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DATA AND CONCLUSIONS FROM TESTS ON SMALL SCREWS

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Introduction

The integrity of many mechanical assemblies and electrical components depends on small threaded fasteners. The design standards for small (less than 1/4 inch in diameter) screws made of stainless steel are not as well developed as those for larger sizes of high strength steels. The typical design approach is based on the application of static design principals. Steady state accelerations are applied to the component or assembly and sufficient screws are installed in mounting hardware for attachment to the next assembly. These design principals have been used successfully for years in a wide variety of applications.

As the parts requiring small screws have continued to decrease in size, some design requirements include greater thread depths and adherence to strict interpretation of the governing thread standards. These design requirements have their origins in the lack of adequate definitions and standards for designs using small threaded fasteners. These design practices have led to significant problems in manufacturing parts with small threaded fasteners by requiring thread depths to four and more diameters of engagement while maintaining thread heights (radial engagement) of 75 percent throughout the thread interfaces. A test program was developed to address questions regarding design and manufacturing issues involving small threaded fasteners which included tensile strength, length of engagement needed to achieve the full strengths of the screws, and verification of the static design principals in dynamic conditions. This paper summarizes the initial results obtained to date from this test program and describes the work-in-progress on the dynamic tests with their related static tests. References 1 and 2 give additional details on this project.

The tests completed give results describing the tensile strengths of four sizes of screws (1/4-20 UNC, #4-40 UNC, #2-56 UNC, and 1.0 UNM (1.0 mm)). Also included in these results are the lengths of engagement needed to achieve these tensile strengths. In order to obtain these results an experimental technique needed to be developed as none was available for small screws.

A discussion of the work-in-progress describes testing activities to determine other strength and force related issues including the effects of the unengaged lengths (the stressed portion of the screw not engaged in threads), the relationships between applied installation torques and the resulting preload in the screws, and the effects of temperature extremes on the strengths of the screws and engaged materials. The description of work-in-progress also gives some initial results from shock tests on a single screw-mass system subjected to various shock pulses and includes plans for additional tests. Planning for sinusoidal vibration tests on a different

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vibration tests are needed to verify that the static design procedures envelope the requirements based on dynamic conditions.

Experimental Program

Prior to describing the test results, a brief description of the experimental plan is needed. A testing program was developed to address six areas: (1) tensile strength, (2) thread engagement, (3) preload versus torque, (4) effects of the unengaged but stressed lengths, (5) effects of shock conditions, and (6) effects of vibration environments. The strength tests give the basis for comparisons to the other tests. The experimental program designed to address these six areas is given in Table 1.

Table 1. Summary of Experimental Program

Test Description	Temperatures	Sizes	Number Threads Engaged	Engaged Materials	Replicates	Installation Torques	Unengaged Lengths	Number of Tests
Tensile Strengths	-	1/4-20 4-40 2-56 1.0UNM	5.8 to 8 or more	Stainless Steel	11 to 25	none	variable	91
Lengths of Engagement	-	same as above	2, 4 6, & 8	Aluminum Hiperco 50 St. Steel	3	none	variable	264
Preloads vs. Torques	-	4-40	2, 4 6, & 8	Aluminum St. Steel	3	40 % 80 %	2	96
Effects of Unengaged Lengths	-	4-40	2, 4 6, & 8	Aluminum Stainless Steel	3	-	3	72
Temperature Extremes	-65°F 165°F	4-40	2, 4 6, & 8	Aluminum St. Steel	3	-	1	48
Shock-1 msec haversine with 2 tests /specimen	-	4-40	2, 4 & 8	Aluminum Steel	5	40 % 80 %	2	120
Vibration - Short Term Sine Survey	-	4-40	4 & 8	Stainless Steel	5	40 % 80 %	1	20

The number of threads engaged in tensile tests varied depending on the lengths of the screws available for testing (the socket head screws were not long enough to engage approximately five threads). The number of replicates indicates the number of times each test condition was repeated except for the tensile strength tests in which as many were tested as possible. The installation torques are calculated from the force values equivalent to 40 and 80 percent of the guaranteed minimum strengths of the screws as shown in Table 2. (The equation $T = 0.2\ FxD$ was used where T is the applied torque in inch-lbs, F is the resulting force in the screw, and D is the nominal diameter in inches.) In Table 1 the value for unengaged lengths in the column indicates the total number of lengths to be tested (e.g., a value of 3 corresponds to both short, medium, and long screws, and 2 means short and long screws) depending on the available lengths of screws. The total number of tests given in Table 1 is determined by multiplying the numbers of variables in each column together. The initial tests performed in the shock laboratory were on an engaged material of 4340 high strength steel. Some additional tests may be performed to confirm that the response of small screws engaged in stainless steel and high strength steel are equivalent.

