Journal of Sound and Vibration (2002) **253**(3), 585–602
doi:10.1006/jsvi.2001.4006, available online at http://www.idealibrary.com on IDEAL®

EXPERIMENTAL STUDY OF LOOSENING OF THREADED FASTENERS DUE TO DYNAMIC SHEAR LOADS

N. G. Pai and D. P. Hess

Department of Mechanical Engineering, University of South Florida, 4202 *East Fowler Avenue, ENB* 118, *Tampa, FL* 33620, *U.S.A. E-mail*: *hess@eng.usf.edu*

(*Received* 10 *April* 2001, *and in final form* 19 *August* 2001)

This paper presents a study on loosening of threaded fasteners subjected to dynamic shear loads. A fundamental analysis of loosening reveals 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. Experimental results illustrating these loosening processes are presented. In addition, the minimum dynamic shear force required to initiate loosening is determined experimentally.

1. INTRODUCTION AND BACKGROUND

Most machines and structures are assemblies of simpler components. Fastening and joining technology used to assemble the components is a key feature of practically all modern machines. Threaded fasteners are commonly used in assemblies due to the advantages they offer, such as the ability to develop a clamping force, and the ease of disassembly for maintenance and repair. Clamping force in a bolt is commonly developed by turning the engaged nut such that it moves against a clamped component and causes an axial elongation in the bolt. The resulting clamping force is a function of the joint stiffness and the bolt axial elongation. It has been widely observed that fasteners turn loose when subjected to dynamic loads in the form of shock, vibration or cyclic thermal loading. This reduces the clamping force and leads to joint failure. Such failures result in higher maintenance expense, costly downtime in machines, and can be catastrophic in safety critical applications.

There have been several studies relating to this problem scattered over the past six decades. For a comprehensive review of the literature and popular methods used to avoid loosening, the reader is referred to recent surveys on the subject [1, 2]. Early research on the subject [3, 4] focused on loosening due to a dynamic load acting along the axis of the fastener (axial loading). Loosening under axial loading was attributed to "frictional ratcheting" action due to nut dilation resulting from radial deformation governed by the Poisson ratio of the materials. Junker [5] showed in the 1960s that transverse or shear loading (perpendicular to the fastener axis) is the most severe form of loading for vibration-induced loosening, and that loosening results from gross slip at the head and thread interfaces. Several studies have been performed to model the loosening of fasteners [6–12] subjected to dynamic shear loading. While each of these studies have contributed to the understanding of loosening, several features that cause slip under shear loading have not been identified. The analysis presented in this paper illuminates the various causes of slip under shear loading and further reveals that there are mainly four possible processes of loosening characterized by gross and localized slip.

0022-460X/02/$35.00

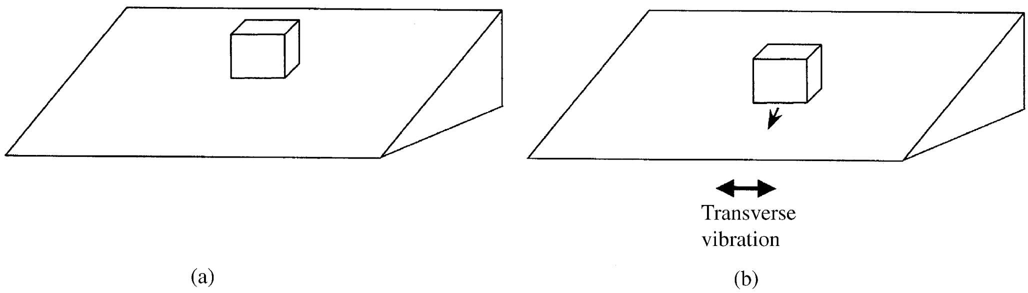

Figure 1. Block on incline system.

Perhaps the incomplete understanding of the loosening process is responsible for limited formal quantitative design guidelines to avoid loosening in spite of the widespread nature of the problem. General guidelines for minimizing the problem include using bolts with large length-to-diameter ratio [13], using high preloads to avoid slip between joints [2, 5], reorienting the joint to subject the fastener to axial loading instead of shear loading, and adding features to minimize slip at the joint [2]. Solutions such as reorienting the joints or redesigning the joint are not always feasible, and effectiveness of the other guidelines is generally difficult to evaluate. As a result, the most widespread solution is the use of various commercially available "anti-loosening" products. However, studies on effectiveness of such features have pointed to the limitations of some of them [14, 15]. Moreover, such products generally add to the cost, weight as well as assembly and disassembly time.

In the light of the existing state, there is a need for a more complete understanding of the vibration-loosening phenomenon. Specifically, it is essential to identify the primary factors that contribute to loosening. This knowledge can then be used to develop quantitative guidelines for the design of joints subjected to dynamic loads, as well as to provide a more complete insight for designers to select anti-loosening devices when needed. In this paper, loosening is viewed as a process involving various causes of slip. The primary causes of slip are identified first, and then the loosening processes for a screw are discussed. These processes are illustrated through experimental results. In addition, the minimum dynamic shear load required to cause loosening is determined experimentally for a few representative cases.

2. SLIP AT FASTENER CONTACT REGIONS

The most widely cited theory for loosening of fasteners under dynamic shear loading was proposed by Junker [5]. This can be illustrated using a block on incline system shown in Figure 1. Here the friction force between the upper block and the incline is sufficient to prevent the block from sliding down the incline in the absence of external loads (see Figure 1(a)). When the incline is subjected to a transverse vibration large enough to overcome the friction between the block and the incline, the block not only slips in the transverse direction, but also down the incline (Figure 1(b)). It is reported [5] that this happens because as soon as friction is overcome in the transverse direction due to the transverse vibration, the joint becomes "free of friction" in other directions. Applying this to a threaded fastener system (see Figure 2), it is stated [5] that as soon as the applied shear loads overcome friction in the transverse direction, the joint becomes free of circumferential friction, and the loosening moment developed due to the component of the preload around

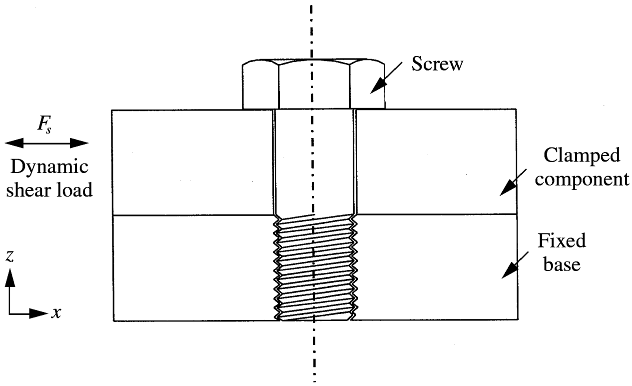

Figure 2. Screw joint subjected to dynamic shear load.

