# Design of Cold-formed Steel Screw Connections

Teoman Pekoz

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# DESIGN OF COLD-FORMED STEEL SCREW CONNECTIONS

by Teoman Pekoz[1]

## ABSTRACT

Results of well over 3500 tests from the United States, Canada, Sweden and the Netherlands are considered to formulate screw connection design provisions. These provisions are intended to be used when a sufficient number of test results is not available for the particular application. The provisions of the European Recommendations are considered and modifications proposed where they are called for.

## 1. INTRODUCTION

At present there are no provisions for screw connections in the American Iron and Steel Institute Specification for the Design of Cold-Formed Steel Structural Members (1). In contrast, there are provisions in the European Recommendations (2) as well as in several national specifications in Europe. Many of the national specifications are in general agreement with the European Recommendations. Therefore the objective of this limited study is to check the provisions of the ECCS Recommendations and determine the necessary Safety and Resistance Factors consistent for the applications and design approaches in the United States. Some modifications to the ECCS Recommendations are suggested. A detailed description of this study is reported in Reference 3.

In this study the results of well over 3500 tests from the United States, Canada, Sweden, Britain and the Netherlands given in References 5 through 8 and 10 are considered. In the types of connections dealt with here the screws are loaded in shear or in tension. The numbers of tests from each source as well as some comments on the test data are summarized in Table 1.

The factors of safety and the resistance factors are determined as described in Reference 4 with the exception that the equations used are not determined explicitly based on the test data but on the design equation of the European Recommendations. The target reliability index customarily used for bolted connections is 4. This is a relatively high value due to the fact that the failure of a bolted connection may lead to an overall failure. In the case of screw connections the result may not be so catastrophic. Thus it was decided that taking the value of the reliability index equal to 3.5 would be reasonable for screw connections in determining the resistance factors and the factors of safety.

For cold-formed steel connections the following statistics were taken from Reference 11:

$M_m = 1.1$, $F_m = 1.0$, $V_m = 0.1$, $V_q = 0.21$, $V_f = 0.1$

In the above

$M_m$ = Mean value of the ratio of the actual material property ($F_y$ or $F_u$) to that specified

$F_m$ = Mean value of the ratio of the actual geometric property (thickness) to that specified

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1 Professor of Structural Engineering, Cornell University, Ithaca, New York 14853

$V_m$ = Coefficient of variation of the ratio of the actual material property ($F_y$ or $F_u$) to that specified
$V_q$ = Coefficient of variation of loading (the value given here is for a live to dead load ratio of 5)
$V_f$ = Coefficient of variation of the geometric property (thickness) to that specified

The force developed per screw depends on several parameters such as type of the screw (diameter, thread, point), strength of the screw, the characteristics of the hole (size, whether it is predrilled or not), the yield and ultimate stresses of the plates, the type and rate of loading (shear, tension, number of cycles applied). These factors affect the strength to varying degrees. It is not possible to reach simple design equations of high accuracy without taking all these factors into account. The provisions studied here are intended to give safe results for practical ranges of these parameters. A higher degree of accuracy can be obtained by testing the screw connections for a more limited range of values of these parameters and base the design values for these limited ranges as discussed in Reference 4.

## 3. GENERAL DESIGN CONSIDERATIONS

The test results used in this study were for a wide variety of connections. These include self-tapping screws installed with or without predrilled holes. The screw diameters varied between .087 in. and .25 in.

If members of different thicknesses were connected, the thinner material was in contact with the head of the screw.

## 4. DESIGN FOR SHEAR

Screw connections loaded in shear can fail in one mode or in combination of several modes. These modes are screw shear, edge tearing, tilting and subsequent pull-out of the screw, bearing of the parent plates. Screw shear load should be relatively well established in the literature of the screw manufacturer, therefore the attention is focused on the other failure modes.

