DEVELOPMENT OF PULL-OUT DESIGN STRENGTH FORMULAE FOR LIGHT GAUGE STEEL ROOFING SYSTEMS

BY

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ABSTRACT

A brief Introduction of steel cladding failures under wind uplift load. Explaining the importance of roof and wall cladding system to support the structural integrity of the whole structure during the cyclone or storm events. The objective of this thesis is to develop a dimensionless formula for predicting pull-out failure under wind uplift loading. Chapter two presents the behaviour of steel roofing systems under wind uplift loading/suction. It also describes the types of cladding, connection, and failure mechanism of the roofing systems. Chapter three and four Presents a review of previous literature published on pull-out and pull-through strength of steel roofing systems subjected to wind uplift/suction. Chapter five presents the detailed analysis to determine the pull out strength of steel roof claddings using Buckingham theorem, excel spreadsheet and solver program.

Thesis Keywords:

pull-out, pull-through, steel, cladding, roofing, joints, screws, sheet, metal, Mahendran, Tang, Mahaarachchi, Gunawan.

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Leonardus Gunawan

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1.0 INTRODUCTION

1.1 Background

Throughout history, cyclones and storms have been responsible for great losses of life and property in many countries around the world. Housing in the tropics, particularly low-rise buildings, have been severely damaged during high-wind events such as cyclones and storms. In December 1974, the northern Australian city of Darwin was severely affected by tropical cyclone Tracy causing an economic loss and severe damage to houses and buildings.

Figure 1.1 Cyclone Tracy in Darwin, 1974 (from BBC)

Information on damage by hurricanes, tornadoes, and other strong winds reveals that low-rise buildings suffer the greatest damage. Because of commonly used low pitch roofs, low-rise buildings are subjected to an uplift loading on the roof and a racking load on the wall. The uplift loading on the roof claddings is transferred to battens which are immediately located beneath the claddings. Investigations of wind damage in low-rise buildings have often shown that the uplift load path has the weakest links, often at connections. Very rarely the members have initiated the failure.

Failures where roof sheeting pulls over the fastener heads are called pull through/pull-over failures and failures where fasteners are pulled out of the battens are called pull-out failures. The majority of roof system failures have been considered due to pull-through failures where the roof sheeting disengage from the battens and cause transverse splitting in the roof sheeting.

The major component of damage as a result from 1974 cyclone Tracy in Darwin is a huge loss of light gauge metal roof cladding that was caused by low cycle fatigue. Low cycle fatigue was defined as failure typically within 10000 load cycle (Morgan and Beck). Furthermore, Morgan and Beck showed that the thin crest-fixed roof sheeting which is common in Australia suffered a fatigue failure near the fasteners area under the action of sustained fluctuating wind loading. Although valley-fixed may have better resistance against cyclic wind loading, they will also fail from similar fatigue failures.

The most common light gauge metal cladding that is used in Australia is of the corrugated and rib/pan profiles and is rolled from 0.42 mm bmt G550 (minimum yield stress of 550 Mpa, measured mean yield stress typically exceeds 700 Mpa).

Natural disasters are becoming of greater concern to the world at large. It is considered that cyclones of today, of the same density as those in the past, would cost much more than in the past. Exposure to a storm or high wind effects an area today more than it would have in the past because standards of living risen and the population density has increased. There are more structures of greater complexity in an area today than ever have been before.

1.2 Problem Definition

The most common connection between steel roof sheeting and battens that have been used in Australia is crest-fixed connection unlike in America and Europe that majority used valley-fixed roofing systems. Therefore the design formulae that have been developed for the valley-fixed, thicker and low strength steel claddings cannot be used for the crest-fixed, thinner and high strength steel claddings. There are only several researches that have been conducted regarding the behaviour of crest-fixed roofing systems.

Currently, no Australian standards has, by calculation, any design provisions for crest-fixed cladding systems, except for the testing provisions given in AS 1562(SA,1992) and AS 4040 (SA,1992) which are considered very expensive (Mahaarachchi, 2003).

Currently individual designers and manufacturers use a large number of tests to determine the required connection strengths (pull-out or pull through / pull-over) for their own specific cladding systems. And the cost of test will obviously be included in the price of the cladding systems.

Because of the lack of understanding, unavailability of design formulae and information, and very expensive testing provisions, the same type of cladding system have been used over and over again without any significant improvement.

Failures at the connections of steel roof cladding systems are a common occurrence during high wind events, which have then led to severe damage to the entire buildings and their contents. (Tang,1998). In overall crest-fixed connection provides better leakage prevention than valley-fixed connection but has lesser strength resistant from wind uplift/suction loading.

1.3 Objective

Based on current knowledge and the problems indentified in the last section, the overall objective of this thesis is to simplify the current design formulae used to determine the strength of the roofing systems.

Detail objective of this thesis is:

> To review nondimensional simplified formula of various steel claddings, steel battens/purlins and screw fasteners subjected to pull-out failures under wind uplift/suction loading.

1.4 Research Method

To achieve the above-mentioned objectives, data from previous research project will be used to develop the formulae. For pull-through failure the data will be taken from Mahaarachi and Mahendran, 2003 and for pull-out failure the data will be taken from Tang and Mahendran, 1998. Microsoft office excel will be used to develop the dimensionless simplified formula for both pull-out and pull-through strength of the roofing systems. The results from excel spreadsheet will be analysed and evaluated to derived appropriate simple design formulae.

1.5 Thesis Content

The material contained in this thesis is divided into 6 chapters:

Chapter 1 Introduction to the topic, background, problem definitions, objectives and the method that will be used to developed the simplified formulae.

Chapter 2 Presents the behaviour of steel roofing systems under wind uplift loading/suction. Describes the types of cladding, connection, and failure mechanism of the roofing systems.

Chapter 3 Presents a review of previous literature published on pull-out strength of steel roofing systems subjected to wind uplift/suction

Chapter 4 Presents a review of previous literature published on pull-through strength of steel roofing systems subjected to wind uplift/suction

Chapter 5 Presents the detailed analysis to determine pull out strength of steel roof claddings using excel spreadsheet including the development of dimensionless simplified formulae

Chapter 6 Presents the conclusions and recommendations from this thesis.

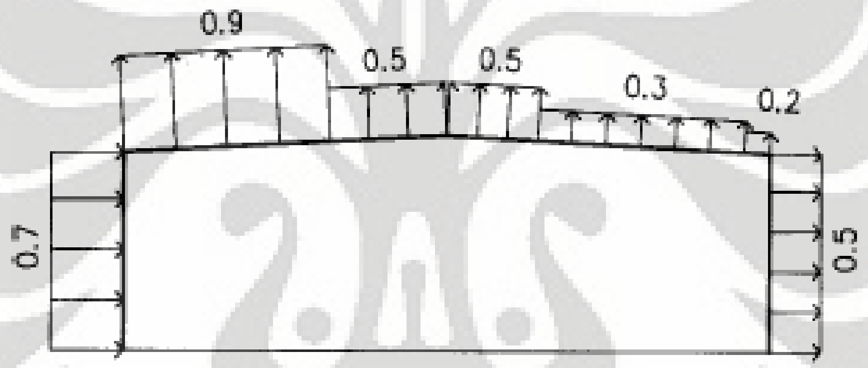
Chapter 3 and 4 present a thorough literature review on each topic of the chapter.

2.0 BEHAVIOUR OF STEEL ROOFING SYSTEMS

2.1 Background

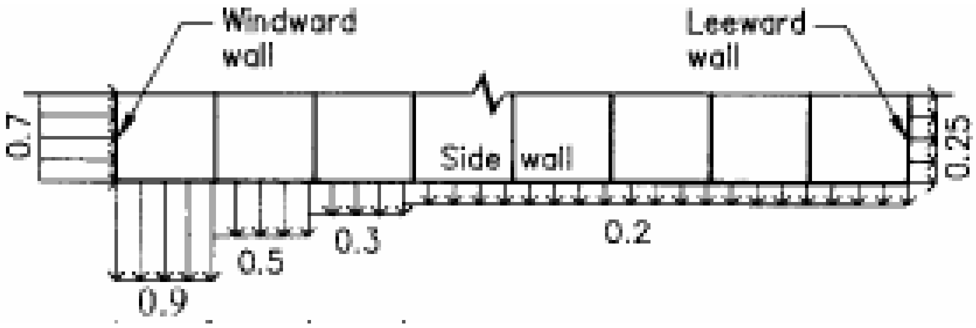
Low-rise buildings usually have low-pitched roofs and are subjected to uplift and racking loads during high-wind events. In addition to shear/racking forces in the sheeting, the wind action creates considerable pressures on both the upper surface and the underside of a roof/wall cladding. These forces may take the form of positive or negative pressure and must be considered in the design and fixing of a roof or wall.

Wind-induced high suction usually develops at the roof eaves closer to the roof corner, or at the roof ridge near the gable end. The external pressure coefficients for the roofs of rectangular enclosed buildings as specified by 'Minimum Design Load of Structure AS 1170.2 (SA, 2002) are shown in Figure 2.1. below. These coefficients allow for the pressures on small areas to be compared with the average increase over the surface.



