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Hex Washer-Head Fastener Pull-Over in Moderately Thin Aluminum

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Editor's Note: This article by James LaBelle and Tanya Dolby on pull-over strength of screws in aluminum complements the earlier article published in Light Metal Age *(October 2008) by Craig Menzemer, Jigar Deliwala, and Randy Kissel on pull-out strength of self tapping screws in screw slots or screw bosses. Both articles reference and expand the design guidelines for screw fasteners in aluminum structures as given in the relevant sections of the* Aluminum Design Manual 2005 *(Section 5.4.2.1 for pull-out and 5.4.2.2 for pull-over or pull-through failures of tension loaded screws). The results of these studies have yielded newly proposed design equations for screw fasteners under tensile loading in aluminum structures. As Randy Kissel and Tanya Dolby both serve on The Aluminum Association Engineering and Design Task Force responsible for* Aluminum Design Manual *content, their work on fastener connections in aluminum structures should merit extra attention.*

Introduction

Pull-over, also termed pull-through, is a mode of failure for a tension-loaded fastener in which the sheet, plate, or extrusion locally tears and/or deforms sufficiently to allow the head to pass completely through. Screws are used to resist tensile design loads in a variety of aluminum structures including skylights, curtain walls, and window framing. The *Aluminum Design Manual (ADM)*[1] includes equation 5.4.2.2-1 for pull-over of tapping screws installed in aluminum. This formula, however, was based on testing of relatively thin aluminum,[7] 1.02 mm (0.040″) maximum, using hex-head fasteners with loose washers that were a metal/rubber combination. Subsequently, limited testing indicated that this equation was likely conservative for greater thicknesses. Thus, a testing program was initiated in order to study behavior and provide design guidance for the pull-over mode for hex-head screws with integral or loose metal-washers, and pan-head screws, installed in moderately thin aluminum. Thicknesses ranged from about 1.02 mm (0.040″) to 6.35 mm (0.25″).

Testing covered a range of fastener-plate combinations (sets) including four screw diameters, five plate thicknesses, and several alloy-tempers. In total, 162 specimens were tested (Figure 1), usually with eight tests for each combination (set) of screw size, plate thickness, and alloy-temper. Pull-over occurred in all of the tests except for those with nominal 6.35 mm (1/4″) thick plates. In these tests, screw failure occurred.

Data analysis included comparisons between test results and predicted (nominal) values based on the *ADM*.

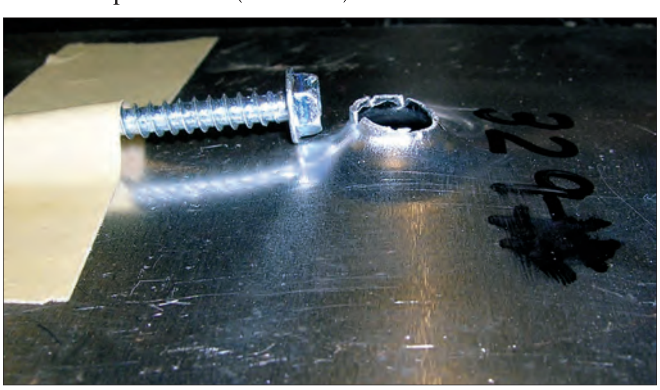

Figure 1. Pull-over specimen (post–test).

In all cases, the *ADM* pull-over prediction was substantially less than the test average for the new data. A simple design equation was developed to more accurately, yet conservatively, model pull-over behavior for screws installed in aluminum with a minimum thickness of 1.02 mm (0.040″) and prescribed hole sizes.

Background

This research was initiated to develop a formula to better predict the pull-over behavior of fasteners, typically with washers, installed in moderately thin aluminum. Prior pull-over tests[5] of countersunk, flat-head screws, together with some pan-head screws (24 tests), revealed that the 2000 *ADM* pull-over equation (same as in the 1994 and 2005 editions), for non-countersunk screws, predicted values that became increasingly conservative as thickness increased.

