AN ENGINEERING INSIGHT TO THE FUNDAMENTALS OF SCREWED SHEET FASTENING TO RESIST CYCLIC LOADING

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Introduction:

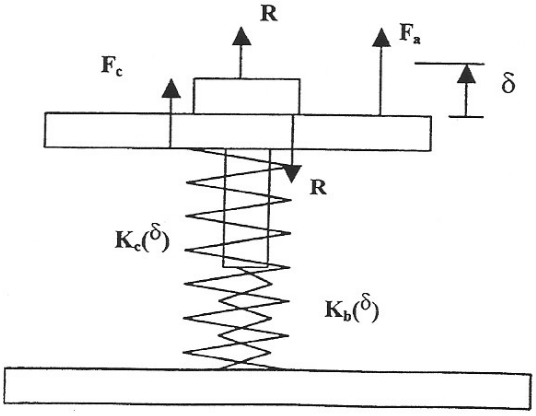
Self-drilling screws are extensively used for fastening sheet metal (eg roofing sheets) to battens made of thin cold rolled sheet metal. With the use of high strength materials and the development of efficient engineering cross-sections it was able to achieve necessary flexural stiffness with even thinner materials. In early days typical thickness of batten materials were 0.7mm, 1.0mm, 1.6mm and 2.0mm whereas material thickness as low as 0.37mm are now being used. The self-drilling screw (SDS) standard AS3566 only specifies the minimum axial force requirement for withdrawal for materials of thickness 1.6mm and some guidelines on the performance of these screws on thinner battens need to be understood. It can be shown that the withdrawal force reduces significantly (more than in proportion to the reduction in thickness) with reducing thickness. Therefore fastening method and fasteners need to be modified to suit these thinner cold rolled steel sections as the fundamental mechanics of a screwed joint is significantly affected by the reducing thickness of the material. This paper intends to identify the key features and performance related parameters in a typical screwed connection using first order approximations. This analysis will then provide some guidelines for the better understanding and engineered design of the screwed joint. Furthermore, an attempt is made to understand the critical features of a screwed joint in a cyclone area.

There are several types of connections based on the materials to be joined. Joining corrugated metal roofing or cladding sheets to wood or metal battens is the main function of SDS. Typically, all roofing sheets are fastened at crests and all cladding sheets are fastened at valleys. In all situations, typically, the strength of the screw is much larger than the corresponding pull-out or pull-through strength. The main failure mode will be either screw pull-through the roofing sheet or pull out of the batten. Pull through is due to the tearing failure of the roofing sheet and pullout may be due to either splitting of the batten material or less likely stripping of the threads. Through careful analysis it can be seen that the splitting of the batten is due to tensile hoop stresses and stress concentration occurring around the edge of the screw hole.

Analysis of a Screwed Joint

In order to understand the fundamental behaviour of a screwed sheet metal joint the following first order analysis has been attempted. Please note that this analysis is no way complete and only tries to identify the first order effects of various parameters associated with a screwed joint. Several assumptions have been made for simplicity. If a rigorous analysis is required Finite Element Modeling may provide for higher order effects. Such an analysis will be extremely costly and time consuming. The analysis presented here will provide an adequate insight to the behaviour of a screwed sheet metal connection.

The main purpose of the screw is to keep together the roofing material and the batten material under designed static and dynamic loading. The fundamental behavior of a bolted joint is comprehensively analysed elsewhere [1]. In comparison to a bolted joint a screwed joint has significantly different characteristics. The ratio between the bolt and joint stiffness is in the order of 1:2 – 1: 7 in a typical bolted joint. However, in a screwed joint this ratio is typically in the order of 1:1000. A screwed joint can be represented by a simple spring system as shown in Figure 1.