(a) External Wind Pressure Coefficients Under Cross Wind

(i) Roof and End Wall Pressure



(ii) Side Wall Pressure

(b) External Wind Pressure Coefficients Under Longitudinal Wind

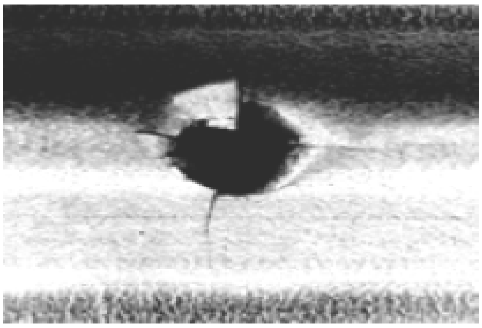
Figure 2.1 Wind Loading on Low-rise Buildings

2.2 Failures of Steel Claddings

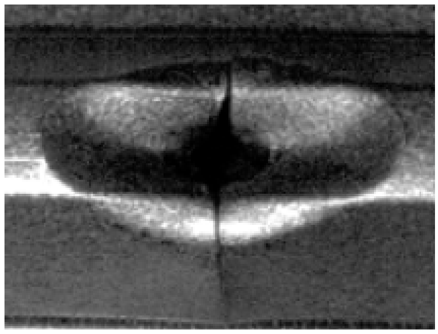
Past observations have shown that the uplift load path is the weakest link in buildings, often at the screw fastener connections. Very rarely were the members found to have initiated the failure. Connections in the roof and wall cladding systems are the weakest link in carrying the fluctuating loading during high wind events (Mahaarachchi, 2003).

Wind uplift loading on the roof/wall is a randomly fluctuating loading and thus causes fatigue failures of steel cladding to batten connections. Thin, crest-fixed steel claddings suffered a fatigue failure of sheeting in the vicinity of screw fasteners under the action of fluctuating wind loading (Mahendran 1990a, b). The presence of large stress concentrations around the connections in steel claddings under sustained fluctuating loadings provided all the ingredients required for a low cycle fatigue in a static structure such as steel claddings. Valley-fixed cladding performs better under cyclic wind loading. However, it also experiences from similar fatigue failures (Mahendran, 1990b).

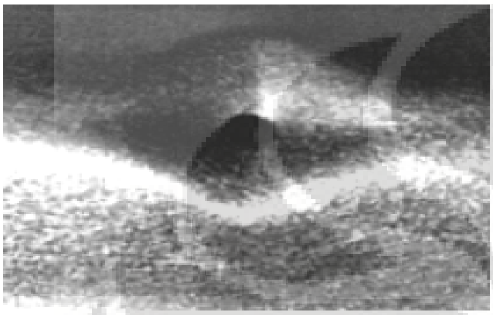
A large number of wind tunnel studies and field measurements have shown that roof claddings in strong winds are predominantly subjected to wind uplift forces (Xu and Teng, 1994). Failures of roof sheeting pulling through or pulling over the fastener heads are commonly referred to as 'pull-through' or 'pulling-over' failures. In some cases, it is caused by the fasteners pulling out of the timber or steel battens, which is called a 'pull-out' failure. For some steel claddings, local dimpling failures occur instead of the above failures. Figure 2.2. shows these local failures of profiled steel claddings.



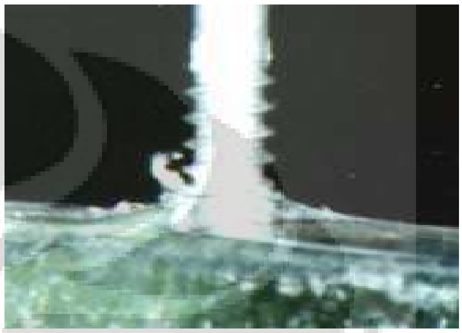
(a) Fatigue pull-through failure



(b) Static pull-through failure



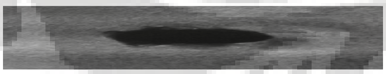
(c) Static dimpling failure



(d) Pull-out failure

Figure 2.2 Local Failures of Steel Claddings

Since separate bracing systems are usually provided to resist racking forces in buildings, roof claddings are not considered to carry any in-plane shear forced due to the racking action of the buildings, referred to as diaphragm action. However, profiled metal claddings may still carry part of the racking force. This may cause tearing of sheeting or bending of screw fasteners. There failures were observed in the laboratory when high racking forces were applied to roof cladding (Mahendran, 1994). This means that performance of roof sheeting may be severely compromised when combined wind uplift and higher racking loads act on the roof cladding, particularly when they are crest-fixed.



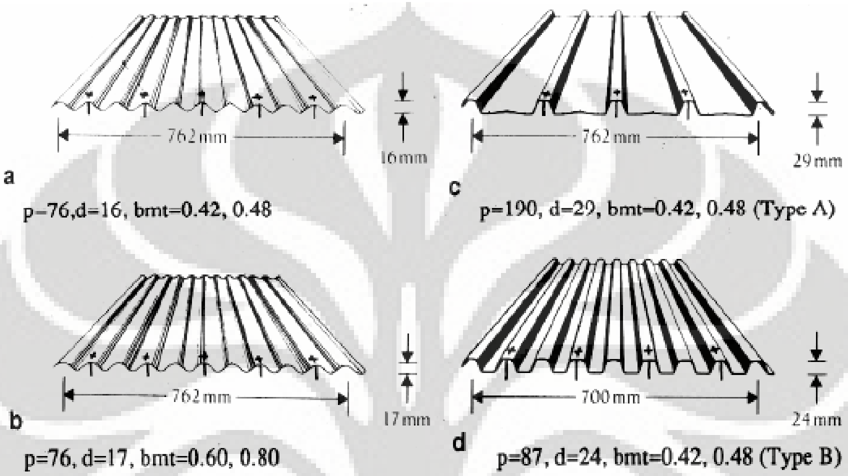
(a) Tearing of Sheeting

(b) Bending of fasteners

Figure 2.3 Failures Due to Higher Racking Loads

2.3 Thin Profiled Steel Cladding

In Australia and in its neighbouring countries, profiled steel roof and wall claddings are commonly used in houses and low-rise commercial and industrial buildings. Most common profiles are shown in Figure 2.4. they are made of very thin (0.42 mm or 0.48 mm) high strength steel (G550 with a minimum yield stress of 550 MPa), but in some cases they are made of G300 steel.



(p = pitch, d = depth, bmt = base metal thickness)

Figure 2.4 Standard Profiled Steel Cladding Systems Used in Australia

G550 Steels are produced using a process called cold reduction, which can be used to increase the strength and hardness, as well as produce an accurate thickness for sheet steels and other product. High compressive force in the stands and strip tension systematically reduces the thickness of steel sheet until the desired dimension is reached. The thickness is reduced by approximately 75 to 85% for the 0.60 and 0.42 mm sheet steel. The milling process causes the grain structure of cold reduced steels to elongate in the rolling direction, which produces an increase in material strength and decrease in material ductility (BHP, 1992, Rogers and Hancock, 1996, 1997a, b, 1998).

The steel roofing systems are always crest-fixed to cold-formed steel purlins/battens or timber purlins using screw fasteners. The crest-fixing is used to eliminate water leakage problems, despite the greater strength obtained from valley-fixed method. However, compared with Australian roof claddings, the roof claddings in USA and Europe are made of thicker (>0.6 mm) and lower strength steels (yield stress < 450 MPa) and are valley-fixed, and the governing load case is downward loading in most cases.

The wind uplift loading on the roof cladding is transferred via screw fasteners to battens or purlins located immediately beneath the cladding. It is important that the cladding is adequately fastened and selected. Inadequacy would lead to premature pull-out failures. The steel cladding manufacturers usually specify the type of screw fasteners to be used. Figure 2.5. shows the three different screw fasteners available in Australia (IITW, 1995).

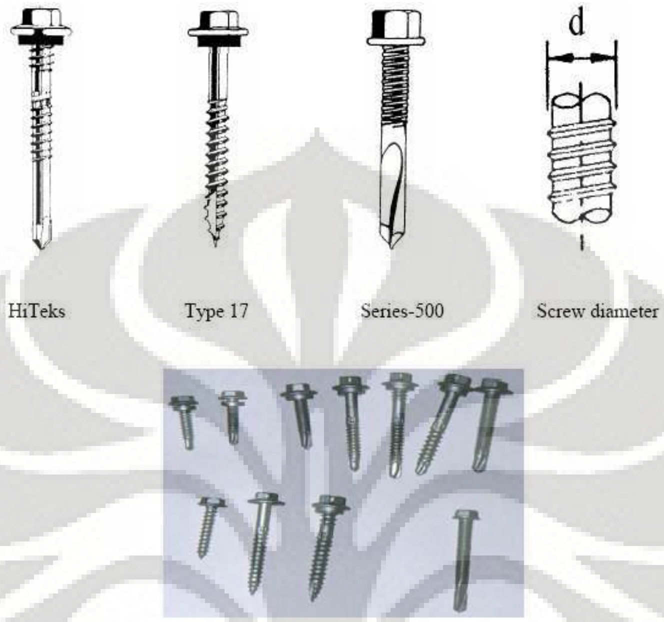


Figure 2.5 Screw Fasteners

Extensive reviews on Australian standards, building regulation and practice were undertaken after cyclone Tracy devastated Darwin in 1974. Research was also carried out to study the static and fatigue behaviour of commonly used crest-fixed roof claddings (Morgan and Beck, 1977, Beck and Stevens, 1979, Mahendran 1990a, b,c, 1994a,b,). A cyclone washer, with the usual screw fastener, delays pull-through failures. The fatigue performance of the cladding is therefore significantly improved (Mahendran, 1990, Xu, 1994).