Subsequent to this earlier work,[5] testing of a much larger number of hex and round head fasteners (81 tests) was conducted by Olive and Stockmann.[6] These tests confirmed that the *ADM* equation was quite conservative for nominal thicknesses from 1.27 mm (0.05″) to 2.29 mm (0.09″), using two alloy-tempers. If specified minimum properties were assumed for the alloy-tempers, then the ratio of the *ADM* prediction to the corresponding average value ranged from 0.24 to 0.49 for all tests. If only the 44 tests in which pull-over occurred were considered, then the ratios ranged from 0.24 to 0.30. This was an exploratory test program and their report did not include tensile coupon results to accurately determine the aluminum's mechanical properties.

Test Program

Fastener sizes included #8-32, #10-24, #12-24, and ¼-20 screws, all with hex-heads that included integral washers. Using the designation #8-32 as an example, 32 is the number of threads per inch. Nominal diameters are: #8 (4.17 mm, 0.164″), #10 (4.83 mm, 0.190″), #12 (5.49 mm, 0.216″), and ¼ (6.35 mm, 0.250″). A test set consisted of eight screws of a given diameter in sheet of a particular thickness. A test series (e.g., sets 1 to 5), 40 tests total, consisted of a given screw size and five sheet thicknesses. Also included were #10–24 and ¼-20 pan-head screws tests (sets 31, 33) from a prior project.[5] All screws were stainless steel (300 series). See Table I for nominal thicknesses and alloys. The actual tempers were not known for all alloys.

Nominal thickness (in)	Aluminum alloy	Average yield strength (psi)	Average ultimate strength (psi)
0.040	5052	20,660	23,600
0.060	3003	18,170	22,170
0.060 (33)	6061	36,680	45,640
0.090	3003	16,660	20,330
0.090 (31)	5005	16,750	20,460
0.125	6063	18,440	23,430
0.250	6105	31,190	35,000

Table I. Summary of tensile coupon data.

Three thicknesses (0.040″, 0.060″, 0.090″) were rolled and two (0.125″, 0.250″) were extruded. As exploratory tests, two sets (21, 22) were added using nominal 0.25″ thickness (6105) and 9.52 mm (3/8″) bolts, without washers and with loose washers. Pull-over was achieved, but this diameter is beyond the *ADM* size range for tapping screws.

Each plate's thickness was measured and then readings were averaged (Table II). Hardness was also measured, using a Webster hardness gage, model B. See Table III for fastener measurements and Table IV for drill and clearance hole diameters.

Aluminum alloy	Nominal thickness (in)	Average thickness (in)	Webster hardness
5052	0.040	0.038	5
3003	0.060	0.0615	5
6061	0.060 (33, pan-head)	0.063	16.3
3003	0.090	0.0865	4 to 4.5
5005	0.090 (31, pan-head)	0.088	4.3
6063	0.125	0.127	6.5 to 7
6105	0.250	0.2485	11 to 12

Table II. Summary of aluminum plate data.

Description	Average major diameter (in.)	Average diameter of integral washer (in.)	Average washer thickness (in.)
#8-32	0.165, 0.166	0.324 to 0.337	0.026
#10-24	0.191, 0.192	0.395 to 0.407	0.033
#12-24	0.218 - 0.220	0.409 to 0.420	0.037
¼-20	0.252 - 0.254	0.482 to 0.492	0.038
#10-24 (31)	0.187	0.369 (head)	(no washer)
¼-20 (33)	0.246	0.481 (head)	(no washer)
3/8-16	0.371	0.6375 points; 0.75 washer	0.049

Table III. Summary of fastener data.