Data from Static Tests

Table 2 summarizes the data from the strength and length of engagement tests. The failure mechanisms for these small threaded fasteners in axial tension included broken screws at the roots of the threads, stripped external threads on the fasteners, and stripped internal threads on the engaged materials.

Table 2. Summary of Strength and Length of Engagement Tests

Screw Size	Measured Strength (Required) lb.	Standard Deviation (Coefficient of Variation)	Engaged Material	Mean Tensile Strength versus Number of Threads Engaged			
				2	4	6	8
1/4-20	4129 (2540)	57.4 (1.4)	Aluminum St Steel	1876 3303	3699 4142	4099 4135	4114 4104
#4-40 (two types)	716 743 (480)	9.5 (1.3) 14.7 (2.0)	Aluminum Hiperco St Steel	413 612 638	672 676 677	701 691 681	721 725 734
#2-56	462 (300)	2.7 (0.6)	Aluminum Hiperco St Steel	238 396 397	437 449 443	449 451 448	457 460 467
1.0 UNM	101 (none)	3.7 (3.7)	Aluminum Hiperco St Steel	42 88 102	75 100 108	83 99 99	98 100 100

The two types of #4-40 screws tested included socket and slotted head screws. The required strength comes from the military specifications (MS). The coefficient of variation is 100 times the ratio of the standard deviation to the mean. The aluminum tested was a 6061-T6, the stainless steel was a 300 series (303), and Hiperco 50 is a magnetic alloy made of approximately equal parts of iron and cobalt. The aluminum and stainless steel were chosen because small screws are commonly engaged in them. The Hiperco was chosen because it presents many machining difficulties with both hard and soft spots and because it has high strain rate sensitivity.

Table 3 summarizes the test results pertaining to the effect of varying thread height (percent thread or radial engagement). One hundred percent thread is line-to-line contact along the surfaces of both the internal and external threads. Zero percent thread implies that the major diameter of the screw's thread could just contact the minor diameter of the engaged material.

Table 3. Summary of Length of Engagement Tests as Functions of Percent Thread

Screw Size	Number Threads Engaged	Mean Maximum Force in lbs., Three Replicates					
		Engaged-Aluminum		Engaged-Hiperco		Engaged-St. Steel	
		55 % thread	75 % thread	55 % thread	75 % thread	55 % thread	75 % thread
1/4-20 UNC	2	1827	1925	NA	NA	3061	3546
	4	3614	3784			4182	4102
	6	4069	4129			4138	4132
	8	4152	4075			4109	4098
#4-40 UNC	2	393	423	613	611	635	641
	4	668	676	675	677	672	682
	6	709	693	692	689	691	689
	8	717	724	726	723	733	735
#2-56 UNC	2	236	241	384	408	387	399
	4	431	443	446	452	442	444
	6	450	447	452	451	451	445
	8	456	458	460	461	467	468
1.0 UNM (1 mm)	2	40	43	78	-	-	105
	4	-	-	100	99	113	103
	6	-	-	98	99	98	100
	8	97	100	101	99	101	99

There were no tests conducted with 1/4-20 screws engaged in Hiperco because there are very few of these parts requiring attachment with this size screw. The lines indicated with a (-) had mixed failure modes with significantly different values of maximum force. (The references also report the extensive work with the load-deflection measurements that were taken for each test. These curves give the strain energy for each screw to failure. These energies are not reported in this paper but they are closely aligned with the strength and length of engagement test results.)

The conclusions from the strength tests are that the experimental procedures reported in References 1 and 2 are valid even for the very small sizes of screws, the data are tightly grouped with more repeatability than expected, and the coefficients of variation do not increase uniformly with decreasing size as was originally expected.

The conclusions from the length of engagement tests are: (1) the strengths for the two values of percent thread tested were essentially the same; (2) the tensile strength of each screw is achieved in four threads except for the 1.0 UNM screws engaged in aluminum which requires eight threads; (3) the tensile strengths of the screws exceeded the military specifications by 49 percent or more; and most important (4) small threaded fasteners transfer forces in the same manner and require the same lengths of engagement as the larger sizes of screws.

The conclusions from the static tests strongly suggested that thread depths in excess of one to two diameters are not needed to develop the strengths of the screws. However, the major design concern is the integrity of these threaded connections in dynamic environments. This concern was addressed by planning sufficient tests in both shock and vibration conditions. The results from these dynamic tests will give evidence to either confirm or show where differences exist between the static design principles and the responses of the screws in shock or vibration conditions.