Figure 2.6 Crests Fixing of Claddings

Cyclone-induced, sustained, fluctuating wind uplift may cause fatigue damage to roofing sheets (Beck and Stevens, 1979) whilst short-term strong wind uplift could damage roofing sheets in the vicinity of screw fasteners by local plastic collapse. The destruction of Darwin in 1974 by cyclone Tracy drew attention to the performance of thin, steel roof claddings.

2.4 Cladding Types

2.4.1 Corrugated Cladding

The large upward deflections of unscrewed crests under uplift loading caused severe cross-sectional distortion of the roofing. A localised diamond-shaped plastic deformation (LPD) is then formed at the crests, centred on the fastener heads. There is reserve static strength beyond the LPD load. Further increase of loading leads to global buckling and yielding at the crests and valleys of each mid-span cross-section, followed by the buckling failure of unscrewed crests at the supports. However, the reserve static strength beyond the LPD load is ignored, particularly from a fatigue point of view (Mahendran, 1990b).

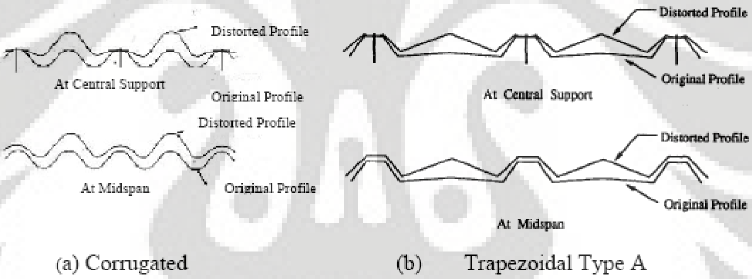


Figure 2.7 **Deformations of two-span claddings under wind uplift loading**

Figure 2.8 **Local Dimpling Failures of Corrugated Claddings**

2.4.2 Trapezoidal Type A Cladding

The trapezoidal Type A cladding profile also displays extensive cross-sectional distortion under wind uplift, as in the case of corrugated cladding. This is attributed to the screwed ribs being separated by wide pans, which lead to a premature localised failure of the screwed crests. The screwed crests under the fastener heads are slightly dimpled at the early stage of loading, but the overall geometric deformation of the cladding is very small. This is followed by combined membrane and bending actions in both longitudinal and transverse directions around the fastener holes. The region around the fastener holes yields at this stage and the dimples under the screw heads become larger. Larger cross-sectional distortion also occurs. With further load increase, splitting occurs in the transverse direction at the screw fastener holes, which leads to a localised pull-through failure. There is no reserve strength beyond the pull-through failure. No global buckling or yielding occurs elsewhere in the cladding. Finite element analysis (Mahendran, 1994) has shown the presence of high membrane strains in the longitudinal direction. Since the high strength steel has limited ductility, transverse fracture occurred at the fastener hole when the membrane stresses reached yielding.

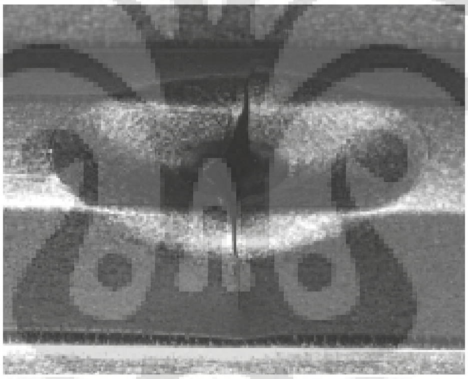


Figure 2.9 Local Pull-through Failure of Trapezoidal Type A Cladding

2.4.3 Trapezoidal Type B Cladding

The local behaviour of the commonly used, alternate crest-fixed trapezoidal Type-B cladding profile is a combination of the corrugated profile behaviour and the trapezoidal Type A cladding profile behaviour. Slight dimpling occurs under the fastener heads at the early stage of loading, followed by a membrane action in the fastener region. With an increase of loading, the dimples become larger and the cladding suffers severe cross-sectional distortion as with the other profiles. Finally the sheeting splits under the fastener heads and leads to a localised pull-through failure. In some cases, the ribs are completely flattened and do not pull-through unless further dimpling occurs at the crest. Eventually, the cladding pulls-through the fasteners at a higher load

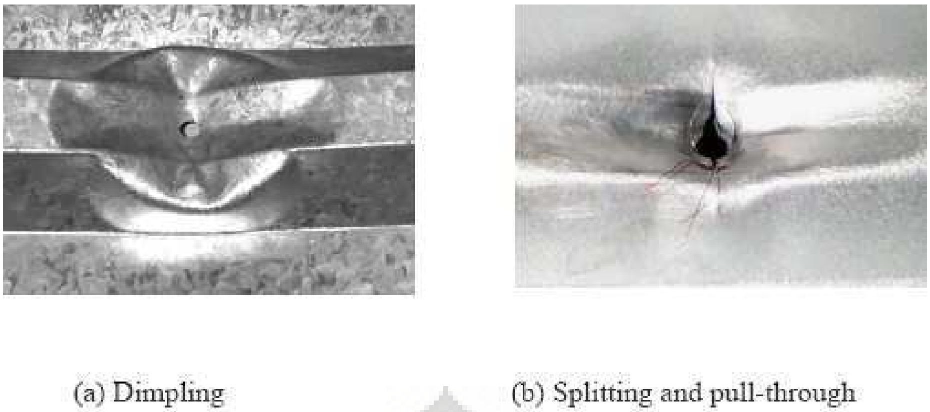


Figure 2.10 Local Failure of Trapezoidal Type B Cladding

The reserve static strength beyond the local failure cannot be guaranteed, and thus the failure load is taken as the load at which the first crest dimples locally at the fastener hole (Mahendran, 1994). There is no global buckling and yielding elsewhere in the cladding.

2.5 Static Behaviour

In Australia, loss of metal roof and wall cladding systems, due to local failures at screwed connections, has been a common occurrence during storms and cyclones for many years. Under wind uplift, the strength of a roofing sheet is primarily determined by its capacity to resist the downward reaction from the fastener. The sheeting can fail locally in the vicinity of the screw fastener by plastic collapse or due to low cycle fatigue (Mahendran, 1990a, b, 1994, Xu and Tang, 1994).

Besides the two common local failures, namely pull-out and pull through failures. The other failures that occur are tensile fracture of the screw and gross distortion or tearing of the sheeting. Some cladding profiles undergo a local dimpling failure around the fasteners instead of a pull-through failure (Mahendran, 1994), especially in some shapes of trapezoidal claddings and when claddings are made of steel with greater ductility. In this case, disengagement of sheeting does not occur and thus is a preferred failure mode. However, Mahendran (1990a) refers to this localised dimpling failure, as a pull-through failure since the sheeting survives only a few cycles of storm/cyclone loading, once a localised dimpling failure has occurred.

Recent research aimed at determining the reason for splitting in G550 steel claddings (Mahaarachchi & Mahendran 2000) has shown that the transverse splitting occurs when:

-. The longitudinal membrane tensile strain is greater than 60% of the total strain at the edge of the fastener holes.

-. The total strain is equal to the measured failure strain from the tensile coupon test of steel (0.02 for 0.42 mm G550 steel).

Material testing has shown that the properties of G550 steel in the longitudinal direction have very little strain hardening and the fracture strain is about 2%. The ultimate strength in the transverse direction is greater than that in the longitudinal direction; however the fracture strain is only about 0.5%. All of these observations indicate that the cladding made of high strength steel has limited ductility.

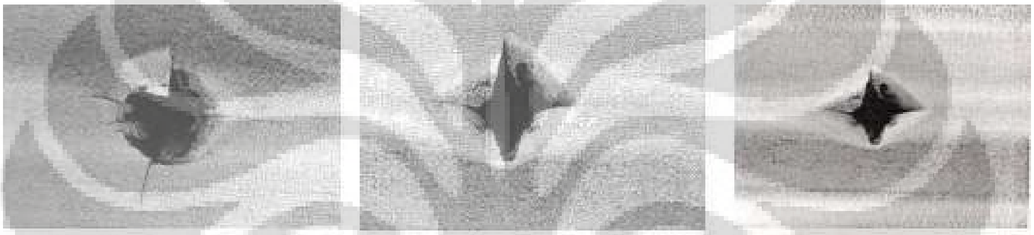
The transverse splitting phenomenon occurs when the longitudinal membrane strain at the edge of the fastener hole reaches the critical strain of steel (Tang, 1998). Since high strength steel has significantly reduced ductility and a failure strain value of 2%, it was considered that premature splitting occurs in the transverse direction, leading it to a pull-through failure (Mahendran, 1994 and Xu, 1994).