Fastener	Drill	Measured size (in)	Hole diameter (in)
#8-32	#16	0.175	0.178 to 0.182
#10-24	#7	0.199	0.197, 0.200
#12-24	#I	0.226	0.226, 0.228
¼-20	#H	0.264	0.263 to 0.272
#10-24 pan-head (31)	#7	0.2025	not meas'd.
¼-20 pan-head (33)	#H	0.265	not meas'd.
3/8-16	#W	0.384	0.387

Table IV. Drill and clearance hole data.

The size of each aluminum test plate was 127 mm x 762 mm (5″ x 30″) by various thicknesses, with one exception. The 3.18 mm (0.125″) thick plate was 102 mm (4″) wide. Each plate had four holes, drilled and located 152 mm (6″) from each end and on center. Hand-held drilling was used, so as to be similar to usual fabrication practices. Two plates for each plate/fastener combination (a test set) were prepared. This usually resulted in a total of eight fastener tests per combination. The fastener's body was gripped using a tensile clamp (Figure 2). A 76 mm (3″) diameter hole was provided in the fixture's plate. The Tinius Olsen machine applied increasing tension, due to a cross-head movement rate of 5.1 mm/min (0.2 in/min), until failure occurred. The most common failure mode (160 tests, which is 20 sets at 8 each) was pull-over. In 18 tests—all in 6.35 mm (1/4″) plate—the fasteners broke. For plates where screws broke, from 2 to 8 of the 8 screws in a given pair of plates were tested. After failure occurred, the plate was re-positioned so the next fastener in the plate could be tested.

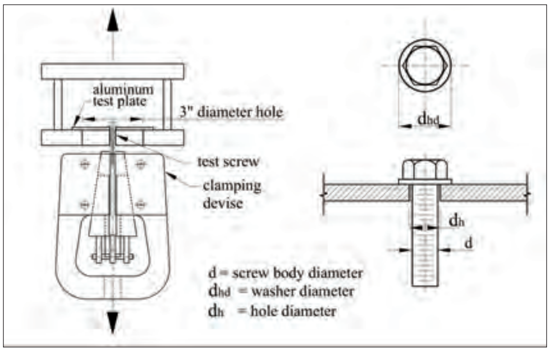

Figure 2. Test fixture and test specimen (plate).

The average failure loads are listed in Table V. Sets 31 and 33 used pan-head screws, without washers. Values in italics indicate fasteners broke.

Test Set	Average thickness (in)	Fastener	Average (lbs)	Max. (lbs)	Min. (lbs)
1	0.0365	#8	327	336	316
2	0.061	"	573	593	556
3	0.087	"	792	830	760
4	0.127	"	1354	1440	1250
5	0.248	#8	*1950*	*1970*	*1940 (n=8)*
6	0.04	#10	450	468	438
7	0.0615	"	727	742	712
8	0.087	"	1042	1068	1024
9	0.126	"	1898	1940	1880
10	0.249	#10	*2185*	*2270*	*2030 (n=4)*
11	0.039	#12	436	455	418
12	0.0615	"	692	726	665
13	0.0865	"	997	1022	978
14	0.127	"	1882	1920	1850
15	0.2495	#12	*2910*	*3000*	*2820 (n=2)*
16	0.039	1/4"	506	530	490
17	0.061	"	854	902	824
18	0.087	"	1184	1220	1140
19	0.128	"	2070	2200	1900
20	0.249	1/4"	*4612*	*4970*	*4320 (n=4)*
21	0.249	3/8"	7204	7240	7140
22	0.249	3/8"	9270	9370	9100
31	0.0888	#10	923	950	911
33	0.0627	1/4"	1784	1840	1740

Table V. Summary of pull-over tests.