Since the stiffness of the screw is extremely large compared to the stiffness of the joint the screw can be represented as a solid body. However, there is flexing occurring at the thread/sheet interface of the fastener which may be considered as the flexing of the screw but at a much lower stiffness. Lets assume the stiffness of the corrugated steel system is k_c, upward force exerted by corrugated steel system is F_c, stiffness at the screw batten interface is k_b, pre-load is F_i, applied load is F_a (upward +), joint stiffness k_a, the displacement due to force F_a is δ and the reaction between the washer head of the screw and the roofing sheet is R. Now,

when F_a is zero $\quad R = F_i$

$$\Delta F_a = k_a\delta; \Delta F_c = k_c\delta; \Delta R = k_b\delta$$
$$R = F_i + k_b\delta; F_c = F_i - k_c\delta; F_a = k_a\delta$$

For equilibrium;

$$R = F_a + F_c$$
$$F_i + k_b\delta = k_a\delta + F_i - k_c\delta$$
$$k_a = k_b + k_c$$
$$\delta = \frac{F_a}{k_a} = \frac{F_a}{k_b + k_c}$$

Now,

$$R = F_i + \frac{k_b}{k_b + k_c} F_a \rightarrow (1)$$

For a sound joint,

$$F_{po} \geq R \geq 0$$

for all applied load conditions.
The reaction R will be zero when the downward applied load is greater than or equal to $(k_b+k_c)F_i/k_b$. This means separation of the roofing sheet from the head of the screw and hence rubbing/fretting type failure at the head/sheet interface. If the applied load is upward separation will not occur as R will stay positive. However, in this case as the load on the screw is increased there is a possibility of pull-out failure. From the above discussion it is apparent the importance of the pre-load and pull-out load in a screwed joint.

Now the design conditions can be prescribed in the following manner;

Design upward force per screw $\quad F_{du}$
Design downward force per screw $\quad F_{dd}$

Now pre-load F_i,

$$F_i \geq \frac{k_b}{k_b + k_c} F_{dd} \text{\_\_\_\_\_\_\_\_\_\_\_\_}(2)$$

and pullout load F_{po},

$$F_{po} \geq F_i + \frac{k_b}{k_b + k_c} F_{du}$$

Hence,

$$F_{po} \geq \frac{k_b}{k_b + k_c}(F_{dd} + F_{du}) \text{\_\_\_\_\_\_\_\_\_\_}(3)$$

Furthermore, the pull through load F_{pt} shall be larger than the pullout load F_{po}.

$$F_{pt} \geq F_{po}$$

The pre-tension F_i can be achieved by driving the screw further after snug tight fit is achieved. This may be controlled by the number of revolutions made after the first contact point. An experimental calibration will provide the relationship between the pre-load and the number of revolutions (or displacement δ) after the initial contact between the head of the bolt and the roofing sheet is made. This relationship may be a characteristic of a particular roofing system. It is also expected that this relationship to be non-linear due to the particular shape of corrugation and associated membrane stresses. Figure 2 shows the expected form for the load displacement curve.

In another sense, the pre-tension can be seen as storing energy in the joint. It has been proven that a joint integrity will improve as the amount of energy stored in the joint increases.

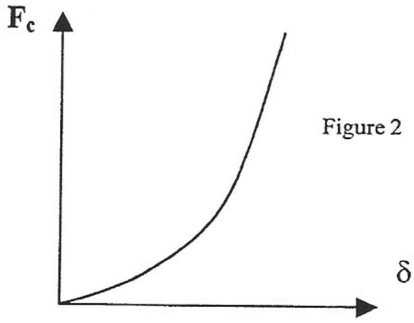


Figure 2

Now that we have established the importance of pull-out load it is important to understand how this load is developed in a screwed sheet metal joint.

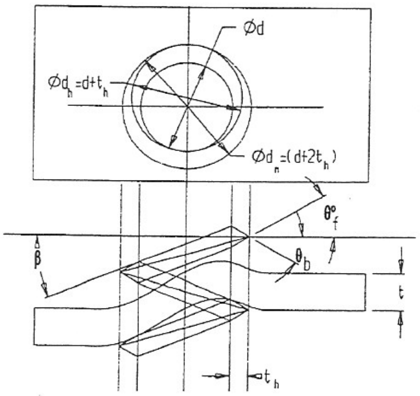
Effect of Screw Parameters

The parameters and limitations associated with self-drilling screws for the building and construction industries are described in detail in AS3566-1988 [2]. It describes various head geometry, drive features, drill points, sizes or screw gauges, thread profiles, and mechanical properties of self-drilling screws. Author does not wish to discuss the above parameters at length in the present paper and makes some effort to identify the effect of such parameters on the performance of the screws in a thin steel sheet connection.