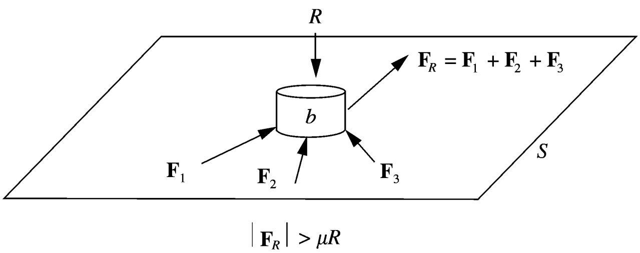

Figure 3. General requirement for slip.

the thread helix causes the fastener to loosen. Although the behavior of friction in this early explanation for loosening is not entirely accurate, it is correct in pointing out that externally applied transverse forces can significantly reduce the holding circumferential friction. A more general treatment of loosening that further develops the above theory starting from basic principles is presented below.

Loosening by definition requires slip between the fastener surfaces, more specifically, it requires slip in the circumferential direction in the loosening sense. For slip to occur, the friction force between two contact surfaces must be overcome by the resultant force tangent to the interface. This general requirement for slip is illustrated in Figure 3, which shows body *b* lying on surface *s*. The friction force that opposes relative motion between *b* and *s* is assumed to take a maximum value of μR, where R is the magnitude of the normal reaction force between *b* and *s*, and μ is the coefficient of friction. For slip to occur between *b* and *s*, the magnitude of the resultant tangential forces acting on *b*, $\mathbf{F}_R = \mathbf{F}_1 + \mathbf{F}_2 + \mathbf{F}_3$, must exceed the magnitude of the friction force, μR. Note that the direction of slip is the same as the direction of the resultant tangential force, $\mathbf{F}_R$.

From the above general condition for slip, it follows that loosening of a threaded fastener will occur if the following two conditions are satisfied at all the fastener contact surfaces: (1) at least one of the forces acting at the contact surfaces acts in the loosening direction (i.e., there is a loosening moment acting on the fastener), and (2) the resultant of all the forces acting tangent to the contact surface overcomes the friction force.

Consider the shear joint shown in Figure 2. It consists of a preloaded screw that attaches the clamped component to a fixed base. The clamped component is subjected to a dynamic shear load, F_S, as shown. Even in the absence of the external shear force, the first

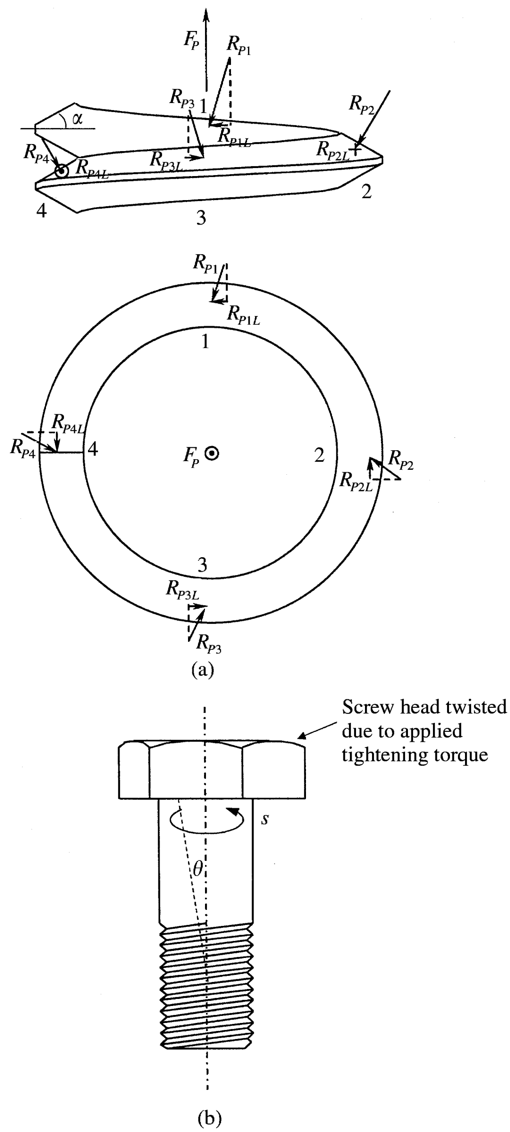

Figure 4. Loosening moments without shear load: (a) moment from component of thread reaction to preload, and (b) moment from torsion stored during tightening.

requirement of loosening is satisfied due to the helical geometry of the thread which produces a loosening moment due to the circumferential components of the reaction forces around the thread. This is illustrated in Figure 4(a), which shows the reaction forces, $R_{Pn,n=1,\ldots,4}$, at four points along the thread due to the preload, F_P. Components of the reaction force tangential to the thread helix, $R_{PnL,n=1,\ldots,4}$, contribute to a loosening moment about the fastener axis. This is commonly illustrated using the general torque-preload equation [2], which has been modified below to represent the condition for maintaining the preload in the absence of external loads:

$$\frac{pF_P}{2\pi} < F_P \frac{\mu_T r_T}{\cos\alpha} + F_P \mu_H r_H, \tag{1}$$

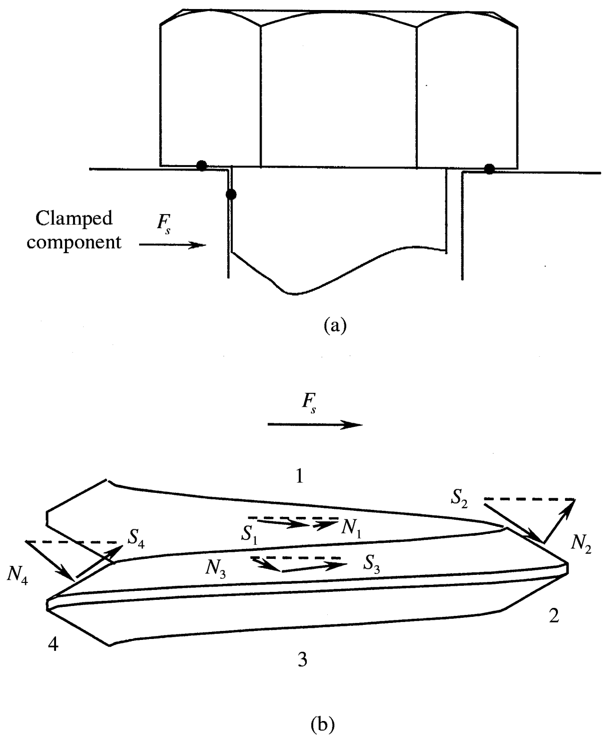

Figure 5. (a) Slip at head due to applied shear force, and (b) forces at thread due to applied shear load.

where p is the thread pitch (mm), F_p the preload (N), μ_T the coefficient of thread friction, r_T the effective thread contact radius (mm), α the half thread angle (30° in most cases), μ_H the coefficient of head friction, and r_H is the effective head contact radius (mm).