Ultimate-Stress Model: Basic mechanics and an overview of the test results both suggest that sheet thickness, yield and/or ultimate aluminum stress, and head diameter (or loose-washer diameter if present) are significant variables

that affect the pull-over strength. Because the nominal pull-over strength for non-countersunk screws (*ADM*) is based on ultimate stress, a trial model based on ultimate stress was developed. Figure 3 is a plot of normalized pull-over values (R_u) versus normalized thickness. R_u is the ratio of pull-over average test values to an assumed upper bound (P_{N1}) based on ultimate shear strength, given in Eq. 1 and 2. The ultimate shear stress is approximated by $F_{tu} / \sqrt{3}$. Normalized sheet thicknesses were obtained by dividing the thickness (t) by the washer diameter (d_{hd}) for each series.

$$P_{N1} = \pi \, t \, d_{hd} \, F_{tu} / \sqrt{3} \qquad (1)$$

$$R_u = P_{test\text{-}av} / P_{N1} \qquad (2)$$

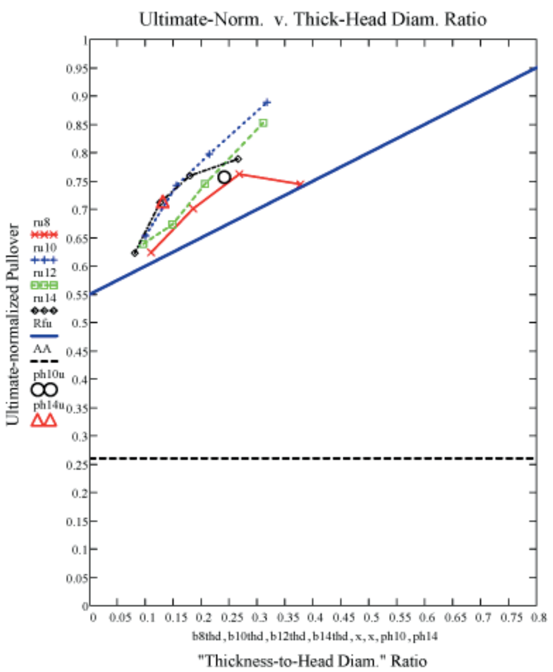

Figure 3. Normalized Pull-over R_u (ultimate stress basis) vs. t / d_{hd}. The designations r8, r10, r12, and r14 each refer to a test series (#8 to 1/4″ screws).

The limit P_{N1} corresponds to "punching shear" of a cylinder (diameter d_{hd} and length t) of aluminum. Figure 3 also shows the sloped, straight-line plot (Rfu) of an approximate lower bound (R_{FU}), of Eq. 3 and Eq. 4, to the normalized average pull-over data. P_{N2} in Eq. 3 is the predicted value obtained by the product of R_{FU} and the upper bound P_{N1}.

$$P_{N2} = R_{FU} \, P_{N1} \qquad (3)$$

The variable R_{FU} is given by Eq. 4:

$$R_{FU} = 0.55 + [(0.95 - 0.55)/0.8] \; t / d_{hd} \quad \leq 0.95 \qquad (4)$$

The ratio of pull-over test average to P_{N1} varies from 0.62 to 0.89, for all tested sizes.

The predictive ratio R_{FU} ranges from 0.58 to 0.74 when applied to the tests with pull-over failure. To avoid a prediction which would exceed the presumed upper limit of P_{N1}, the maximum value of t/d_{hd} with this model is limited to 0.8. At this value, R_{FU} equals 0.95.

ADM Equation: A comparison of test averages to nominal pull-over strength P_{nov}, based on the *ADM*, was also made. P_{nov} is given in Eq. 5. P_{nov} values range from 29% to 42% of the corresponding test averages. For hex washer-head and pan-head fasteners, except for a slight deviation for the #8 screws in 0.125″ sheet, the percentage decreases as thickness increases, for a given head diameter.