In all the tests, edge failure was observed for edge distance (distance from the center of the screw to the free edge) equal to or less than three times the diameter of the screw. This was remarkably consistent. For this reason, for shear connections all the data used to evaluate other failure modes excluded those expected to have edge failure.

The provisions of the European Recommendations (2) are as follows:

The shear capacity, $P_{ns}$ in tilting and bearing may be taken as

a. for $t_2/t_1 = 1.0$ the smaller of

$P_{ns} = 3.2\ (t_1^3\ d)^{1/2}\ F_y$ and (Eq. 1)

$P_{ns} = 2.1\ t_1\ d\ F_y$ (Eq. 2)

b. for $t_2/t_1 \geq 2.5$

$P_{ns} = 2.1\ t_1\ d\ F_y$ (Eq. 3)

c. for $1.0 < t_2/t_1 < 2.5$

$P_{ns}$ may be taken by linear interpolation between above two cases.

In the above, $t_1$ is the thickness of the member in contact with the screw head, $t_2$ is the thickness of the other member and d is the nominal screw diameter. These equations can be used with any consistent unit system.

The above provisions were checked against a large number of test results. In addition, a variation of the above, using the ultimate stress $F_u$ instead of $F_y$ was also checked. The results of the correlations are given in Table 2. It is seen in this table that the use of $F_u$ gave significantly better correlation. Also given in this table are the resistance factors, $\phi$, and factors of safety required for different reliability indices.

The values of $P_m$ indicate that the above expressions give mean calculated strengths that are significantly higher than 1. In order to have the equations give means closer to 1 the coefficients of the above equations were multiplied by 1.3. The factor 1.3 was chosen on a qualitative basis considering the nature of the available information from different sources. With these modifications the above equations become:

a. for $t_2/t_1 = 1.0$ the smaller of

$$P_{ns} = 4.2\ (t_1^3\ d)^{1/2}\ F_u \text{ and} \qquad \text{(Eq. 4)}$$

$$P_{ns} = 2.7\ t_1\ d\ F_u \qquad \text{(Eq. 5)}$$

b. for $t_2/t_1 \geq 2.5$

$$P_{ns} = 2.7\ t_1\ d\ F_u \qquad \text{(Eq. 6)}$$

c. for $1.0 < t_2/t_1 < 2.5$

$P_{ns}$ is to be determined by linear interpolation using a. and b. above.

Correlation of equations 4 through 6 is given in Table 3. On the basis of this table, a factor of safety of 3.0 for use in an allowable stress design approach and a resistance factor, $\phi$, of 0.5 for use in an LRFD based approach appear reasonable.

Due to the brittle and sudden nature of screw shear fracture, it is desirable to avoid this type of failure. For this reason the ECCS Recommendations require the shear strength of the screw itself to be 1.25 times the nominal strength $P_{ns}$.

## 5. DESIGN FOR TENSION

Screw connections loaded in tension can fail either by pulling out of the screw from the plate (pull-out) or pulling of material over the screw head and the washer if any is present (pull-over) or by tensile fracture of the screw.

### 5.1 PULL-OUT DESIGN CONSIDERATIONS

The provisions of the European Recommendations are as follows:

The tensile capacity, $P_{not}$, may be taken as

$$P_{not} = .65\ t_c\ d\ F_y \qquad \text{(Eq. 7)}$$

where $t_c$ is the depth of penetration or the thickness of the material $t_2$, d is the nominal screw diameter. This equation can be used with any consistent unit system.

A large number of test results were checked against the results predicted by Eq. 7. In addition, the test results were checked against Eq. 7 with $F_u$ substituted for $F_y$. These results are presented in Table 4. Table 4 also gives the resistance factors, $\phi$, and factors of safety required for the given reliability indices. The values of $P_m$ indicate that Eq. 7 gives mean calculated strengths that are significantly higher than 1. In order to have the equation give means closer to 1 the coefficient 0.65 was multiplied by 1.3. With these modifications Eq. 7 becomes:

$$P_{not} = 0.85\ t_c\ d\ F_u \qquad \text{(Eq. 8)}$$

The results evaluated using Eq. 8 are shown in Table 5.