The term on the left-hand side of equation (1) is the loosening moment developed due to the preload and helical slope of the thread, while the terms on the right-hand side of the equation are the holding friction moments at the thread and the head, respectively.

In most applications with screws, the preload is developed by applying a tightening torque to the screw head. A portion of the applied torque is retained in the screw as torsion due to the friction at the head and thread contact surfaces (Figure 4(b)). This stored torsion in the bolt also provides a loosening moment at the head at the onset of loosening.

In the absence of external loads, the second requirement for loosening is generally not satisfied since the magnitude of the loosening moment due to the preload and the stored torsion is in equilibrium with the frictional moments. It follows that for the second requirement of loosening to be satisfied, external loads acting on the fastener must contribute in order to overcome the friction forces. Several major factors that contribute to satisfying the second requirement as a result of an applied shear load are discussed below with reference to the system shown in Figure 2.

The most apparent factor that contributes to slip is an applied shear force [5]. The shear force is transferred from the clamped component to the fastener through friction between the head-bearing surface and the clamped component, and possibly due to contact between the fastener and surface of the hole in the clamped component (see Figure 5(a)). To illustrate the effect of the shear force at the threads (Figure 5(b)), the shear force has been resolved along the thread surface and normal to the thread surface. The components of shear force

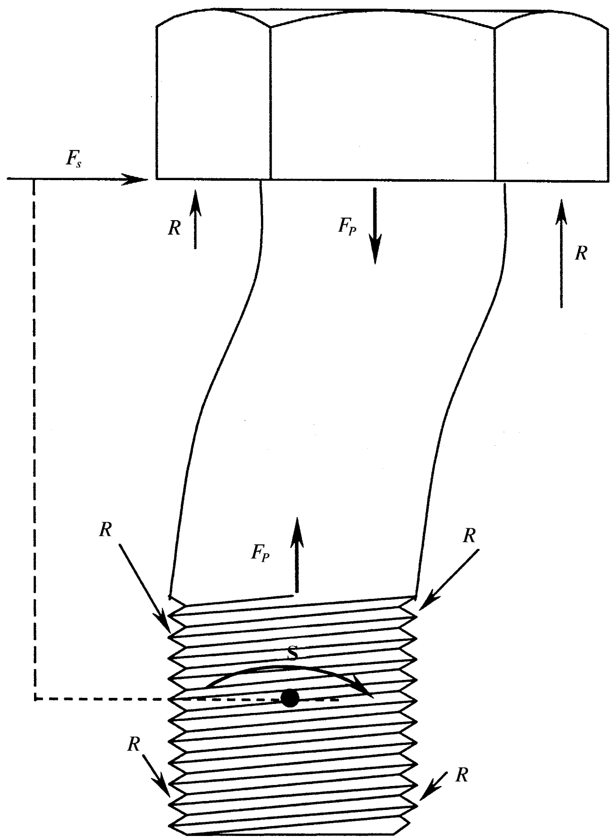

Figure 6. Bending of screw and associated slip at threads due to applied shear force.

acting along the thread surface (shown at four points), $S_{n,n=1,\dots,4}$, contribute to slip. The components acting normal to the thread surface, $N_{n,n=1,\dots,4}$, alter the normal contact force between the internal and external threads. Components N_1 and N_2 increase the normal contact force, while N_3 and N_4 reduce any existing normal contact force (such as due to the preload). In the cases where there is net increase in the normal contact force due to the applied shear force, the resulting increased thread reaction force contributes to the loosening moment due to its circumferential component shown earlier in Figure 4(a).

The shear force acting at the fastener head develops a bending moment on the fastener as shown in Figure 6. The bending moment causes the thread surfaces to turn about the bending axis (a line going into the page). Thread slip due to the bending moment is represented by S in Figure 6. It can be seen that the bending moments cause the normal reaction, R, to change at the head and the threads. If the moment is sufficiently large, certain regions of the head (e.g., the left side) can even lose contact. In addition, an increase in the thread reaction force due to the bending moment would contribute to the circumferential loosening moment shown in Figure 4(a).

The final factor that contributes in overcoming the friction force is the elastic deformation at the contact surfaces. This is illustrated in Figure 7, which shows the state of the screw head and a thread before and after application of a load, F. As a result of the load, the screw head bends, and the resulting elastic deformation at the contact surfaces tends to cause slip. In addition to bending, elastic deformation can also occur at the contact surfaces due to

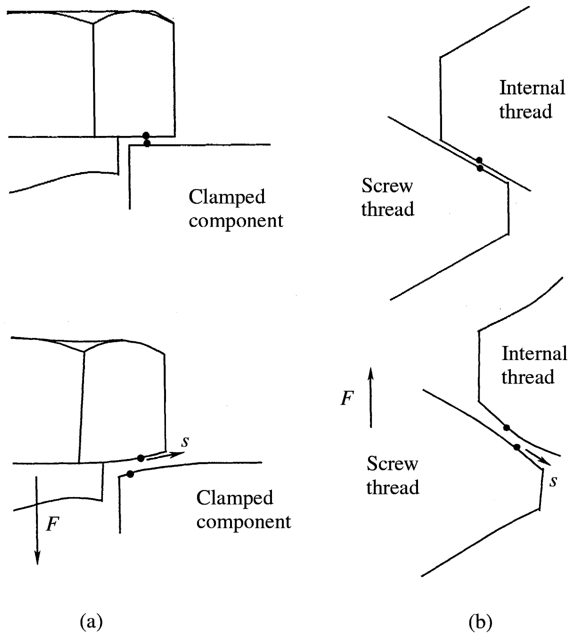

Figure 7. Slip due to elastic deformation: (a) at screw head, and (b) at a thread.

axial loads as governed by the Poisson ratio of the materials. Note that any change in load (increase or decrease) changes the elastic deformation, and therefore contributes to slip. Under dynamic shear loading, the load at the contact regions changes due to the applied shear force (Figure 5) and the bending moments (Figure 6).