$$P_{nov} = C \, t_1 \, F_{tu1} \, (D_{ws} - D_h) \qquad (5)$$

Let C equal one, the washer diameter D_{ws} equal the head diameter d_{hd} and the hole diameter D_h equal the drill-bit diameter d_h so that Eq. 5 may be expressed as given in Eq. 6, using P'_{nov}:

$$P'_{nov} = t \, F_{tu} \, (d_{hd} - d_h) \qquad (6)$$

The ratio $R_{nov\text{-}n1}$, of P'_{nov} to P_{N1}, is given in Eq. 7:

$$R_{nov\text{-}n1} = \sqrt{3} \, (d_{hd} - d_h) \, / \, (\pi \, d_{hd}) \qquad (7)$$

Mathematically, the ratio $R_{nov\text{-}n1}$ cannot exceed 0.55, even as d_h gets very small. For the hex washer-head and pan-head screws in this study, $R_{nov\text{-}n1}$ ranges from 0.242 to 0.278. Thus the P'_{nov} values average about 26% of the upper limit P_{N1}. See the constant value line in Figure 3. Compare that to a range of 58% to 74%, of P_{N1}, for the predicted values (P_{N2}), on the sloping line, for these screws. Thus, in all cases, the *ADM*-predicted values are substantially smaller than sloping-line prediction (P_{N2}) values for the hex washer-head and pan-head screws.

Yield-Based Model: A predictive model incorporating the aluminum yield stress was also explored for several reasons. One is that the pull-over failure mode, at least in thin and moderately thin aluminum, includes a relatively large distortion of the sheet in the local region around the hole. A second is that prior work showed that yielding was a substantial factor in the pull-out mode for thin sheets.[1,2] A third reason to consider yield is that there is a wide range of tensile yield-to-ultimate ratios (F_{ty}/F_{tu}), about 0.28 to 0.93, for the various alloy-temper combinations[3] in the ADM. The present research used specimens with a yield-to-ultimate range of 0.79 to 0.89, so lower ratios were not included in this testing. Figure 4 is a plot of R_y (ratio of pull-over test average to a yield-based, assumed "upper bound" P_{ny1}) versus t/d_{hd} (ratio of thickness to head diameter).

With this model, the "upper bound" P_{ny1}, based on shear-yield ($F_{ty} / \sqrt{3}$), is given by Eq. 8:

$$P_{ny1} = \pi \, t \, d_{hd} \, F_{ty} / \sqrt{3} \qquad (8)$$

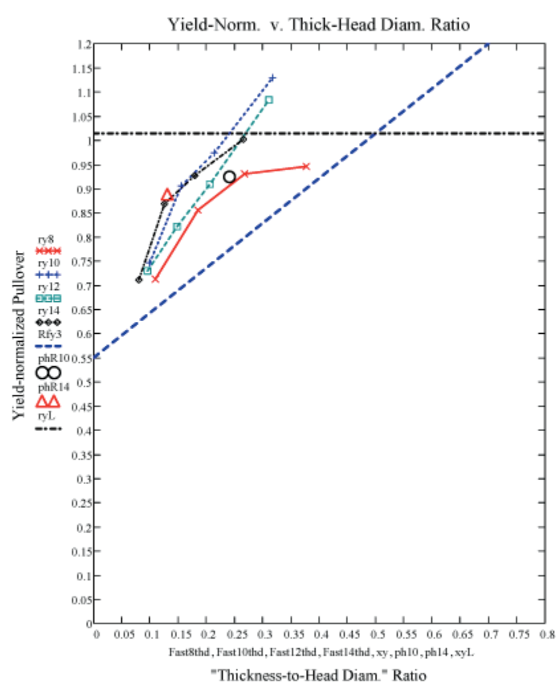

Figure 4. Normalized Pull-over R_y (yield basis) vs. t / d_{hd}.

A lower-bound prediction of pull-over values (P_{ny3}) is expressed in Eq. 9:

$$P_{ny3} = R_{FY} P_{ny1} \quad (9)$$

The variable R_{FY} is the sloped straight line in Figure 4 and is given by Eq. 10:

$$R_{FY} = 0.55 + [(1.2 - 0.55) / 0.7] (t / d_{hd}) \quad (10)$$

The predicted ratio (R_{FY}) ranges from about 64% to 90%, of P_{ny1}, for those screws whose tests resulted in pull-over failure. As a conservative measure, P_{ny3} will be limited to about 1.0 P_{ny1}, as shown in Figure 4. If the value of t / d_{hd} is limited to 0.5, R_{FY} is equal to a maximum of 1.014.