Figure 2.11 Splitting Phenomenon

Tang (1998) attempted to prove the above hypothesis and establish a failure criterion for splitting/fracture. The results from finite element analyses showed that the failure load did not correspond to the 2% membrane strain. The longitudinal membrane strains varied depending on other parameters, such as the diameter of the screw head or washer, the cladding thickness, the yield stress and the profile geometry. Therefore, the 2% failure strain level may not appropriate and further research is needed to establish the critical strain at which splitting/fracture occurs under the combined membrane and bending actions.

2.6 Fatigue Behaviour

Premature local pull-through failures can be caused by the low cycle fatigue failure in the vicinity of fastener holes under the sustained fluctuations of wind uplift. The presence of high stress concentrations around the fastener holes under wind uplift is attributed to the fatigue failure. During cyclonic winds, the sustained wind loading fluctuates and causes fatigue cracking around the regions of fastener holes till the sheeting pulls through the fastener heads. The fatigue strength of the crest-fixed steel cladding is dependent on the geometry of the profile. The fatigue strength is 20 to 50% lower than the strength corresponding to static type failures (Mahendran, 1994). For the safe design of metal claddings, designer should have the actual cyclones/storm loading data, and design methods based on observed structural behaviour under such loading.



(a) (b) (c)

Figure 2.12 Fatigue Failures of Steel Claddings

3.0 PULL OUT FAILURE

Steel Cladding systems can also suffer from another type of local failure when the screw fasteners pull-out of the steel battens, purlins or girt. In recent times, very thin high strength steel battens of various shapes have been used in housing, industrial and commercial buildings where the local pull-out failure can be critical failure mode. Such a pull-out failure also leads to the rapid disengagement of the rood and wall claddings, causing severe damage to the entire building. This failure mode has not been well researched for Australian cladding systems.

Traditionally, timber purlins and battens have been used in housing and hence pull-out failures have not been a common occurrence or a problem. This situation has changed due to the increasing use of thin, high steel battens and purlins in housing (Mahendran and Tang, 1998, Baskaran, 1997). It is likely that sustained cyclic loading conditions during storms could lead to premature fatigue pull-out failures in a similar manner to pull-through failure.

An experimental investigation using both two-span cladding tests and small scale tests were conducted under static wind uplift/suction load conditions for a range of screw fasteners and steel purling/battens which are commonly used in Australia and its neighbouring countries. Sustained cyclic loading conditions during storms could lead to premature fatigue causing pull-out failures in a similar manner to pull-through failures.

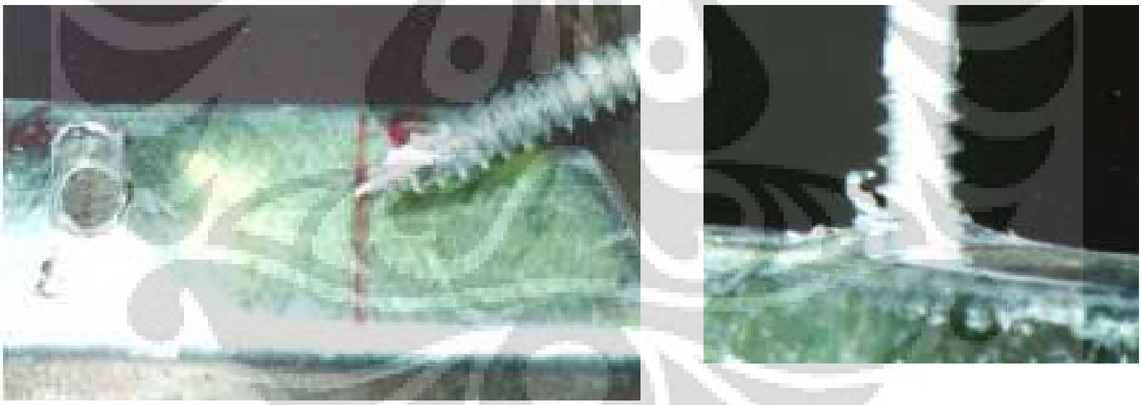


Figure 3.1 Pull-Out Failures

The screw fasteners connections should survive both pull-through and pull-out failures when subjected to the standard fatigue tests simulating cyclic wind uplift loading on roof claddings. An improved formula was then developed in terms of the thickness and ultimate tensile strength of steel, and thread diameter and pitch of screw fasteners under static wind uplift load conditions.

There were two different types of pull-out failure modes. In thin steels, for which the thickness is less than the thread pitch, the steel around the screw hole was bent as the threads of the screw fastener were withdrawn. In thicker steels, where the thickness is greater than the thread pitch, the steel around the screw hole was sheared off as the threads of the screw were withdrawn. Figure 3.2 shows these two pull-out failure modes.

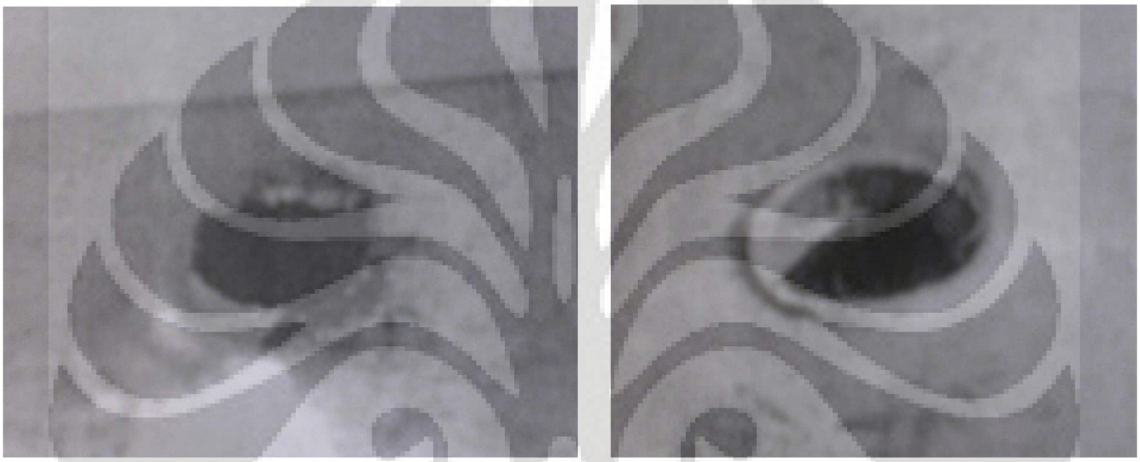


Figure 3.2 Pull-Out Failure Modes

3.1 Current Design Methods

The American Provisions (AISI, 2005) and the European Provisions (Eurocode, 1992) include design formulae for screw connections in tension. They apply to many different screw connections and fastener derails. Therefore, these design formulae imply a greater degree of conservatism. These formulae are valid for self- drilling or self-drilling screws with 2.03 mm < d < 6.35 mm, where d is the nominal screw diameter. The pull-out capacity, F_{ou}, is calculated as follows:

AISI (2005) $F_{ou} = 0.85\ t\ d\ f_u$ **eq. 3.1**

Eurocode (1992) $F_{ou} = 0.65\ t\ d\ f_y$ **eq. 3.2**

Where:

- t = Thickness of member
- d = Screw diameter
- F_u = Ultimate tensile strength of steel
- F_y = Yield stress of steel

To obtain the design pull-out capacity, a capacity reduction factor of 0.5 is applied to those equations. These equations can be used with any consistent unit system. Pekoz (1990) and Toma et al, (1993) present the background to the American and European equations, respectively. The difference between these equations is partly due to the European equation being based on a characteristic strength (5 percentile) whereas the American equation is based on an average strength.

In contrast to the American and European situations, Australian design codes do not recommend any design formula. At present, the design for the pull-out failure of screwed connections in tension is mainly based on laboratory experiments. However, AISI equation has been included in the limit states version of AS4600 (SAA, 2005).

These design formulae were developed for conventional fasteners and thicker mild steel and therefore there is a need to verify the applicability of these formulae for thinner, high strength steel that is being commonly used in Australia. At present, the American and Australian codes recommend the use of 75% of the specified minimum strength for high strength steels such as G550 steel with thickness less than 0.9 mm to allow for the reduced ductility of these steels. As an alternative to the design method, the limit states version of AS4600 (SAA, 2005)

3.2 Tang Experiments

The behaviour of connections in thin-walled elements is characterised by reduced plate stiffness. In order to study the pull-out failure of thin steel cladding systems commonly used in Australia, Tang carried out investigations for a range of screw fasteners and steel battens, purlins, and girts. The general standard cross section test method was not used. Instead two-span cladding test ans small batten/purlin tests were conducted to better simulate the realistic behaviour of steel roof and wall cladding systems.

3.2.1 Two-Span Cladding Tests

Tang used the conventional two-span cladding test method using air bags. It involves three battens connected to a support frame made of two large wooden sections that were fixed to the strong floor. The middle steel roof batten was connected to strain gauge steel rods at both ends, whereas the two outside battens were fixed to the wooden frame. Two air bags located under the steel cladding and within the battens were used to simulate the wind uplift loading on the cladding system. The pressure in the air bags was increased until the screw fasteners pulled-out of the middle steel batten. The test used trapezoidal sheeting and in order to eliminate pull-through failure, the sheeting was crest-fixed with cyclone washers. Later on Tang found that the air bag pressure loading is non uniform in the entire sheeting and the inadequacy of the simple formula based on ideal two-span beams to predict the central support reaction. The use of coefficient 1.25 in the simple formula is questionable (Mahendran, 1994).