Major factors that satisfy the two requirements for loosening can be summarized as follows. The loosening moment required for loosening is developed due to the circumferential component of the reaction force around the thread helix. The preload (Figure 4(a)), the applied shear force (Figure 5(b)), and the bending moment (Figure 6) contribute to the reaction force at the threads that develops the loosening moment. In addition, torsional energy stored during tightening (Figure 4(b)) can contribute to initial stages of loosening. Factors that contribute to overcoming the friction force, and thereby satisfying the second requirement for loosening, are the shear force (Figure 5(a) and 5(b)), the bending moment (Figure 6), and the elastic deformations of the contacting bodies (Figure 7).

An important feature of slip in fasteners is that it is influenced by clearances that determine the state of side contact between the internal and external threads, as well as between the fastener and the sides of the clamped component hole. Once side contact occurs, the components of the forces acting normal to the side contact are opposed by the normal reaction at the contact interface instead of friction. As a consequence, the resultant slip force that acts to overcome friction is reduced. In addition, the side contact also provides additional frictional resistance to the slip tangential to the contact, i.e., in the circumferential direction.

3. LOOSENING PROCESSES

The previous section highlights the causes of slip resulting from an applied shear force. The applied shear force also changes the reaction force distribution as illustrated by

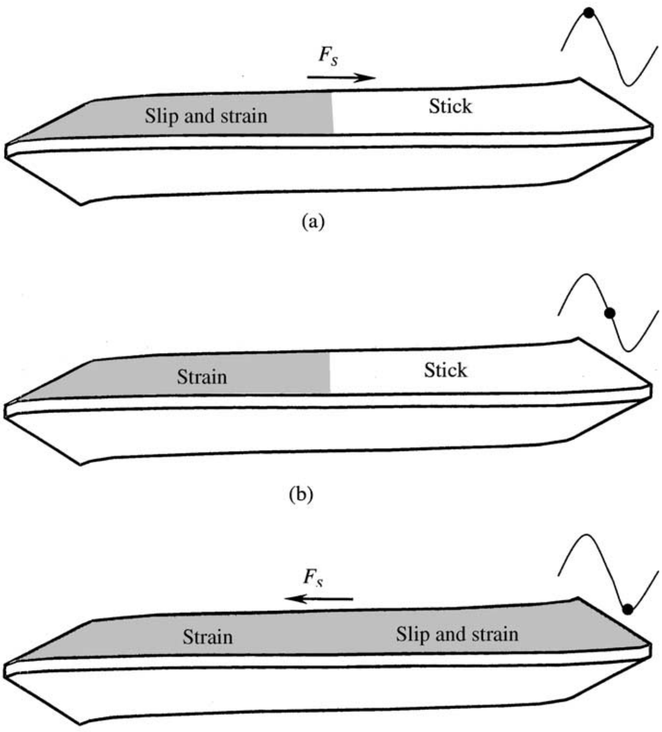

Figure 8. Accumulation of localized slip over a cycle of loading.

Figures 5(b), and 6. Since friction force is a function of the normal reaction, it follows that the friction force developed at the contact regions is influenced by the change in reaction force. It is evident that both the slip force distribution and the friction force distribution are not uniform at the contact regions. In addition, since the various causes of slip described are mainly a function of the applied shear force, the slip force is not just directly related to the normal force. As a result, the condition for slip might be satisfied in certain regions of contact, while the remaining contact regions stick. The occurrence of slip in local regions of contact is defined as the process of localized slip. Localized slip generally occurs in regions with low normal reaction and corresponding low frictional resistance.

The screw in the joint shown in Figure 2 will undergo significant loosening only if entire contact regions at the head and thread undergo slip in the loosening sense. When a joint is subjected to cyclic shear load, localized slip occurring at the contact surfaces can accumulate over the loading cycles and cause loosening slip over the entire contact. To qualitatively illustrate the process, consider Figure 8, which shows a thread at three different times during applied cyclic shear load. At the point when the shear load acts in the right direction, the left region of the threads undergoes slip due to the various causes of slip discussed earlier. Since the slip is localized, the threads undergo local elastic deformation, which includes a component in the circumferential direction due to the loosening moment. As the shear load is reduced, part of the deformation is retained as strain energy by friction (Figure 8(b)). When the shear force direction changes (see Figure 8(c)), the right side of the threads undergoes slip; consequently, there is slip over the entire thread contact over one cycle of shear loading which is stored as strain (see Figure 8(c)). The result from the above process is a torsional strain on the entire thread surface. The above process of localized slip might be initially restricted to a few threads, and subsequently progress to all the threads. The loosening moment developed due to torsion at the threads acts on the screw head, and causes the head to turn in a similar process of localized slip.

From the above example, it can be seen that in addition to the various factors presented in section 2 (see Figures 4–7), the strain energy stored by the friction due to localized deformation also contributes to slip. Note that preload, torsion stored due to tightening torque (Figure 4(b)), and strain energy due to localized deformation (Figure 8) are all a result of friction-storing energy from an applied load in the form of elastic deformation. It follows that friction can store strain energy from other forms of deformation, such as bending of the bolt, and this stored energy also contributes to slip.

The process of localized slip accumulating over a complete cycle can occur at a relatively low shear load compared to the shear load required to cause complete slip. At sufficiently high amplitudes of shear, the condition for slip is satisfied over the entire contact. In such cases, the entire contact undergoes slip in less than half a loading cycle. For a fastener to loosen, the contact surfaces at the head and thread must either undergo localized slip that accumulates, or complete slip. Any combination of the above conditions will lead to loosening. For example, localized slip at the head and complete slip at the thread is a sufficient condition for loosening. If however, either of these conditions is not satisfied at the thread and the head, then there can be no loosening. As a result, the following four possible processes of loosening exist: (1) localized head slip and localized thread slip; (2) localized head slip and complete thread slip; (3) complete head slip and localized thread slip; (4) complete head slip and complete thread slip. The fourth process is the process of loosening which has been previously modelled [6–12].

An important aspect of all four loosening processes is that after the initially stored torsion (Figure 4(b)) is lost, the loosening moment at the head is provided by the torsion developed by the slip and the resulting strain at the threads. This implies that all loosening processes after the loss of initially stored torsion involve thread loosening, which causes torsion in the screw body, followed by head loosening.

4. EXPERIMENTS

4.1. LOOSENING PROCESSES

Loosening processes of a screw subjected to dynamic shear load was studied experimentally with a machine similar to the transverse vibration tester developed by Junker [5]. Figure 9 shows the schematic layout of the test machine. It consists of a top plate clamped to a rigid fixed base through a threaded insert using the test screw. Roller bearings are placed between the top plate and the fixed base to minimize sliding friction, and prevent galling. Cyclic shear load is applied to the top plate by an arm connected to an eccentric setting which is driven by a 5 HP AC motor through a pulley arrangement. Load cells are used to measure the shear force acting on the top plate, and the screw preload. In addition, the transverse displacement of the plate is measured through an LVDT placed at the end of the plate.