Proposed Design Equation

The data's maximum coefficient of variation is 6.7%. This is less than the acceptable maximum of 10.7% calculated according to the test section of the *ADM* using a resistance factor of 0.533, which equals a load factor[4] of 1.6 divided by the safety factor of 3.0. In all cases, the proposed predicted values, based on the yield model, are less than the test averages, and range from 75% to 96% of the corresponding test averages.

The nominal strength P for screws ranging from #8 to 1/4″ (the maximum size permitted in the *ADM* specification), is given as:

$$P = [0.55 + (0.65 / 0.7) (t / d_{hd})] \pi d_{hd} t F_{ty} / \sqrt{3} \quad (11)$$

By simplifying Eq. 11 for P and rounding slightly, the proposed equation for nominal pull-over strength per screw (for #8 to 1/4″ screws; $t \geq 0.040''$), with the term $t/d_{hd} \leq 0.5$, is:

$$P = (1.0 + 1.7 t / d_{hd}) d_{hd} t F_{ty} \quad (12)$$

The limit on t/d_{hd} is intended to restrict the nominal strength so that it does not exceed approximately the shear-yield strength of the aluminum at the washer's circumference. The allowable values are equal to P divided by the safety factor of 3.0, per section 5.4 of the *ADM* specification. Washers are to be made only of metal. Nominal hole sizes are limited to the nominal drill diameters in Table IV. It should be noted that the proposed equation is similar in form to that for pull-over of countersunk head screws, as given in the *ADM* specification.

Conclusion

This article has presented pull-over test results (primarily for four thicknesses of aluminum sheets and four sizes of screws, most with integral washers) and comparisons with several predictive models. Based on the yield model, it is proposed to use a simple and conservative equation for the nominal strength: $P = (1.0 + 1.7 t / d_{hd}) d_{hd} t F_{ty}$. The term t/d_{hd} is to be less than or equal to 0.5.

Acknowledgements

The support of the writers' employers and the helpful comments of members of the Engineering Design Task Group of The Aluminum Association are gratefully acknowledged.

Notations

- C = coefficient that depends on screw location (*ADM*)
- d_{hd} = diameter of washer, or head if no washer
- d_h = drill-bit diameter
- D_h = hole diameter (*ADM*)
- D_{ws} = washer diameter (*ADM*)
- F_{tu}, F_{tu1} = tensile ultimate strength
- F_{ty} = tensile yield strength
- n = number of individual tests in a set
- P = nominal pull-over strength of an installed screw
- P_{N1} = upper bound based on ultimate shear strength
- P_{N2} = predicted value equal to the product of R_{FU} and the upper bound P_{N1}
- P_{nov} = nominal pull-over strength based on the *ADM*
- P'_{nov} = nominal pull-over strength, based on substitution of variables in the *ADM* equation
- P_{ny1} = upper bound based on shear-yield strength
- P_{ny3} = predicted value equal to the product of R_{FY} and the upper bound P_{ny1}
- R_{FU} = ratio of P_{N2} to P_{N1}; see Eq. 3 and Eq. 4
- R_{FY} = ratio of P_{ny3} to P_{ny1}; see Eq. 9 and Eq. 10
- $R_{nov\text{-}n1}$ = the ratio of P'_{nov} to P_{N1}; see Eq. 7
- R_u = ratio of test average to an ultimate-based, upper-bound P_{N1}; see Eq. 2 and Figure 3
- R_y = ratio of test average to a yield-based, upper-bound P_{ny1}; see Figure 4
- t, t_1 = plate or sheet thickness

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