Figure 3 shows the schematic of a screwed connection. The following parameters are of importance;

Thread helix angle	$\beta = \tan^{-1}(p/2\pi d)$
Thread minor diameter	d
Thread height	t_h
Thread major diameter	$d_m = d + 2t_h$
Thread pitch	p
Thread flank angle forward	θ_f
Thread flank angle backward	θ_b
Drilled hole diameter	d_h
Length of drill point	l_d
Thickness of sheet metal	t
Ultimate tensile strength of sheet metal	f_u
Ultimate shear strength of sheet metal	f_s
Yield strength of sheet metal	f_y

Figure 3



As shown in Figure 3 the optimum hole diameter can be given by; $d_h = d + t_h$;
the corresponding contact area between the thread and the sheet metal can be approximately given by;

$$A_c = \pi\left(\frac{(d+2t_h)^2}{4} - \frac{(d+t_h)^2}{4}\right)$$

$$= \frac{\pi}{4}\left(2dt_h + 3t_h^2\right)$$

Similarly, the shear area can be approximated by;

$$A_s = \phi\pi(d + 2t_h)t$$

where ϕ is a factor less than 1 which accounts for the shear area that may not be effective. If a pure shear failure occurs at pull out then the pull out load F_{po} can be given by,

$$F_{po} = 0.62 f_u \phi\pi(d + 2t_h)t$$

This equation resembles the Australian Standard provisions for pull-out capacity;

$$F_{po} = 0.85 t d f_u$$

where d in this case is the nominal diameter of the screw. This implies a value of 0.43 for ϕ. However, when a typical pull-out failure is carefully examined it is apparent that the failure is not pure shear failure.

Now lets look at the bearing failure mode. Assuming the applied load is distributed equally over the bearing area;

$$F_{po} = \frac{\pi}{4} f_u \left(2dt_h + 3t_h^2\right)$$

This formula doesn't contain sheet metal thickness and this failure mode is highly unlikely.

Lets look at the force distribution around the drilled hole in a screwed connection.

The applied axial force F provides a force normal to the backward flange of the screw thread F_n and a radially outward load of F_r;

$$F_r = F\tan(\vartheta_b)$$

$$F_n = \frac{F}{\cos(\vartheta_b)}$$

The helix angle of the thread also makes forces normal to the thread surface and along the circumference. Now the force normal to the backward flange of the screw thread is;

$$F_{nT} = \frac{F}{\cos(\vartheta_b)\cos(\beta)}$$

Now the total force acting along the circumference can be approximated by,

$$F_{rT} = F\left(\tan(\vartheta_b) + \tan(\beta)\right)$$

As a first order approximation it can be assumed that this force is acting over an area A_t of;

$$A_t = A_t(d, t, .t_h)$$

Based on this area for tearing failure;

$$F_{po} = \frac{A_t(d, t, .t_h) f_u}{\left(\tan(\vartheta_b) + \left(\frac{p}{2\pi d}\right)\right)} \text{———} (4)$$

This formula probably best describes the final failure mechanism and relative effects of each of the screw parameters.

In order to establish the batten stiffness (k_b) theory of thin plates [3] can be used. The relationship between radius (r), deflection (w), Shear force per unit length (Q), plate thickness (t), Young's Modulus (E), and Poisson's ratio (ν) in the elastic region can be given as;

$$\frac{d}{dr}\left(\frac{1}{r}\frac{d}{dr}\left(r\frac{dw}{dr}\right)\right) = \frac{Q}{D}$$

$$Q = \frac{F_0}{2\pi r}; D = \frac{Et^3}{12(1 - \nu^2)}$$

and

$$\sigma_{\vartheta} = \frac{12 M_{\vartheta} z}{t^3}$$

$$M_{\vartheta} = -D\left(\frac{1}{r}\frac{dw}{dr} + \nu \frac{d^2 w}{dr^2}\right)$$

where z is the distance along thickness from the neutral plane. Maximum stress will occur when $z = t/2$, hence,

$$\sigma_{\vartheta,\max} = \frac{6 M_{\vartheta}}{t^2}$$

By applying appropriate boundary conditions a formula for yield load F_y and $k_b$can be given as;