Figure 10 shows a typical hysteresis curve that is used to study the loosening process of a fastener during a cycle of loading. It is a graph of the shear load acting on the top plate versus its transverse displacement. The slope of the graph represents the transverse stiffness of the test joint. In the absence of slip, the screw would merely bend and therefore the graph would be a straight line. However, due to slip at the thread and head, the slope of this graph reduces and over a complete cycle it forms a hysteresis loop. The slope of the hysteresis

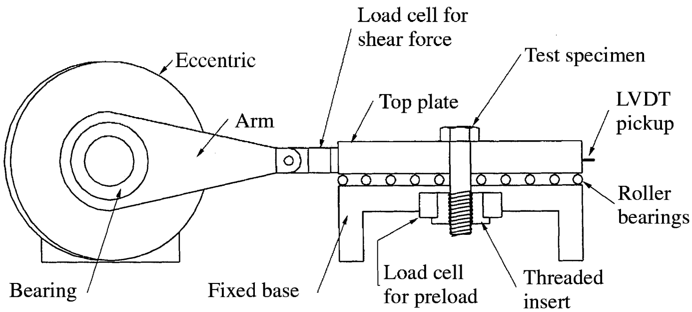

Figure 9. Transverse vibration test apparatus.

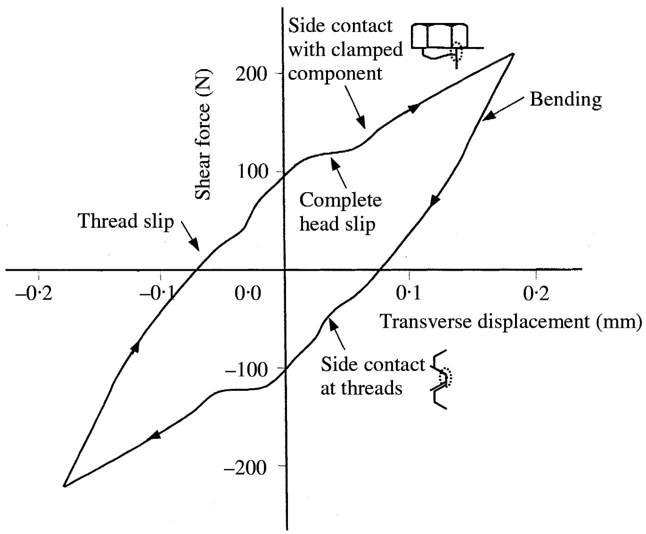

Figure 10. General features of hysteresis curve.

curve is steepest when pure bending occurs, and lowest when complete head slip occurs. The increase in slope after complete head slip (see Figure 10) occurs as a result of contact of the screw body with the internal surface of the hole in the clamped components. Another important characteristic of the hysteresis curve is the small stiffening that occurs before head slip, which indicates a side contact at the threads. In addition to the hysteresis curve, loosening can also be assessed by observing preload as a function of the loading cycles (see Figure 12(b) for example).

A large number of tests were conducted to study the loosening processes of a variety of fasteners under different friction and shear loading conditions. Figure 11 illustrates the four loosening processes described in the previous section for a 63·5 mm long, Grade 5, 0·5–13 UNC screw (12·7 mm diameter) with different preloads as well as different head and thread lubrications at ± 1 mm eccentric setting. Curve 1 (solid line) represents the loosening process due to localized head slip and localized thread slip at a preload of 10·4 kN with both head and threads lubricated with machine oil. Curve 2 (dotted line) represents the loosening process characterized by localized head slip and complete thread slip at 8·8 kN preload with the screw head lubricated with machine oil, and the threads with MoS_2 grease. Note that

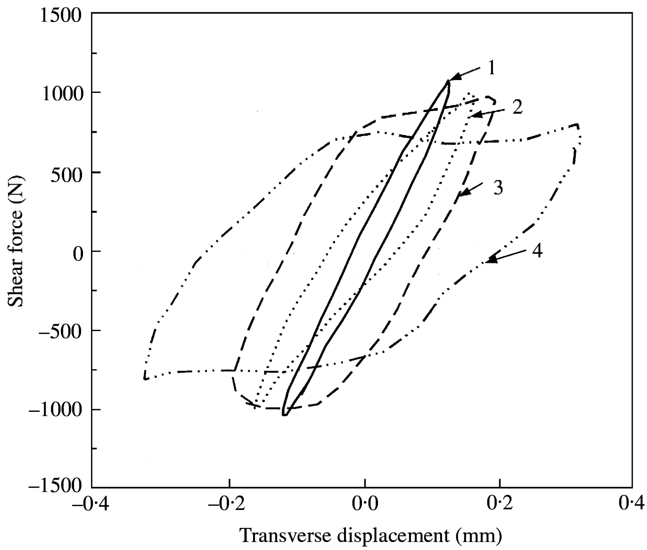

Figure 11. Hysteresis curves for different loosening processes: ——, localized head slip with localized thread slip; · · ·, localized head slip with complete thread slip; - - -, complete head slip with localized thread slip; – · · · –, complete head slip with complete thread slip (63·5 mm long, Grade 5, 0·5–13 UNC screw, $\pm$ 1 mm eccentric setting).

the slope of curve 1 is steeper than curve 2, which indicates partial thread slip at curve 1, and complete thread slip at curve 2. Curve 3 (dashed line) represents the loosening process of complete head slip and localized thread slip. This was obtained at a preload of 8·8 kN with MoS_2 grease at the head, and machine oil at the threads. Comparing curves 1–3, it can be seen that the slope of curve 3 reduces at high amplitudes of shear force due to the occurrence of head slip, which does not occur for curve 1. Finally, curve 4 (dot-dash line) represents the loosening process of complete slip at the head and the threads for the same lubrication condition as curve 2, but at a preload of 6·5 kN. Note that until the occurrence of head slip (indicated by nearly zero slope), the curve has a slope comparable to that of curve 2.

Figure 12 shows the progressive loosening process of a 63·5 mm long, Grade 5, 0·5–13 UNC 13 screw lubricated with machine oil at the head and threads. The hysteresis curves shown in Figure 12(a) indicate that the loosening process starts with partial head slip and complete thread slip and then progresses to complete slip at both head and threads. The hysteresis curves at lower preloads also indicate the occurrence of side thread contact, and side head contact. Figure 12(b) shows the preload versus loading cycles, which is seen to be fairly uniform.