Because of the difficulties with the air bag method, a different method of simulating the uniform wind uplift pressure using bricks on the inverted steel cladding was also attempted. This test gives a reasonable agreement with the result from the airbag method.

3.2.2 Small Scale Tests

Although the two-span cladding test methods using air bags or bricks were the preferred methods to simulate a uniform wind uplift pressure, there were numerous difficulties in conduction these tests. Since pull-out failures are localized around the screw holes on the batten/purlins, a small scale tests method was attempted to simulate this failure. Tang attempts to model this using a single batten/purlin with four screw fasteners located at their nominal spacing. Equal tension force was applied to screw heads using a distributed loading method.

In order to simplify the multiple screw fastener test method further, a batten supported at a shorter span with only one screw fastener was used with tension force being applied to the head of the fastener. Since the pull-out failure essentially involves the local deformation around the fastener hole, this test method was expected to produce the same results as other methods. It was also found that changing the test span in the single screw fastener method did not cause any changes to the failure load. It was considered that this method would simulate the local flexing of the steel batten around the fastener hole and the appropriate tension loading in the screw fastener to produce the pull-out failure load one would obtain by testing a two-span cladding system.

During the test, it was observed that there were two different types of pull-out failures modes. In thin steels, for which the thickness is less than the thread pitch, the steel around the screw hole was bent as the threads of the screw fastener were withdrawn. In thicker steels, where the thickness is greater than the thread pitch, the steel around the screw hole was sheared off as the threads of the screw were withdrawn.

In general, it was found that Type17 screw fasteners gave a highest pull-out load compared with other screw fasteners of the same size. This implies that the type of thread and drill point may influence the pull-out strength. However, this aspect was not investigated in detail.

3.3 Tang's Formulae

Based on test results using the small scale test method, Tang (1998) suggested Equation 3.3 to better model the observed behaviour for pull-out strength F_{ou}.

$$F_{ou} = k\, d\, p^{0.2}\, t^{1.3}\, f_u \qquad \textbf{eq. 3.3}$$

Where: k = Thickness coefficient

= 0.7 (G250, G500, G550 for t < 1.5 mm)

= 0.8 (G450 for 1.5 mm < t < 3 mm)

= 0.75 (G250, G450, G500, G550 for t < 3 mm)

t = Thickness of cladding member

d = Screw diameter

p = Screw pitch

F_u = Ultimate tensile strength of steel

Table 3.1 Test to Predicted Values Based on Measured Properties from Tang (1998)

Grade (MPa)	t (mm)	k	Mean	COV
G250, G500, G550	t < 1.5	0.7	1.02	0.18
G450	1.5 < t < 3	0.8	0.93	0.1
G250, G450, G500, G550	t < 3	0.75	0.96	0.16

As seen in the results in Table 3.1, the mean Test to Predicted values are very close to 1.0 for all coefficient which reveal the adequacy of Tang's design formula in predicting the pull-out failure loads. The values of K were adjusted to give the best agreement with test results in order to recommend a capacity factor of 0.5 used by the American and Australian Codes (AISI, 1989, SAA, 1994). This is considered acceptable as the coefficients of variation are still within 0.18 and the mean values varied between 0.96 and 1.02 (see Table 3.1).

4.0 PULL THROUGH FAILURE

Past research and field damage investigations have shown that the light gauge steel cladding may fail locally in the vicinity of screw fasteners. This localised failure can be static or fatigue. Premature pull-through failure could occur by low cycle fatigue cracking under sustained fluctuations of wind uplift loading (Beck and Morgan, 1977 and Beck and Stevens, 1979 and Mahendran 1990). Experiments indicated that large membrane stresses were present in the longitudinal direction, which reached yielding. It was noted that there was no buckling or global yielding of the section elsewhere in the sheeting. This indicated that the cladding strength was determined by this localised pull-through or dimpling strength of their screwed connections, as the load per fastener at the critical central support was the most important parameter. End spans of a root or wall cladding system are generally subjected to greater uplift/suction forces during high wind events. The past analyses of a multi-span cladding assembly (Mahendran, 1994c, Xu and Teng, 1994, Mahendran and Tang, 1998) have indicated that the second support from the eaves or ridge of the root is very often critically loaded when subjected to wind uplift loading. Observations from field damage and laboratory experimental investigations have revealed that pull-through failures are highly localized around the fastener holes (Mahendran, 1994, Morgan and Beck, 1977). The strength of screw fastener connections is dependent on the type of cladding profile, its thickness, strength and ductility of the steel and also the type and size of fastener.

The pull-through strength is very dependent on the cladding thickness, but is less dependent in the strength of the cladding material. Changes to the screw shaft/hole diameter affect the strength of the crest-fixed connections only marginally for all three profiles (Mahendran, 1994).

4.1 Splitting Criterion

The two-span steel sheeting is subjected to two types of deformations due to global bending of two span sheets and local bending action around the fastener hole. The sheeting around the fastener hole is subject to both global bending effects, and local effects due to the presence of fastener reaction, leading to large longitudinal membrane strains near failure. This provides some explanation for the premature transverse splitting at the fastener hole. The improved finite element model using an appropriate splitting criterion enables accurate prediction of the pull-through failure load. Therefore it can be used to model the local pull-through failures in the less ductile G550 steel claddings that are initiated by transverse splitting at the fastener hole.

4.2 Effects of Cyclone Washers

The static and fatigue performance of the commonly used alternate crest-fastened steel claddings can be improved by using cyclone washers, fastening at every crest or at alternate valleys without cyclone washers or by increasing the strength of steel. Fastening at every crest of fastening at alternate valley fastening is not acceptable to the building industry, because these methods are subjected to the splitting of timber battens and water leakage respectively. Since high strength steel has limited ductility, the use of higher strength steel is considered to be inadequate. Alternatively, reducing the design load can reduce the risk of local failure. However, the steel cladding industry would not accept this approach.

The use of cyclone washers is considered to be the best option. The cyclone washers restrict the cross-sectional distortion that increases the local dimpling load. Thus, the stress concentrations in the region around the fastener holes are reduced under cyclic wind loading and the formation of fatigue cracking is delayed. However, cyclone washers are not commonly used in all cyclone prone areas of Australia.

At the time when cyclone washer-fastener assemblies were developed, it was believed that the fatigue problem of light gauge steel cladding had been rectified. The solution obviously not a satisfactory one, as the washers are unpopular with builders and are not commonly used except, in the northern territory. It is further noted that these washers have become thinner, following the same trend as cladding.

Since the behaviour of light gauge steel cladding is dependent on the geometry and type of cladding profiles, it is possible to improve the static and fatigue performance of the cladding by optimising the profile geometry.

4.3 Current Design Method

The pull-through/local dimpling failure strength of screwed connections is very important in the design of profiled steel cladding systems. Past research has concentrated on using experimental methods to develop empirical formulae for failure strengths. Currently European and American standard test methods and design formulae are available mainly for valley-fixed cladding. There are no standard test methods for Australian cladding systems that are crest fixed. Currently the European (Eurocode, 1992, ECCS, 1983) and American (AISI, 1989, 1992, 2005) design provisions give design methods for a range of mechanically fastened connections such as bolts and screws in cold-formed thin-walled sheeting and members. For these fasteners, under different types of loading, such as tension, shear and combined loadings (predominantly static loading), a design method based on laboratory testing and/or calculation using design formulae is recommended. The pull-through strength of screw fasteners in tension, F_{ov}, is calculated as follows.

AISI (2005)	F_{ov}	$=1.5\ t\ d\ f_u$	**eq. 4.1**
Eurocode (1992)	F_{ov}	$=1.1\ t\ d_w\ f_y$	**eq. 4.2**

Where:

t	= thickness of member
d	= larger value of the screw head or the washer diameter <12.7 mm
F_u	= Ultimate tensile strength of steel
F_y	= Yield stress of steel
d_w	= The washer diameter

Pekoz (1990) and Toma et al, (1993) present the background to the American and European equations, respectively. The difference between these equations is partly due to the European equation being based on a characteristic strength (5 percentile) whereas the American equation is based on an average strength.

In contrast to the American and European situations, Australian design codes do not recommend any design formula. At present, the design for the pull-through failure of screwed connections in tension is mainly based on laboratory experiments. However, AISI equation has been included in the limit states version of AS4600 (SAA, 2005) but its applicability to Australian Steel cladding systems in questionable.

These design formulae were developed for conventional fasteners and thicker mild steel and therefore there is a need to verify the applicability of these formulae for thinner, high strength steel that is being commonly used in Australia. At present, the American and Australian codes recommend the use of 75% of the specified minimum strength for high strength steels such as G550 steel with thickness less than 0.9 mm to allow for the reduced ductility of these steels. As an alternative to the design method, the limit states version of AS4600 (SAA, 2005).

The AS 4600 provides appropriate design rules and guidelines for many commonly used cold-formed steel members such as Z, C and box members. However, it does not address the design of light gauge steel claddings under wind uplift loading.