### 5.2 PULL-OVER FAILURE

The provisions of the European Recommendations are as follows:

The tensile capacity, $P_{nov}$, may be taken as

$$P_{nov} = 15\ t\ F_y \qquad \text{(Eq. 9)}$$

where t is the thickness of the material. In this equation $P_{nov}$, t, $F_y$ are in N, mm and N/mm$^2$, respectively.

In imperial units, the above becomes

$$P_{nov} = 0.59\ t\ F_y \qquad \text{(Eq. 10)}$$

In this equation $P_{nov}$, t, $F_y$ are in kips, inches and ksi, respectively.

Test results were compared with the results calculated using Eq. 10 as well as those calculated using Eq. 10 with $F_u$ substituted for $F_y$. It is seen in Table 6 that the use of $F_u$ gives somewhat better correlation. Table 6 also gives the resistance factors, $\phi$, and factors of safety required for given reliability indices. The values of $P_m$ indicate that Eq. 10 gives mean calculated strengths that are significantly higher than the observed values. In order to have the equations give means closer to 1, the coefficient .59 was multiplied by 1.3. With these modifications Eq. 10 becomes:

$$P_{nov} = 0.77\ t\ F_u \qquad \text{(Eq. 11)}$$

The results evaluated using Eq. 11 are shown in Table 7.

The above equations do not contain the washer diameter $d_s$ as a variable. However, the British Standard (Reference 9) does contain it as follows:

$$P_{nov} = 1.1\ t\ d_s\ F_y \qquad \text{(Eq. 12)}$$

This equation is valid for any consistent unit system.

A series of tests reported in Reference 10 was evaluated using Eqs. 10 and 12. It was seen that for small $d_s$ values (though it is not very clear from the reference, these cases could be when no washer is used and $d_s$ could have beed the screw head diameter) these equations can be unconservative. In order to avoid these unconservative cases yet maintain the formulation based on $F_u$ rather than $F_y$, Eq. 12 was modified as follows:

$$P_{nov} = 1.5\ t\ d_w\ F_u \qquad \text{(Eq. 13)}$$

where $d_w$ is the larger of the screw head diameter or the washer diameter which shall be taken not larger than 1/2 inch (or 12.7 mm).

### 6. SUMMARY AND CONCLUSIONS

The recommended design equations for shear are Eqs. 4 through 6. The recommended design equations for pull-out and pull-over are Eqs. 8 and 13, respectively.

Scope of applicability and other considerations are discussed above. Based on Tables 3, 5 and 7, it was decided to use a uniform factor of safety of 3.0 and a resistance factor, $\phi$, of 0.5. These values give reliability indices of about 3.5.

The design equations are similar to those of the British Standard (Reference 9) and the ECCS Recommendations (Reference 2) with the following exceptions:

- The coefficients of the equations are different to give values closer to nominal strength

- Factors of safety and resistance factors are different

- Tensile strength rather than yield stress is used. This leads to considerably better agreement between the observed and calculated results.

- For the case of pull-over failure, the provision proposed is basically the same as that of the ECCS Recommendations for screws with usual washer sizes. However for small screw washer sizes or screws without washers the possible unconservatism in the ECCS Recommendations is eliminated through the use of an equation similar to the one stipulated in the British Standard.

**ACKNOWLEDGEMENTS**

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**APPENDIX - NOTATION**

$d$ = Nominal screw diameter

$d_w$ = Larger of the screw head diameter or washer diameter to be taken not larger than 1/2 inch (or 12.7 mm).