Figure 13(a) shows other commonly obtained preload versus cycles graphs. Curve 1 illustrates the case where loosening ceases after a few cycles with a 63·5 mm long, Grade 5, 0·5–13 UNC screw. In such cases, the initial loosening is due to the contribution of the stored torsion energy developed during tightening of the screw. The other two curves illustrate the case where a drastic change in the rate of loosening is observed. Curve 2 was obtained for 63·5 mm long, Grade 5, 0·5–13 UNC screw with MoS_2 grease at the head and machine oil at the threads, while curve 3 was obtained with machine oil at the head and MoS_2 grease at the threads. To understand the cause of the change of rate of loosening, the hysteresis curves at two points were obtained (see Figure 13(b) and 13(c)). Figure 13(b) shows the hysteresis curves at points A and B for curve 2. It can be seen that loosening at the initial rate of loosening is characterized by localized thread slip, while that at the high rate of loosening is characterized by complete thread slip. Similarly, from Figure 13(c), the

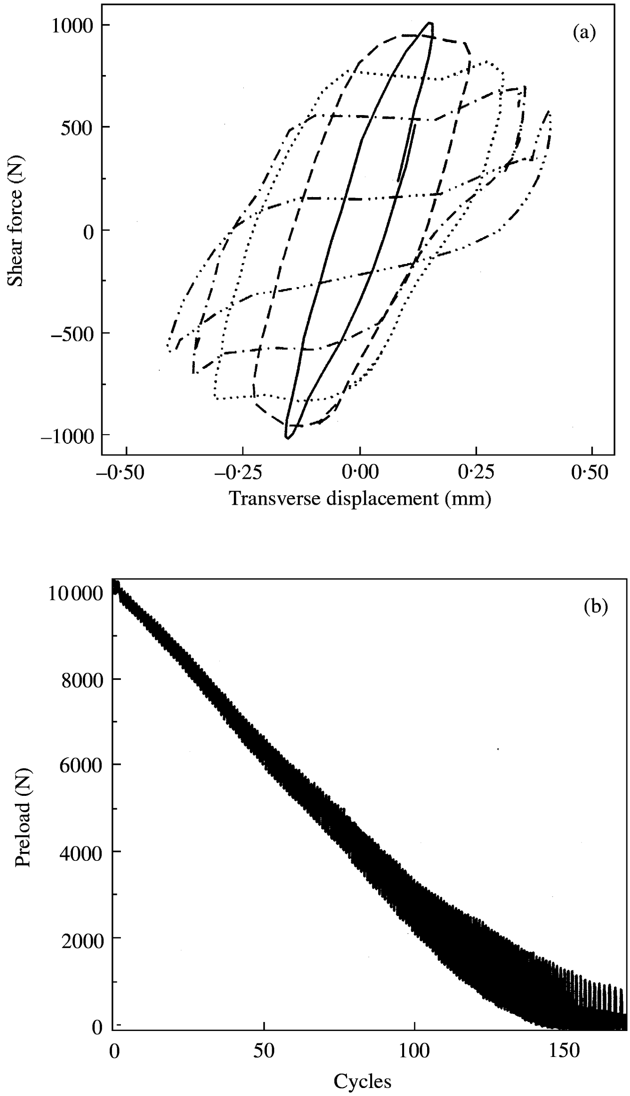

Figure 12. Progressive loosening of screw: (a) hysteresis curves at different preloads: ——, 10 kN; - - -, 9 kN; · · ·, 7·5 kN; ·-·-·-, 5 kN; -·-·-, 3·6 kN, and (b) preload versus cycles (63·5 mm long, Grade 5, 0·5–13 UNC screw, machine oil at head and threads, loading at 15 Hz with $\pm$ 1 mm eccentric setting).

loosening process at the initial rate of loosening is characterized by localized head slip at point A, but by complete head slip at the rapid rate of loosening (point B). These data suggest that the rate of loosening reflects the loosening process changing from localized slip to complete slip at the head or the thread. For the earlier case shown in Figure 12(b), the transition from localized head slip to complete head slip occurs within the first 5 cycles; therefore, the rate seems nearly uniform.

4.2. CRITICAL SHEAR FORCE

One recommendation for the design of joints [2, 5] to avoid loosening is that the shear force should be lower than the friction force between the clamped components. For the joint

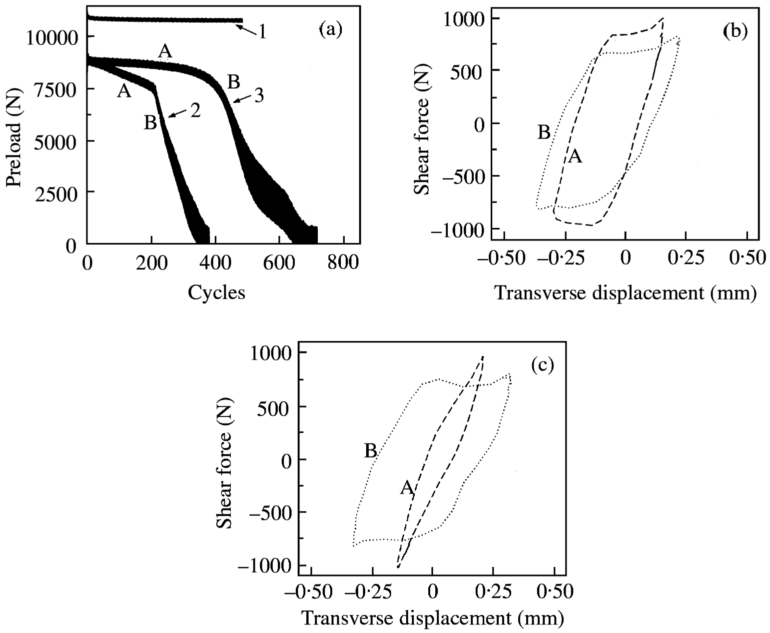

Figure 13. (a) Different characteristics of loosening rate observed during experiments; (b) hysteresis curves for case 2: - - -, point A; ····, point B, and (c) hysteresis curves for case 3: - - -, point A; ····, point B.

shown in Figure 2, this requirement can be stated as

$$F_S < \mu_C F_P, \tag{2}$$

where μ_C is the coefficient of friction between the clamped components.

Another design recommendation for shear joints is to exclude the effect of friction between the clamped components in design calculations (i.e., $\mu_C = 0$) due to the large uncertainty involved with friction [16]. Here the entire applied shear load is assumed to act on the fastener. If the shear loads acting on such joints are dynamic, then loosening is possible. Such a failure can be avoided by ensuring that the dynamic shear load is insufficient to cause fastener loosening.

