASME Pressure Vessels and Piping Division, **367**, 117-123 (1998)
12. N. Pai, D. Hess, "Experimental study of loosening of threaded fasteners due to shear dynamic shear loads," Journal of Sound and Vibration, **253**, 585-602 (2002)
13. N. Pai, D. Hess, "Three-dimensional finite element analysis of threaded fastener loosening due to dynamic shear load," Engineering Failure Analysis, **9**, 383-402 (2002)

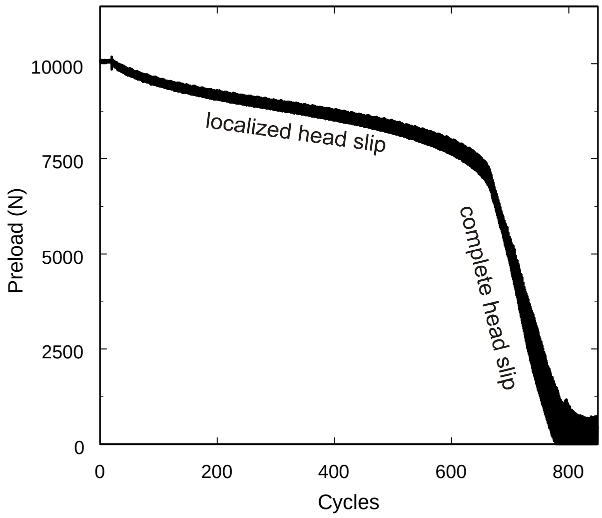


*Figure 1     Typical loosening sequence of a screw during a transverse vibration test.*

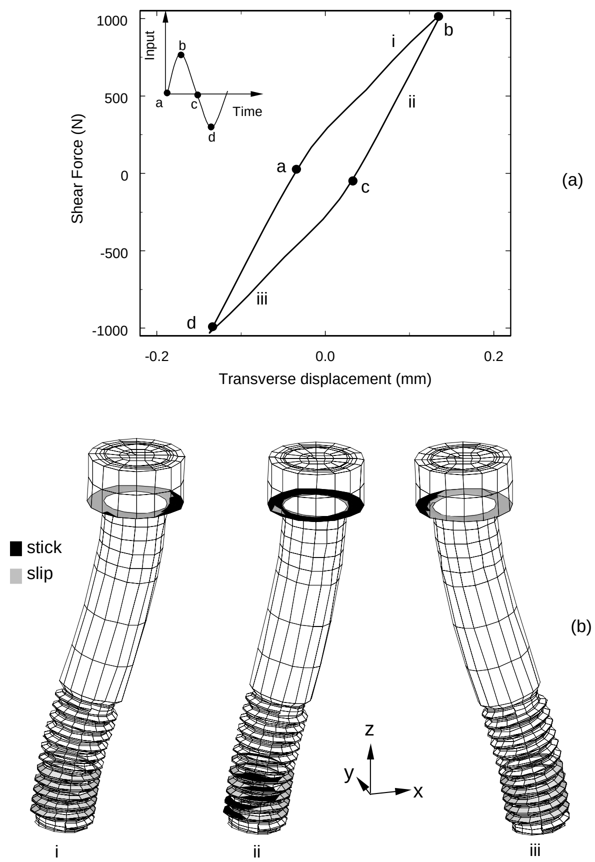


*Figure 2     Loosening process characterized by localized head slip with complete thread slip: (a) hysteresis curve, and (b) contact status.*

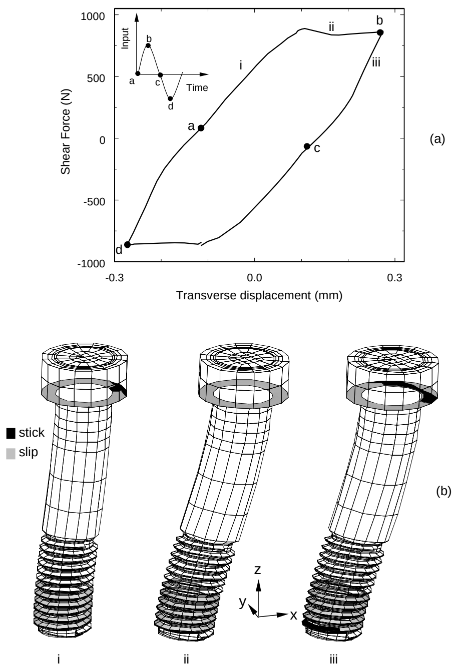


*Figure 3 Loosening process characterized by complete head slip with complete thread slip: (a) hysteresis curve, and (b) contact status.*

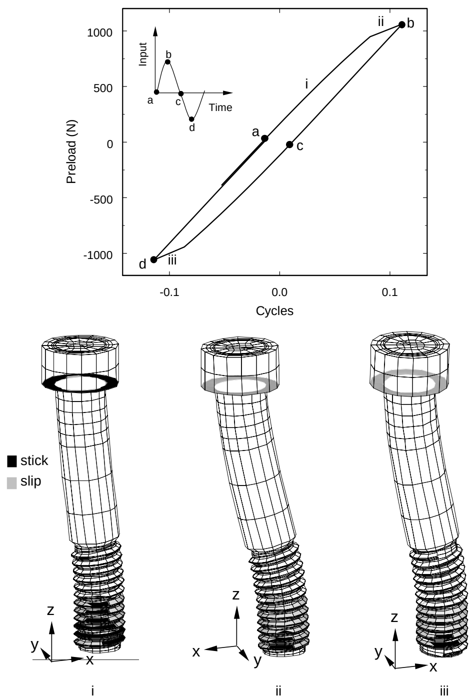


*Figure 4 Loosening process characterized by complete head slip with localized thread slip: (a) hysteresis curve, and (b) contact status.*

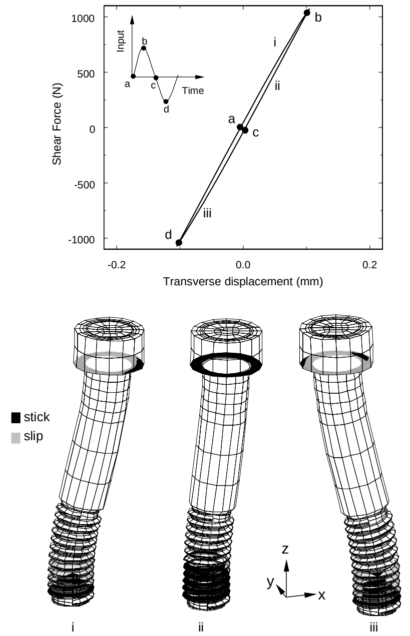


*Figure 5 Loosening process characterized by localized head slip with localized thread slip: (a) hysteresis curve, and (b) contact status.*

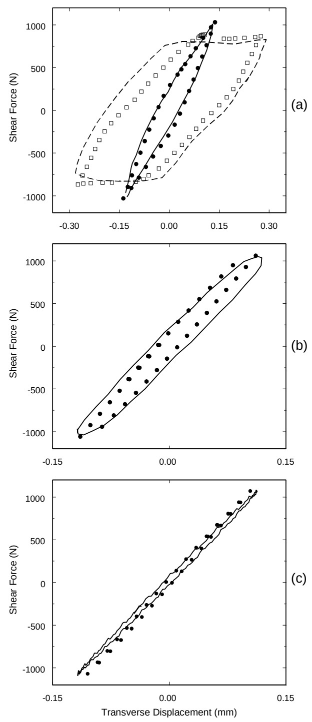


*Figure 6 Comparison of experimental hysteresis curves and FE results.*