4.4 Mahaarachchi Experiments

Past researchers (Mahendran, 1994c, Xu, 1994, Tang and Mahendran, 1997) have shown that local pull-through failures initiated by transverse splitting/fracture occurred at the screw fasteners connections of crest-fixed steel claddings made of less ductile, thin G550 steels. Finite element analyses of these cladding systems could not predict the pull-through failure load, since they were based on elastic-perfect-plastic material behaviour with infinite ductility.

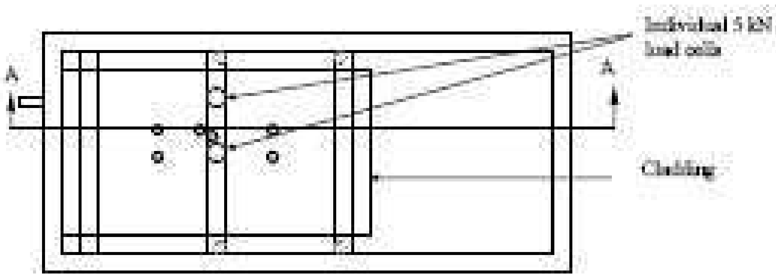
A series of large-scale test was conducted on a range of crest-fixed steel cladding systems, under simulated wind uplift loads, using a large air-box test facility. Roof claddings are predominantly subjected to wind uplift loading due to the combination of external and internal wind pressures. Ideally, an investigation on roof or wall claddings would be carried out on large-scale, multi-span cladding assemblies subjected to realistic wind pressure loading. However, due to practical considerations, a two-span cladding assembly, with simply supported ends, subjected to a uniform wind uplift pressure, is considered adequate to model the critical regions of a multi-span roof.

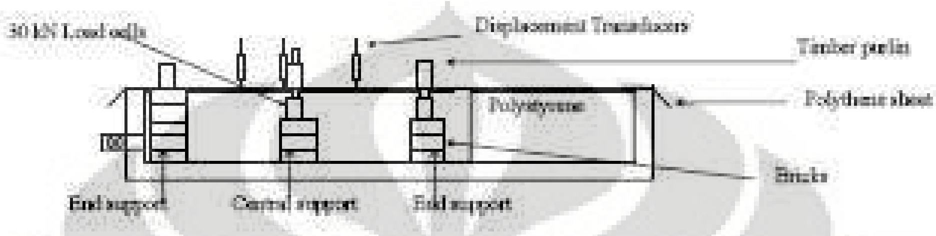
In order to accurately simulate a uniform wind uplift pressure and its effects, a large air box was used. It was essential that the main loading parameters at the critical central support, namely the fastener reaction, the bending moment and the strains around the fastener, were modelled correctly. Hence a number of different spans, screw head diameters and different geometries were selected in order to include a wide spectrum of roof cladding assemblies.

A series of small-scale tests was also conducted using a test method recommended by Mahendran (1994a) for crest-fixed steel claddings. The main aim of these small-scale tests was to investigate the strain behaviour around the fastener holes at failure.

4.4.1 Large Scale Tests

The entire large-scale test were conducted on a large air box and thus allowed accurate simulation of uniform wind uplift or suction pressure on claddings of varying sizes.





(a) Schematic diagram

(b) Photograph showing the Air box

Figure 4.1 Experimental Set-Ups for Large Scale Tests

4.4.2 Small Scale Tests

In this method, a small-scale cladding of approximately 240 mm x 240 mm with the screw fastener at the middle, was tested under tension loading of the fastener, to determine the strength of the screw connections of the cladding. In the large-scale sheeting, under wind uplift loading, the sheets around the fastener holes deflected upwards, but the sheeting under the fastener head remained fixed. The small-scale test was designed so that the reverse would occur.

The sheeting was fastened to a small, rectangular, wooden frame made of four 25 mm x 50 mm members to simulate appropriate boundary conditions. The transverse distance between the supports was equal to the distance between the fasteners, i.e. The pitch of the cladding for trapezoidal Type A and twice the pitch for corrugated and trapezoidal Type claddings, whereas the longitudinal distance between the two supports was 200 mm, being equal to 1.05 – 1.3 times the fastener spacing. The central fastener was not actually fastened to the wooden frame, but was free to move vertically. The wind-uplift loading on the small-scale cladding models was simulated by applying a tension force in the fastener. The specially made central fastener had the same fastener head, but was made to be about 200 mm long, so that a load cell could be incorporated on to its length. Static wind-uplift loading was simulated, simply by tightening the long fastener by hand. The same strain gauge arrangement was used in these tests, as in the large-scale test.

Figure 4.2 Experimental Set-Ups for Small Scale Tests

5.0 DEVELOPMENT OF DESIGN FORMULAE

5.1 General

The small scale test was used to determine pull-out failure loads of a range of Type 17, HiTeks, and 500 series screws. To fully understand the structural behaviour of steel cladding systems, affected by a range of parameters, a large number of small scale test were required.

Assumptions were made to determine the governing factor for the two pull-out failure modes. In thin steels, for which the thickness is less than the thread pitch, the steel around the screw hole was bent as the threads of the screw fastener were withdrawn. Assumption for this case is the cladding thickness governs the failure mode. In thicker steels, where the thickness is greater than the thread pitch, the steel around the screw hole was sheared off as the threads of the screw were withdrawn. Assumption for this case is the screw pitch governs the failure mode.

Very thin steel is for cladding thickness below 0.5 mm, thin steel between 0.5 mm and 1.5 mm while above 1.5 mm is considered thick steel.

5.2 Parametric Studies

The behaviour of crest-fixed steel claddings subjected to wind uplift loading is dependent on a range of parameters, including cladding thickness, screw properties and ultimate tensile stress.

The following parameters, including all the important screw properties, were varied in this study. Base metal thickness of steel t from 0.4 mm to 3 mm, steel ultimate tensile stress f_u from 320 to 480 MPa, diameter of screw head d from 4.87 to 6.41 mm and screw pitch from 1.06 to 2.54 mm.

Considering the data limitation of screw properties and time frame given to the project, it is quite hard to derive accurate formulae. The data scatter in failure load was not investigated in detail and considered as outside the scope of this thesis.

5.2.1 Effect of Screw Properties

Tang's experiments used nominal diameter of the Screw and the thread pitch thickness. Tang also used three different kinds of screw (Type17, HiTeks, and 500 Series). These screws gave different failure load despite their same size in diameter and pitch thickness. Based on this, there must be another factor that differentiates their capacity to withstand tensile force. Assumption for this case is each type of screw gives a different amount of contact area between the screw thread and cladding. Further research that includes Major diameter, Minor diameter, and Thread Angle of the screws is needed to improve the understanding of the screw behaviour. The load capacity for each kind of screw will be discussed later on in this thesis.

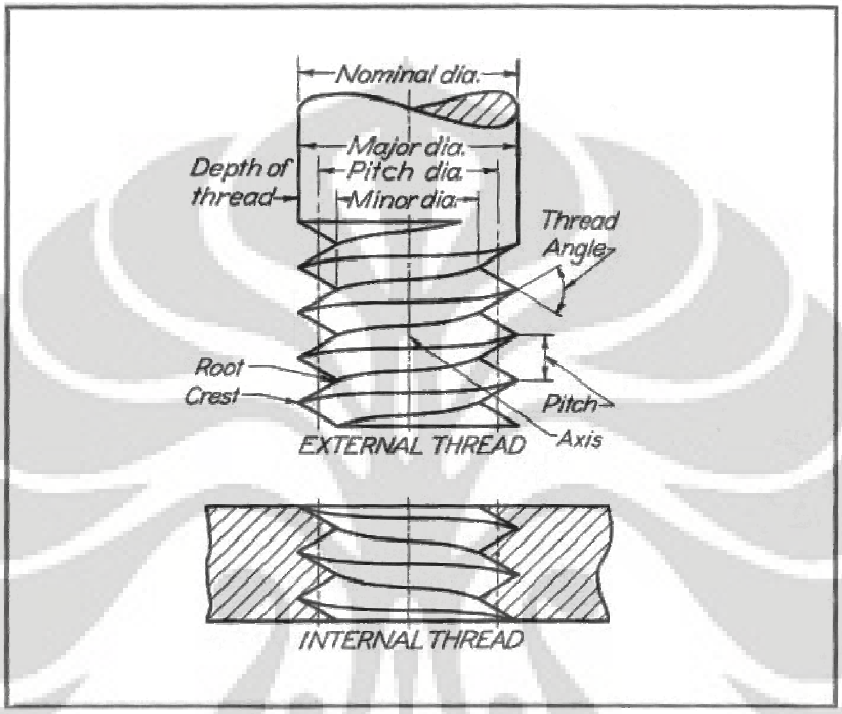


Figure 5.1 Screw Terminology

5.2.2 Effect of Screw Diameter

Table 5.1 shows the fastener load at failure obtained when the screw diameter varied from 4.87 mm to 5.43 mm for different thickness and steel grades. The result shows that an increase of screw diameter has a greater effect on thinner steel than thicker steel. Table 5.1 shows that in general the fastener loads at failure do not vary much with varying screw diameter. It was also noticed that the variation was not uniformed for all cladding thickness.