It has been shown [5] that under shear loading, fastener threads generally slip before the head. Therefore in general, the occurrence of loosening is determined by the state of head slip. The requirement for avoiding loosening due to complete head slip can be stated in simple terms as

$$F_S < \mu_H F_P. \tag{3}$$

The above expression is based on fastener loosening caused by complete head slip. However, as a result of localized slip and other factors discussed in sections 2 and 3, loosening occurs at significantly lower loads. Equation (3) can be modified to include an empirical term, L, to account for these factors. Now, the conditions for avoiding loosening becomes

$$F_S < L\mu_H F_P, \tag{4}$$

where L is defined as the loosening factor.

TABLE 1

Estimated coefficient of friction of fastener materials

Material	Lubrication	Avg. μ	Std. dev (%)
Grade 5	Oil	0·158	3·2
Grade 5	MoS_2 grease	0·086	1·3
Grade 8	Oil	0·161	1·0
Brass	Oil	0·223	2·2

TABLE 2

Loosening factors for 63·5 *mm long, Grade* 8, 0·5-*UNC* 13 *screws lubricated with machine oil*

No.	Preload (kN)	Avg. L	Std. dev. (%)
1.	10·7	0·59	1·6
2.	17·5	0·64	1·9
3.	25·2	0·66	3·6

The transverse vibration test apparatus, which by design has $\mu_c \approx 0$, can be used to determine the loosening factor, L. The apparatus was used to determine the minimum shear load required to cause sustained loosening for a few representative cases, and L was calculated from these data. The minimum dynamic shear force that causes sustained loosening in a fastener is defined as the critical shear force F_{SC}. The ratio of the critical shear force, F_{SC}, to the force required for complete head slip ($\mu_H F_P$) defines the loosening factor, L.

One way to determine the critical shear force, F_{SC}, is to develop the desired preload in the test fastener, and then gradually increase the amplitude of the applied cyclic shear force until the fastener begins to loosen. However, the test apparatus used in the study was designed to operate only at three eccentric settings; as a result, a gradual increase in the applied shear force was not possible. The approach used here was to maintain a specific shear loading, and then control the preload to determine the loosening factor, L. The procedure is as follows. The test screw is subjected to a shear load at 15 Hz at one of the eccentric offset settings (± 1, $\pm 1{\cdot}5$, or ± 2 mm). The initial preload in the screw is nominally low so as to ensure that the screw loosens under the applied shear load. The preload is then gradually increased until no loosening occurs under the applied load for at least 2000 cycles. The ratio of the measured shear load amplitude to the product of the head friction, μ_H, and measured preload, F_P, gives the loosening factor, L, for the specific value of preload. The coefficient of friction μ_H was estimated using the common torque–preload relationship. The coefficient of friction at the head and the thread is assumed to be equal, and is estimated by measuring torque–preload data. The measured torque–preload data is used together with the common torque–preload equation [2] to obtain the value of the coefficient of friction. The data for the coefficient of friction obtained from five repetitions are presented in Table 1.

Tests were conducted with a 63·5 mm long, Grade 8, 0·5–13 UNC screw fastener at eccentric settings of ± 1, $\pm 1{\cdot}5$ and ± 2 mm to determine the influence of the preload on the loosening factor. The fasteners were lubricated with machine oil. Table 2 presents the average L from three repetitions. The loosening factor, L, is seen to be between 0·59 and 0·66

TABLE 3

Loosening factors for 0·5-*UNC* 13 *screws lubricated with machine oil*

No.	Material	Preload (kN)	Length		Avg. L	Std. dev. (%)
1.	Grade 5	18·9	63·5 mm	2·5″	0·59	4·1
2.	Grade 5	23·3	76·2 mm	3·0″	0·46	1·4
3.	Brass	9·2	76·2 mm	3·0″	0·51	1·3

at the three preloads. These values of L indicate that shear load required for sustained loosening is about 59–66% of the shear force required to cause complete head slip. This is expected since the loosening process at the initial stages is characterized by localized slip; therefore, it occurs at relatively low values of shear force. The loosening factor is seen to increase slightly as the preloads increase. Note that the preload at which the fasteners were tested is well below the fastener yield load of 82 kN.

Additional tests were run at $\pm 1{\cdot}5$ mm setting on 0·5–13 UNC screws, which were lubricated with machine oil. The data presented in Table 3 are the average of three repetitions. The loosening factor, L, for a Grade 5, 63·5 mm screw (Test 1), is seen to be about 30% higher than L for a Grade 5, 76·2 mm screw (Test 2). This is most likely because the shorter screw develops a lower bending moment, which is a significant cause of slip and loosening (see Figure 6). The loosening factor for a 76·2 mm brass screw (Test 3) is seen to be about 10% higher than that for a same length Grade 5 screw (Test 2). The modulus of elasticity of brass is nearly a third of that of steel, therefore, the load distributions and the relative contribution to slip due to the bending and elastic deformation are likely to be significantly different. As with the previous set of tests, the preload levels used in these tests are lower than the yield of 57 kN for the Grade 5 screws, and 25 kN for brass.

5. DISCUSSION

This paper further develops the understanding of loosening under shear loading originally studied by Junker [5]. In addition to loosening caused by complete slip as revealed by Junker, the analysis presented here shows that loosening in fasteners can also result from the accumulation of localized slip in the form of elastic deformation. Junker presented data showing loosening rate to be the same at loading frequencies of 10 and 3000 cpm. This was attributed to the fact that loosening is mainly a function of the amplitude of the relative motion per cycle, and not the frequency. Even in the loosening processes identified by the current analysis, the loosening rate is largely independent of the frequency since they are governed by elastic deformations, which depend only on the amplitude of the applied load.

A result of the process of localized slip is that loosening occurs at relatively low shear loads. This is indicated by the values of loosening factors, which range from 0·46 to 0·66 in tests presented here. These data can be used in equation (4), which provides a quantitative guideline for the design of shear joints to avoid loosening. Although the number of cases presented here are very limited, the results indicate that a fastener can loosen at roughly half the shear load required for complete head slip.