$t_c$ = Depth of penetration or the thickness of the material

$t_1$ = Thickness of the member in contact with the screw head

$t_2$ = Thickness of the member not in contact with the screw head member

$P_{nov}$ = Nominal tensile capacity determined by pull-over

$P_{not}$ = Nominal tensile capacity determined by pull-out

$P_{ns}$ = Nominal shear capacity in tilting and bearing

$V_f$ = Coefficient of variation of the geometric property (thickness) to that specified

$V_m$ = Coefficient of variation of the ratio of the actual material property ($F_y$ or $F_u$) to that specified

$V_q$ = Coefficient of variation of loading (the value given here is for a live to dead load ratio of 5)

**TABLE 1**

**TEST RESULTS CONSIDERED**

| Ref. | No. of Tests | Screw sizes (No.) | Comments |
|---|---|---|---|
| | | **SHEAR** | |
| 5 | 940 | 6 to 14 | (1) |
| 6 | 960 | 8 to 14 | |
| 7 | 105 | 4 to 14 | |
| 8 | 178 | 6 to 14 | (2) |
| | 83 | 6 to 14 | (3) |
| | 16 | 6 to 14 | (4) |
| | 4 | 6 to 14 | (5) |
| | | **PULL-OUT** | |
| 5 | 500 | 6 to 14 | |
| 6 | 340 | 8 to 14 | |
| 7 | (6) | 4 to 14 | |
| | | **PULL-OVER** | |
| 6 | 340 | 8 to 14 | |
| 7 | (6) | 4 to 14 | |
| 10 | 22 | 4 to 14 | |

(1) Only ultimate material strength reported, some screw shear noted but tests where this occurred not identified

(2) Single screw single shear tests

(3) Two screw single shear tests

(4) Two screws in a line perpendicular to the direction of force, single shear

(5) Single screw double shear

(6) Test results are given as plots, no detailed information on material properties given

## TABLE 2

## SHEAR BEHAVIOR

## REQUIRED RESISTANCE AND SAFETY FACTORS

| Ref. | | $F_u$[1] | | $F_y$[1] | | $F_u$[3,4] | |
|---|---|---|---|---|---|---|---|
| | $\beta_o$ | $\phi$ | F. S. | $\phi$ | F. S. | $\phi$ | F. S. |
| 5 | 3 | 0.8050[2] | 1.9049[2] | | | 0.1951 | 7.8611 |
| 5 | 4 | 0.5714 | 2.6834 | | | 0.1409 | 10.8803 |
| 6[4] | 3 | 1.1572 | 1.3250 | 1.4342 | 1.0691 | | |
| 6[4] | 4 | 0.8687 | 1.7650 | 1.0717 | 1.4308 | | |
| 7 | 3 | 0.7572 | 2.0251 | 0.9384 | 1.6340 | | |
| 7 | 4 | 0.5017 | 3.0562 | 0.6174 | 2.4836 | | |
| 7[5] | 3 | 0.9991 | 1.5347 | 1.0892 | 1.4077 | | |
| 7[5] | 4 | 0.7026 | 2.1824 | 0.7602 | 2.0170 | | |
| 8 | 3 | 0.6313 | 2.4287 | 0.8571 | 1.7889 | | |
| 8 | 4 | 0.4446 | 3.4488 | 0.6000 | 2.5555 | | |

| Ref. | $P_m$ | $V_p$ | $P_m$ | $V_p$ | $P_m$[3,4] | $V_p$[3,4] |
|---|---|---|---|---|---|---|
| 5 | 1.3450 | 0.2309 | | | 0.3091 | 0.2038 |
| 6[4] | 1.6349 | 0.1346 | 2.0545 | 0.1442 | | |
| 7 | 1.5555 | 0.3245 | 1.9696 | 0.3335 | | |
| 7[5] | 1.7169 | 0.2715 | 1.9148 | 0.2813 | | |
| 8 | 1.0804 | 0.2426 | 1.4934 | 0.2512 | | |