Shock Tests

The goal of the shock test portion of the study on small screws is to determine the failure level in g's of the screws under certain prescribed sets of test conditions. The test conditions were developed to give results which should lie on both sides of a failure level thus defining both the failure levels and the probabilities of failure. That is, a single test specimen gives two data points - one prior to failure and one beyond failure. Failures could consist of loss of preload, stripped threads, or broken screws. The shock tests were conducted using a haversine pulse with a duration of approximately 1 millisecond. The uncertainties associated with shock tests for the same basic conditions is about 15 percent in terms of repeating the peak amplitude and pulse duration. However, the measurements of acceleration can be made to about 10 percent accuracy. Comparisons of static strengths and shock test forces can also be made.

The first series involved testing #4-40 UNC screws which were installed with the same torques (8 inch-lb) into a single high strength 4340 steel test cylinder and mounting plate. The test hardware is shown in Figure 1 and some of the initial data are given in Table 4. The test hardware was subjected to a vibration survey which indicated that the first resonant frequency was above 2,000 Hz. This high resonant frequency allows various shock pulse durations to be used. The 1 millisecond haversine was chosen because it gave enough velocity change to initiate potential failures. A typical shock pulse shown in Fig. 2. The mode of failure in these test data is loss of preload.

The data from these initial tests indicate that trends exist to establish failure levels. However, a statistical analysis of the data will be needed before failure levels and probabilities of failure can be established. To date, methods of shock testing small threaded fasteners have been developed which yield the data needed to verify static design principles by comparisons of the dynamic and static failure forces.

Vibration Tests

Our objective in the vibration portion of this study is to determine what effect the number of engaged threads has on the joint integrity. While failure in the static tests is defined as broken screws or stripped threads, the definition of failure under vibration conditions is not as straight forward. However, joint failure in vibration environments is generally interpreted as loss of preload. Once preload in a joint is lost the integrity of the joint is reduced.

To simulate a generic screw joint we used a single screw-mass test assembly shown in Fig. 3. This assembly is similar to the system used in the shock tests. This screw-mass system is attached to an electro-dynamic shaker and excited in the axial direction (parallel to the major axis of the screw) to induce a tension force in the joint. At frequencies well below joint resonance the assembly acts as a rigid body so that the force on the joint can be computed from the measured acceleration of the mass.

We plan to investigate the length of engagement effect by monitoring the preload change in the joint. A series of tests will be performed where the mass-screw assembly will be excited by sinusoidal vibration at a level near the preload. Table 1 summarizes the conditions of the short term vibration tests. Results from these tests will determine if further vibration tests can yield information consistent with static design principles.

To measure preload, each joint will be loaded in tension until joint separation occurs. The force required to initiate separation should be just greater than the preload (e.g., the point where the external load is taken entirely by the screw.) When the preload is exceeded, a change of slope of a force-deflection curve indicates the point where the screw begins to elongate further. Figure 4 illustrates the test apparatus that will be used to generate the load-deflection curve. This apparatus is similar to the fixtures shown in Ref. 1 with the force measured by a load cell and the deflection measured by a capacitance gage.

To date, methods of testing small threaded fasteners in vibration have been developed. These methods will give the data needed to verify that the static design principles apply to vibration conditions.

Summary

Methods have been developed to test small threaded fasteners statically, in shock conditions, and in vibration environments. The data obtained to date indicate that failure conditions can be defined or estimated. Shock and vibration test procedures have been developed to verify static design principles with trends from the initial data indicating that the kind of data needed for this verification is being obtained.

Acknowledgment

The authors are indebted to Kathleen Diegert for her help in defining statistical significant tests and for analyzing the data obtained.

References:

1. Diegert, K. V., Dorrell, L. R., Reese, R. T., and Lazarus, L. J., "Small Screw Study - Interim Report on Fastener Tensile Strength and Optimum Thread Depth," SAND89-1320, Sandia National Laboratories, Albuquerque, NM 87185

2. Dorrell, L. R. and Laing, J., "Test Methods for a Small Screw Study," Proc. SEM Spring Conference, June 5-7, 1990, Society for Experimental Mechanics, Bethel, CT.