The objective of this study was to improve the understanding of the loosening process as a step towards the development of quantitative design guidelines. The present work is aimed at providing a more complete understanding of the primary aspects of the loosening

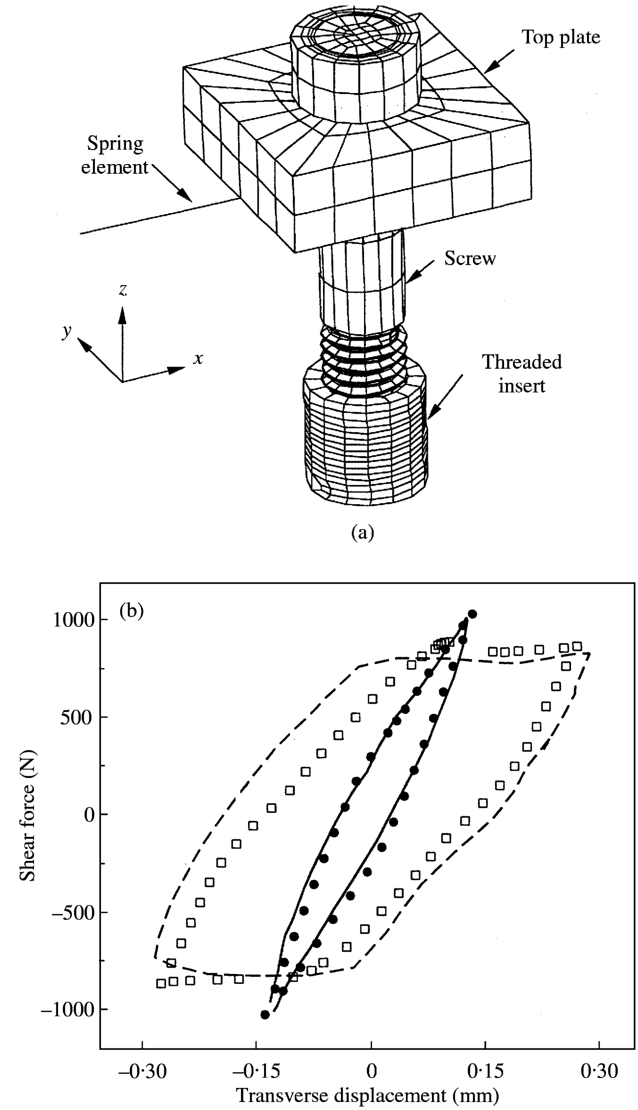

Figure 14. (a) Typical finite element mesh, and (b) a comparison of experimental hysteresis curves and FE results. Complete thread slip with local head slip: ——, experiment; ●, FE; complete thread slip with complete head slip: - - -, experiment, □, FE [17].

phenomenon. As a result the study is restricted to loosening in simple shear joints at low preloads to avoid the influence of yielding. From the present analysis of all the factors that influence loosening, it is clear that the fastener geometry, stiffness, and contact with friction must be included in any model of the loosening phenomenon. A three-dimensional finite element (FE) model has been developed and used to further validate and study the identified loosening processes. Figure 14(a) shows a typical mesh utilized for the finite element analysis, while Figure 14(b) presents a comparison between FE analysis and experimental results for loosening processes characterized by compete head and thread slip, and local head slip with complete thread slip. For complete details of the FE model and additional results, the reader is referred to reference [17]. Future work could include additional factors such as yielding and other loadings.

6. CONCLUSIONS

Loosening of threaded fasteners due to dynamic loads was treated as a process resulting from various causes of slip. The analysis reveals that loosening can occur due to localized slip at the contact surfaces. Experimental results confirmed the occurrence of loosening due to localized slip. In addition, experimental results indicate that the minimum shear load required to initiate loosening is significantly lower than the shear required to cause complete head slip. The loosening process at these lower levels of shear load is found to be characterized by localized slip at the contact surfaces.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support from the National Science Foundation under Grant No. CMS-9629217.

REFERENCES

1. D. P. HESS 1998 in *Handbook of Bolts and Bolted Joints* (J. H. Bickford and S. Nasser, editors), 757–824. New York: Marcel Dekker. Vibration- and shock-induced loosening.
2. J. H. BICKFORD 1995 *An Introduction to the Design and Behavior of Bolted Joints*. New York: Marcel Dekker; third edition.
3. J. N. GOODIER and R. J. SWEENEY 1945 *Mechanical Engineering* **67**, 798–802. Loosening by vibration of threaded fastenings.
4. J. A. SAUER, D. C. LEMMON and E. K. LYNN 1950 *Machine Design* **22**, 133–139. Bolts: how to prevent their loosening.
5. G. H. JUNKER 1969 *SAE Transactions* **78**, 314–335. New criteria for self-loosening of fasteners under vibration.
6. T. SAKAI 1978 *Bulletin of JSME* **21**, 1385–1390. Investigations of bolt loosening mechanisms (1st Report, On bolts of transversely loaded joints).
7. A. YAMAMOTO and S. KASEI 1984 *Bulletin Japan Society of Precision Engineering* **18**, 261–266. A solution for self-loosening mechanism of threaded fasteners under transverse vibration.
8. O. VINOGRADOV and X. HUANG 1989 *Proceedings of 12th ASME Conference on Mechanical Vibration and Noise, Montreal, Quebec*, 131–137. On a high frequency mechanism of self-loosening of fasteners.
9. A. DAABIN and Y. M. CHOW 1992 *Mechanism and Machine Theory* **27**, 69–74. A theoretical model to study thread loosening.
10. R. I. Zadoks and X. Yu 1993 *American Society of Mechanical Engineers Nonlinear Vibrations* **DE-54**, 79–88. A preliminary study of self-loosening in bolted connections.
11. R. I. ZADOKS and X. YU 1997 *Journal of Sound and Vibration* **208**, 189–209. An investigation of the self-loosening behavior of bolts under transverse vibration.
12. S. KASEI and H. MATSUOKA 1998 *American Society of Mechanical Engineers Pressure Vessels and Piping Division (Publication) PVP* **367**, 117–123. Considerations of thread loosening by transverse impacts.
13. A. W. HESTON in *Handbook of Bolts and Bolted Joints* (J. H. Bickford and S. Nasser, editors), 317–340. New York: Marcel Dekker. VDI joint design procedures.
14. N. SASE, K. NISHIOKA, S. KOGA and H. FUJII 1996 *Transactions of the Japan Society of Mechanical Engineers Part C*, 1527–1532. Analysis of screw fastener loosening and development of evaluation method.

15. G. S. HAVILAND 1983 *Mechanical Engineering* **105**, 17–31. Designing with threaded fasteners.
16. R. T. BARRETT in *Handbook of Bolts and Bolted Joints* (J. H. Bickford and S. Nasser, editors), 369–398. New York: Marcel Dekker. Design of joints loaded in shear.
17. N. G. PAI and D. P. HESS 2002 *Engineering Failure Analysis* **9**, 383–402. Three-dimensional finite element analysis of threaded fastener loosening due to dynamic shear load.