Table 5.1 Effect of Screw Diameter on the Fastener Load at Failure

Screw Head Diameter (mm)	Steel Grade (MPa)	Fastener Load at Failure (N)							
		Thickness t (mm) - Percentage Difference (%)							
		0.4		**0.6**		**1**			
4.87	G250	417	14.87	593	14.84	1343	11.32		
5.43		479		681		1495			
		1.6		**1.9**		**2.4**		**3**	
4.87	G450	3508	23.26	4698	-2.38	6598	8.15	8972	5.13
5.43		4324		4586		7136		9432	
		1.2							
4.87	G500	2558	13.60						
5.43		2906							
		0.42		**0.6**		**0.95**			
4.87	G550	747	9.64	952	6.20	2062	14.74		
5.43		819		1011		2366			
HiTeks 1.06 mm Screw Pitch									

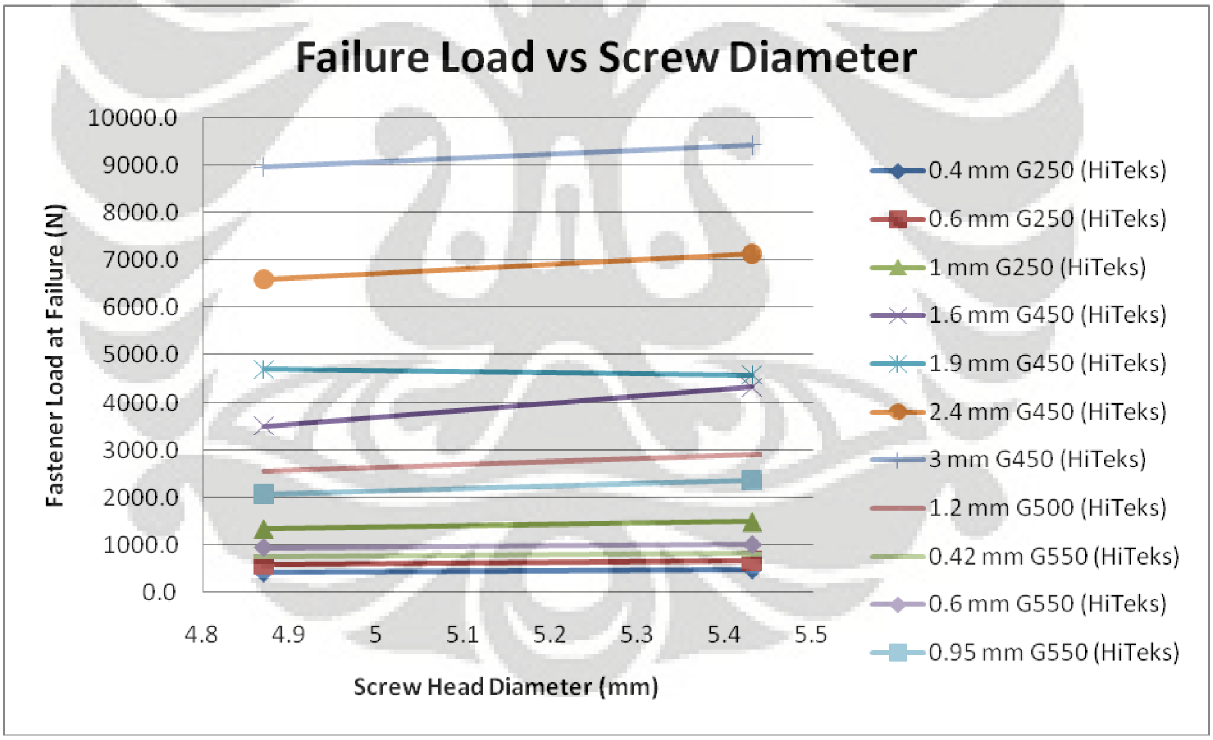


Figure 5.2 Effect of Screw Diameter on the Fastener Load at Failure

5.2.3 Effect of Screw Pitch

Tables 5.2 to 5.4, show the fastener load at failure obtained when the screw pitch varied from 1.06 mm to 1.59 mm for different thickness and steel grades.

The result shows that an increase of screw pitch has a greater effect on thinner steel than thicker steel. Tables 5.2 to 5.4 show that in general the fastener loads at failure do not vary much with varying screw diameter. It was also noticed that the variation was not uniformed for all cladding thickness.

Table 5.2 Effect of Screw Pitch on the Fastener Load at Failure HiTeks 10-

Screw Pitch (mm)	Steel Grade (MPa)	Fastener Load at Failure (N)							
		Thickness t (mm) - Percentage Difference (%)							
		0.4		**0.6**		**1**			
1.06	G250	417	32.85	593	14.67	1343	20.28		
1.59		554		680		1696			
		1.6		**1.9**		**2.4**		**3**	
1.06	G450	3508	26.85	4698	5.49	6598	18.46	8972	
1.59		4450		4956		7816		-	
		1.2							
1.06	G500	2558	14.70						
1.59		2934							
		0.42		**0.6**		**0.95**			
1.06	G550	747	22.22	952	13.97	2062	22.41		
1.59		913		1085		2524			
HiTeks 4.87 mm Screw Diameter									

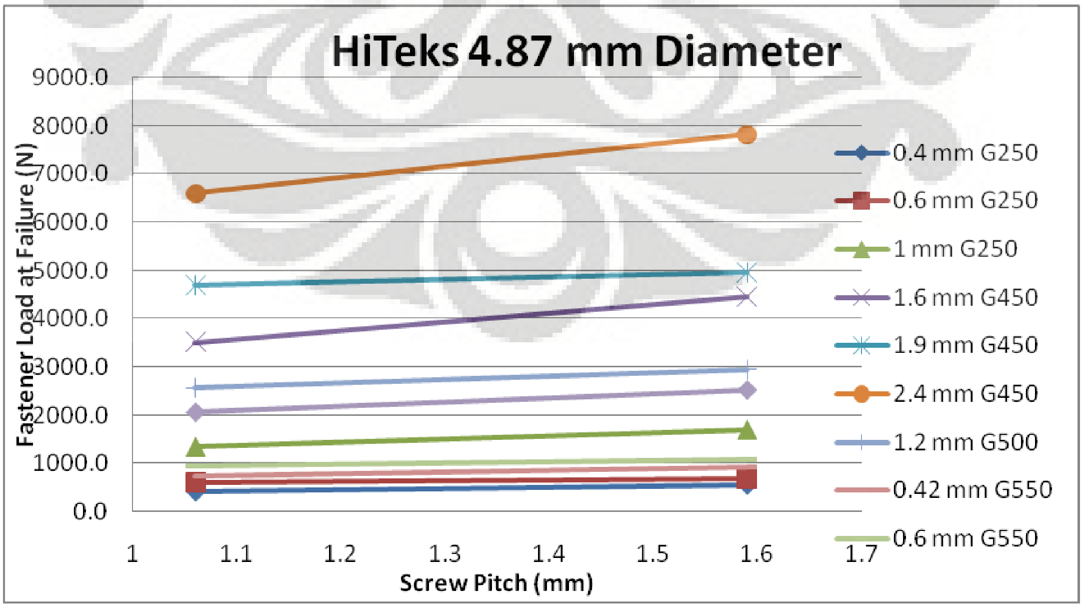


Figure 5.3 Effect of Screw Pitch on the Fastener Load at Failure HiTeks 10-

Table 5.3 Effect of Screw Pitch on the Fastener Load at Failure HiTeks 12-

Screw Pitch (mm)	Fastener Load at Failure (N)								
	Steel Grade (MPa)	Thickness t (mm) - Percentage Difference (%)							
		0.4		**0.6**		**1**			
1.06	G250	479		681		1495			
1.81		576	25.89	775	27.90	1493	13.31		
2.31		603		871		1694			
		1.6		**1.9**		**2.4**		**3**	
1.06	G450	4324		4586		7136		9432	
1.81		4700	22.85	5230	24.23	8282	27.16	9488	18.66
2.31		5312		5697		9074		11192	
		1.2							
1.06	G500	2906							
1.81		3054	16.17						
2.31		3376							
		0.42		**0.6**		**0.95**			
1.06	G550	820		1011		2366			
1.81		874	13.41	1036	32.25	2460	12.85		
2.31		930		1337		2670			
HiTeks 5.43 mm Screw Diameter									