(1) $F_y$ indicates the use of Eqns. 1 through 3 in predicting the strength. $F_u$ indicates using the same equations with $F_u$ substituted for $F_y$

(2) For $t_1 < .125$ in

(3) For $t_1 \geq .125$ in

(4) Screw shear possible therefore the values shown may be conservative

(5) For aluminum

## TABLE 3

## SHEAR BEHAVIOR

## REQUIRED RESISTANCE AND SAFETY FACTORS

| Ref. | | $F_u$ [1] | | $F_y$ [1] | | $F_u$ [3,4] | |
|---|---|---|---|---|---|---|---|
| | $\beta_o$ | $\phi$ | F. S. | $\phi$ | F. S. | $\phi$ | F. S. |
| 5 | 3.0 | 0.6192[2] | 2.4763[2] | | | 0.1500 | 10.2195 |
| 5 | 3.5 | 0.5217 | 2.9391 | | | 0.1275 | 12.0229 |
| 5 | 4.0 | 0.4395 | 3.4884 | | | 0.1084 | 14.1445 |
| 6[4] | 3.0 | 0.8902 | 1.7225 | 1.1032 | 1.3899 | | |
| 6[4] | 3.5 | 0.7713 | 1.9881 | 0.9536 | 1.6079 | | |
| 6[4] | 4.5 | 0.6682 | 2.2946 | 0.8244 | 1.8600 | | |
| 7 | 3.0 | 0.5824 | 2.6326 | 0.7219 | 2.1241 | | |
| 7 | 3.5 | 0.4741 | 3.2341 | 0.5855 | 2.6188 | | |
| 7 | 4.5 | 0.3859 | 3.9731 | 0.4749 | 3.2286 | | |
| 7[5] | 3.0 | 0.7685 | 1.9952 | 0.8379 | 1.8301 | | |
| 7[5] | 3.5 | 0.6445 | 2.3792 | 0.7000 | 2.1906 | | |
| 7[5] | 4.0 | 0.5405 | 2.8371 | 0.5848 | 2.6221 | | |
| 8 | 3.0 | 0.4856 | 3.1574 | 0.6593 | 2.3256 | | |
| 8 | 3.5 | 0.4075 | 3.7624 | 0.5516 | 2.7796 | | |
| 8 | 4.0 | 0.3420 | 4.4834 | 0.4616 | 3.3221 | | |

| Ref. | $P_m$ | $V_p$ | $P_m$ | $V_p$ | $P_m$ [3,4] | $V_p$ [3,4] |
|---|---|---|---|---|---|---|
| 5 | 1.0346 | 0.2309 | | | 0.2378 | 0.2038 |
| 6[4] | 1.2576 | 0.1346 | 1.5804 | 0.1442 | | |
| 7 | 1.1965 | 0.3245 | 1.5151 | 0.3335 | | |
| 7[5] | 1.3207 | 0.2715 | 1.4729 | 0.2813 | | |
| 8 | 0.8311 | 0.2426 | 1.1488 | 0.2512 | | |

(1) $F_u$ indicates the use of Eqns. 4 through 6 in predicting the strength. $F_y$ indicates using the same equations with $F_y$ substituted for $F_u$.

(2) For $t_1 < .125$ in

(3) For $t_1 \geq .125$ in

(4) Screw shear possible therefore the values shown may be conservative

(5) For aluminum

**TABLE 4**

**PULL-OUT BEHAVIOR**

**REQUIRED**

**RESISTANCE AND SAFETY FACTORS**

| Ref. | | $F_u$ (1) | | $F_y$ (1) | |
|---|---|---|---|---|---|
| | $\beta_o$ | $\phi$ | F. S. | $\phi$ | F. S. |
| 5 | 3 | 0.8328 | 1.8412 | | |
| 5 | 4 | 0.5845 | 2.6234 | | |
| 6 | 3 | 0.6461 | 2.3733 | 0.8235 | 1.8621 |
| 6 | 4 | 0.4369 | 3.5095 | 0.5586 | 2.7451 |

| Ref. | $F_u$ (1) | | $F_y$ (1) | |
|---|---|---|---|---|
| | $P_m$ | $V_p$ | $P_m$ | $V_p$ |
| 5 | 1.4399 | 0.2475 | | |
| 6 | 1.2487 | 0.2982 | 1.5769 | 0.2942 |