Table 4. Results of Shock Tests on #4-40 UNC Screws

Eight Threads Engaged			
Maximum Amplitude g's	Duration milliseconds	Velocity Change m/sec.	Lost Preload
1453	1.03	6.7	
1489	1.00	6.7	yes
1493	0.98	6.7	yes
1492	0.728	6.7	yes
1271	1.02	6.1	yes
1396	0.792	6.4	yes
1339	0.99	6.4	
1388	0.88	6.4	yes
1357	0.91	6.4	
1379	0.92	6.4	yes
1347	0.95	6.4	yes
1375	0.78	6.1	yes
1219	0.95	6.1	yes
1544	0.854	7.6	yes
1423	0.909	7.9	yes
1300	0.944	7.6	
1474	0.858	7.9	
1387	0.963	7.9	
1476	0.848	7.9	
1549	0.870	7.6	
1736	0.988	10.1	yes
1634	0.98	9.8	yes
1542	0.972	9.1	yes
1324	1.163	8.8	

Four Threads Engaged			
Maximum Amplitude g's	Duration milliseconds	Velocity Change m/sec.	Lost Preload
1456	0.80	6.4	
1675	0.69	6.7	yes
1339	0.957	6.7	
1734	0.70	6.7	yes
1526	0.72	6.4	yes
1332	0.957	6.7	
1388	0.73	6.4	yes
1193	1.01	6.1	
1283	0.87	6.1	yes
1296	0.814		
1087	0.982	6.7	
1323	0.884	7.9	
1584	1.098	8.2	
1698	0.868	8.8	yes
1681	0.89	9.1	yes
1610	0.866	8.5	
1685	0.86	8.5	yes
1634	0.87	8.2	yes
1454	1.166	8.8	yes
1393	0.918	8.8	
1476	0.936	9.1	
1576	1.012	9.4	yes
1472	1.088	9.1	
1590	1.118	9.4	yes
1458	1.19	9.4	
1487	1.246	9.4	yes
1557	0.80	7.6	yes
1297	1.024	7.3	
1419	1.02	7.9	
1530	0.8	7.6	yes