$$F_y = \frac{\varphi f_y t^2}{C_1\left(\frac{d_e}{d}, \nu\right)} \cos(\vartheta_b)\left(\frac{2\pi d}{\sqrt{p^2 + 4\pi^2 d^2}}\right) \qquad \text{\_\_\_\_\_\_\_\_\_\_\_\_(5)}$$

$$k_b = \frac{E t^3}{C_2\left(\frac{d_e}{d}, \nu\right)\left(\frac{d_e}{d}\right)^2 d^2}$$

where C_1 and C_2 are functions of d_e/d (d_e is the diameter of the area on the batten that has been affected by deformation) and ν, and φ is a factor compensating for inaccuracies of the assumptions. For various values of d_e/d and $\nu=0.3$, C_1 and C_2 can be given as;

d_e/d	C_1	C_2
1.25	0.115	0.00129
1.5	0.220	0.0064
2.0	0.405	0.0237

The value d_e depends on the grade and thickness (stiffness) of the batten material.

Discussion and Conclusions:

A general behaviour of a screwed roofing sheet to batten joint has been analysed. In order to prevent rubbing and fretting at the screwhead/sheet interface the concept of pre-tension in the joint is introduced. Equations (2) and (3) describes the design conditions for pre-load and pull-out load. Once the design upward and downward loads are known the pull-out strength per screw and the optimum pre-load can be calculated.

In order to understand the effect of various features of the screw on its pull-out performance a combination of Equations (4) and (5) can be used. Based on these formulae the following basic trends can be established.

Pull-out load can be increased by;

a) increasing tensile strength of the sheet metal
b) increasing thread height
c) increasing sheet metal thickness
d) decreasing backward flank angle θ_b
e) decreasing pitch of the thread
f) and increasing minor diameter.

It has been found in recent times the drill point of SDS made smaller in an attempt to increase the pull-out load. As long as the drilled hole diameter is $\geq(d + t_h)$ this will not interfere with the performance. However, if the drill point is smaller than the above value this has the potential to;

a) increase the hoop stresses on the hole and hence to cause premature failure
b) damage to the coatings on the screw due to positive rubbing
c) increase installation torque requirement.

Furthermore, if the screw is unable to drill a clean hole the jagged edges on the hole may lead to stress risers making the performance unreliable. This effect is worsened when fastening to thin sheet metal.

There is another geometric relationship that need to be considered when deciding the pitch or TPI (threads per inch) of the screw. If the total thickness of the materials to be joined is t_j;

$$p \geq t_j + t_h(\tan(\vartheta_b) + \tan(\vartheta_f))$$

In case of roof sheet fastening (crest fastening) t_j is the thickness of the batten material. For wall cladding (valley fastening) t_j = (thickness of corrugated sheet + thickness of the batten material). In order to be able to drill through the material before the thread is engaged the length of the drill point (l_d);

$$l_d > t_j$$

T-17 Screws:

T-17 (Type 17) is also considered as a self-drilling fastener in AS3366. Instead of a defined drill point this fastener has a slot made at the tip facilitating for penetrating through thin (G550, thickness 0.42mm) sheet metal. The purpose of the slot mainly is to sharpen the point and to provide a cutting edge so that it can easily pierce the sheet metal.

In some occasions it was found that T-17 screws perform better than ordinary self-drilling screws for fixing steel roofing sheets to thinner gauge metal battens. Folding of material at the edge of the hole in T-17 drilling process instead of cutting and removing material makes the hole less susceptible to tearing which is the common mode of failure. This effectively increases the thickness of the sheet metal as seen by the screw. As discussed earlier the thickness increase will have the greatest impact on increasing the pull-out load. Furthermore, if the drill point in a self-drilling screw makes a hole larger than the "minor diameter+thread height" of the screw the pull out performance will be significantly affected. As a T-17 screw opens up the whole just to fit in the screw this variability does not arise with T-17 screws hence making it a more reliable fastener for fastening to thin metal battens than SDS with well defined drill points.

References:

1. Fernando, S., "An Engineering Insight into the Fundamental Behaviour of Tensile Bolted Joints," Steel Construction, Journal of the Australian Institute of Steel Construction, Vol.35, No.1, March 2001.
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