(1) $F_y$ indicates the use of Eq. 7 in predicting the strength. $F_u$ indicates using the same equation with $F_u$ substituted for $F_y$

TABLE 5

PULL-OUT BEHAVIOR

REQUIRED

RESISTANCE AND SAFETY FACTORS

| Ref. | | $F_u$ (1) | | $F_y$ (1) | |
|---|---|---|---|---|---|
| | $\beta_o$ | $\phi$ | F. S. | $\phi$ | F. S. |
| 5 | 3.0 | 0.6406 | 2.3935 | | |
| 5 | 3.5 | 0.5367 | 2.8571 | | |
| 5 | 4.0 | 0.4496 | 3.4104 | | |
| 6 | 3.0 | 0.4970 | 3.0853 | 0.6334 | 2.4207 |
| 6 | 3.5 | 0.4087 | 3.7518 | 0.5217 | 2.9392 |
| 6 | 4.0 | 0.3361 | 4.5624 | 0.4297 | 3.5687 |

| Ref. | $F_u$ (1) | | $F_y$ (1) | |
|---|---|---|---|---|
| | $P_m$ | $V_p$ | $P_m$ | $V_p$ |
| 5 | 1.1076 | 0.2475 | | |
| 6 | 0.9605 | 0.2982 | 1.2130 | 0.2942 |

(1) $F_u$ indicates the use of Eq. 8 in predicting the strength. $F_y$ indicates using the same equation with $F_y$ substituted for $F_u$.

**TABLE 6**

**PULL-OVER BEHAVIOR**

**REQUIRED**

**RESISTANCE AND SAFETY FACTORS**

| Ref. | | $F_u$ (1) | | $F_y$ (1) | |
|---|---|---|---|---|---|
| | $\beta_o$ | $\phi$ | F. S. | $\phi$ | F. S. |
| 6 | 3 | 0.7923 | 1.9352 | 0.9367 | 1.6369 |
| 6 | 4 | 0.5608 | 2.7340 | 0.6534 | 2.3468 |

| Ref. | $F_u$ (1) | | $F_y$ (1) | |
|---|---|---|---|---|
| | $P_m$ | $V_p$ | $P_m$ | $V_p$ |
| 6 | 1.3353 | 0.2352 | 1.6500 | 0.2563 |

(1) $F_y$ indicates the use of Eq. 10 in predicting the strength. $F_u$ indicates using the same equation with $F_u$ substituted for $F_y$.

TABLE 7

PULL-OVER BEHAVIOR

REQUIRED

RESISTANCE AND SAFETY FACTORS

| Ref. | | $F_u$[1] | | $F_y$[1] | |
|---|---|---|---|---|---|
| | $\beta_o$ | $\phi$ | F. S. | $\phi$ | F. S. |
| 6 | 3.0 | 0.6095 | 2.5158 | 0.7206 | 2.1279 |
| 6 | 3.5 | 0.5128 | 2.9903 | 0.6018 | 2.5479 |
| 6 | 4.0 | 0.4314 | 3.5542 | 0.5026 | 3.0508 |

| Ref. | $F_u$[1] | | $F_y$[1] | |
|---|---|---|---|---|
| | $P_m$ | $V_p$ | $P_m$ | $V_p$ |
| 6 | 1.0272 | 0.2352 | 1.2692 | 0.2563 |

(1) $F_u$ indicates the use of Eq. 11 in predicting the strength. $F_y$ indicates using the same equation with $F_y$ substituted for $F_u$.