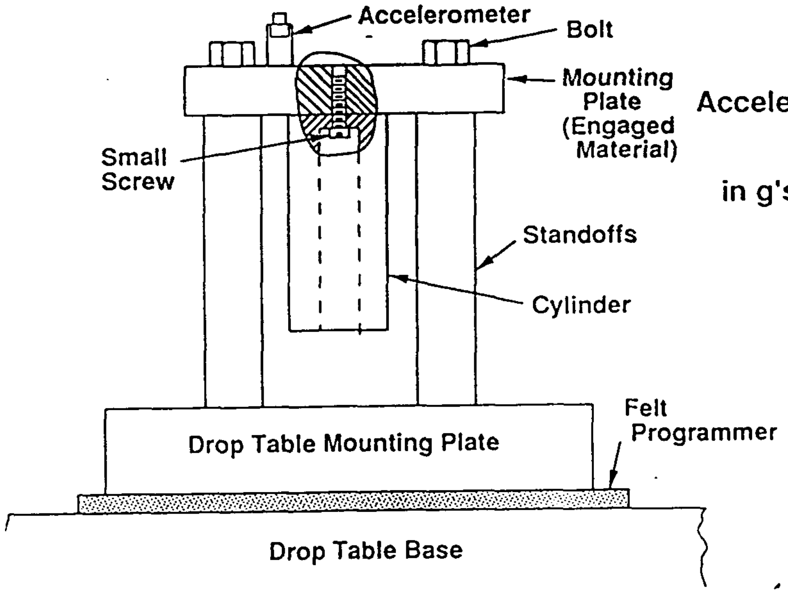

Figure 1. Shock Testing Fixture

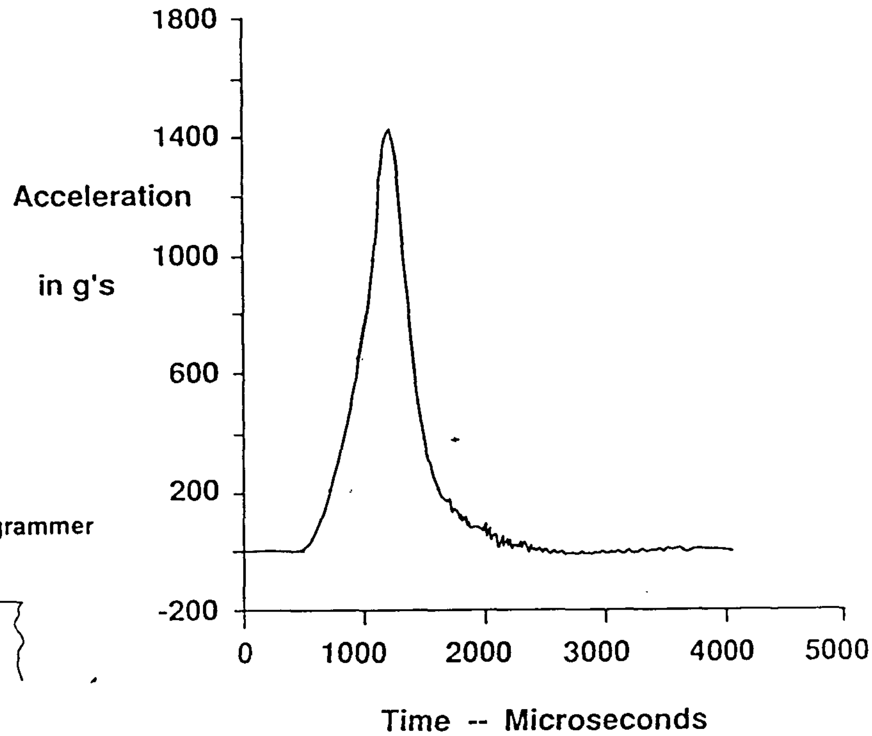

Figure 2. Typical Shock Pulse

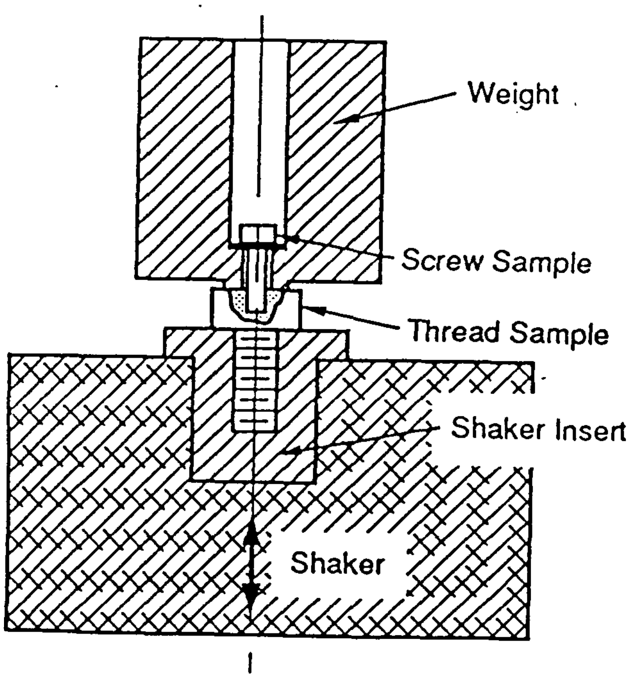

Figure 3. Vibration Test Fixture

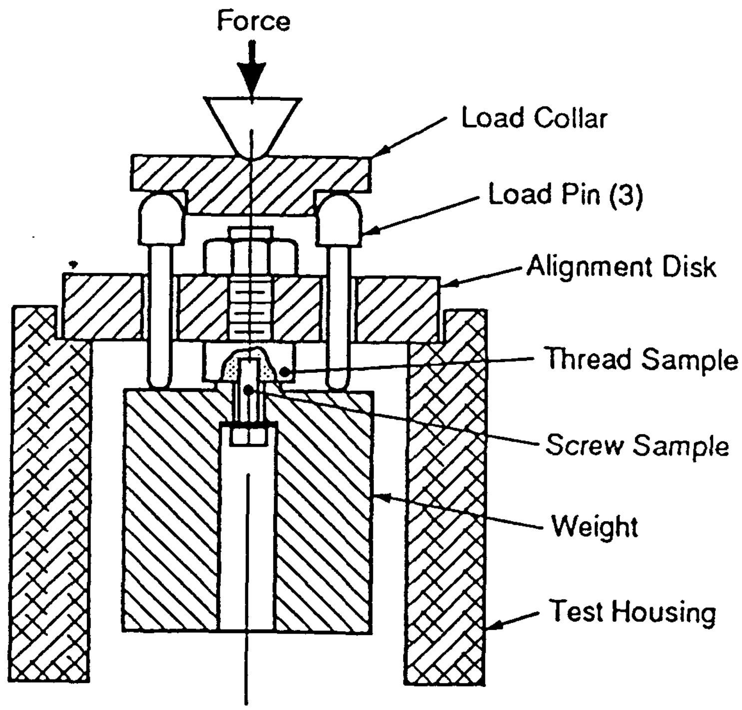

Figure 4. Preload Measurement System for Vibration Test Specimens