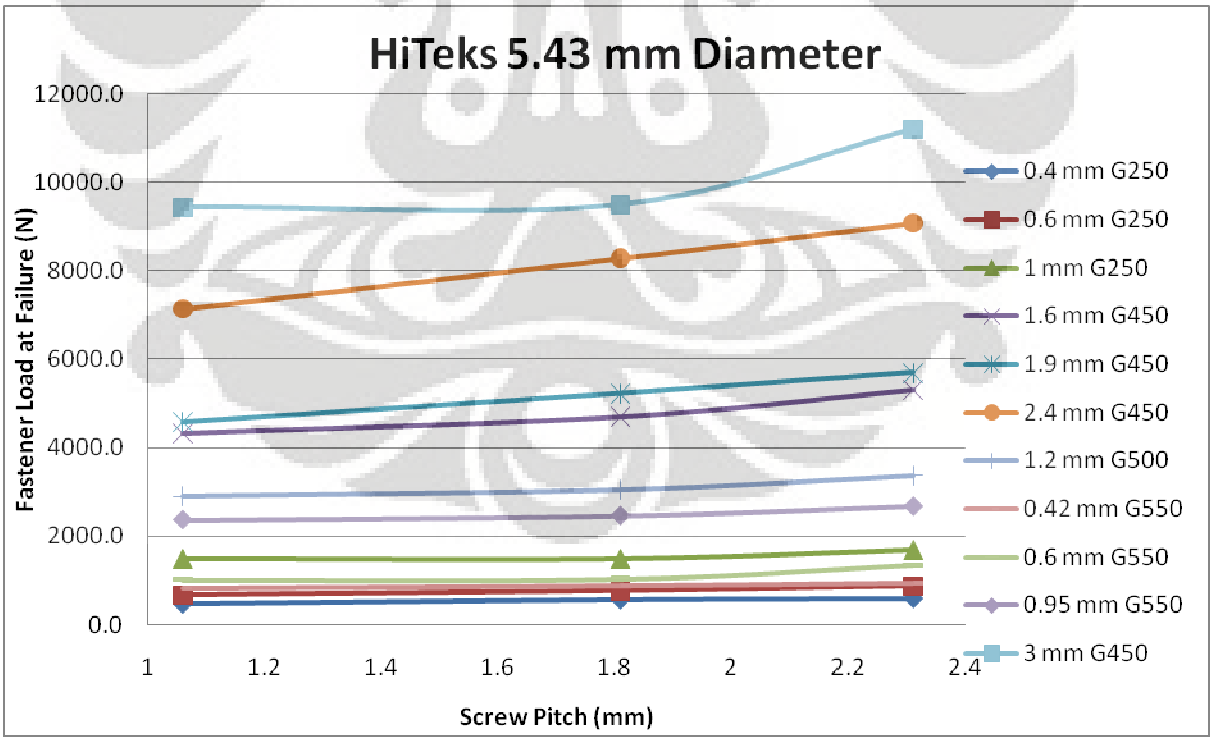


Figure 5.4 Effect of Screw Pitch on the Fastener Load at Failure HiTeks 12-

Table 5.4 **Effect of Screw Pitch on the Fastener Load at Failure HiTeks 14-**

Screw Pitch (mm)	Fastener Load at Failure (N)								
	Steel Grade (MPa)	Thickness t (mm) - Percentage Difference (%)							
		0.4		**0.6**		**1**			
1.27	G250	590	21.36	802	9.10	1800	11.78		
2.54		716		875		2012			
		1.6		**1.9**		**2.4**		**3**	
1.27	G450	4894	12.87	5274	18.39	8098	13.86	10990	10.46
2.54		5524		6244		9220		12140	
		1.2							
1.27	G500	-							
2.54		-							
		0.42		**0.6**		**0.95**			
1.27	G550	959	12.51	1590	-1.38	2692	9.36		
2.54		1079		1568		2944			
HiTeks 6.41 mm Screw Diameter									

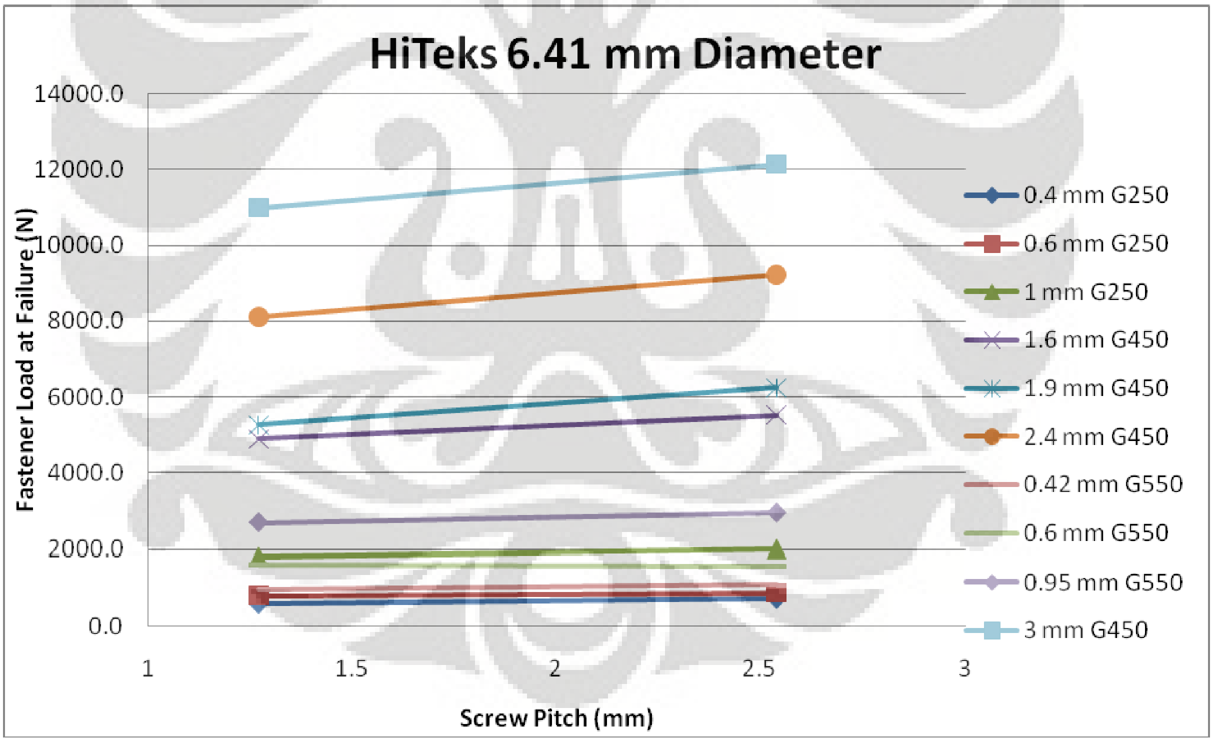


Figure 5.5 **Effect of Screw Pitch on the Fastener Load at Failure HiTeks 14-**

5.2.4 Effect of Screw Type

Tables 5.5 to 5.8, show the difference in fastener load at failure from different types of screws. For Type 17 and HiTeks comparison 5.43 mm and 6.41 mm screw diameters were used. For HiTeks and 500 Series comparison 4.87 mm and 5.43 mm screw diameters were used. For comparison purposes, failure load for 500 series screw were obtained based on Tang's formula for pull-out (see Tables 5.7 to 5.8)

Table 5.5 Capacity Difference Between Type 17 and HiTeks 1

<table>
<tr><td colspan="2"></td><td colspan="3">TYPE 17</td><td colspan="3">HITeks</td><td></td></tr>
<tr><td colspan="2">Thread Form Pitch</td><td colspan="2">Diameter d (mm)</td><td rowspan="2">Load(N/f)</td><td colspan="2">Diameter d (mm)</td><td rowspan="2">Load(N/f)</td><td rowspan="2">Diff (%)</td></tr>
<tr><td>(/inch)</td><td>p (mm)</td><td>Nominal</td><td>Measured</td><td>Nominal</td><td>Measured</td></tr>
<tr><td rowspan="11">11</td><td rowspan="11">2.31</td><td rowspan="11">5.43</td><td rowspan="11">5.53</td><td>750</td><td rowspan="11">5.43</td><td rowspan="11">5.52</td><td>603</td><td>24</td></tr>
<tr><td>1049</td><td>871</td><td>20</td></tr>
<tr><td>1925</td><td>1694</td><td>14</td></tr>
<tr><td>5660</td><td>5312</td><td>7</td></tr>
<tr><td>6314</td><td>5697</td><td>11</td></tr>
<tr><td>9460</td><td>9074</td><td>4</td></tr>
<tr><td>10390</td><td>11192</td><td>-7</td></tr>
<tr><td>3756</td><td>3376</td><td>11</td></tr>
<tr><td>1188</td><td>930</td><td>28</td></tr>
<tr><td>1515</td><td>1337</td><td>13</td></tr>
<tr><td>3226</td><td>2670</td><td>21</td></tr>
<tr><td colspan="8"></td><td>13</td></tr>
</table>

Table 5.6 Capacity Difference Between Type 17 and HiTeks 2

		TYPE 17			HITeks			
Thread Form Pitch		Diameter d (mm)			Diameter d (mm)			
(/inch)	p (mm)	Nominal	Measured	Load(N/f)	Nominal	Measured	Load(N/f)	Diff (%)
				874			716	22
				1284			875	47
				2306			2012	15
				6206			5524	12
				6962			6244	11
10	2.54	6.41	6.34	10944	6.41	6.39	9220	19
				N/A			12140	-
				4340			N/A	-
				1322			1079	22
				1769			1568	13
				3558			2944	21
								17

Table 5.7 Capacity Difference Between 500 Series and HiTeks 1

					Load Predicted Based on Tang's			
		HITeks			500 Series			
Thread Form Pitch		Diameter d (mm)			Diameter d (mm)			
(/inch)	p (mm)	Nominal	Measured	Load(N/f)	Nominal	Measured	Load(N/f)	Diff (%)
				417			349	19
				593			498	19
				1343			1178	14
				3508			3878	-10
				4698			3739	26
24	1.06	4.87	4.67	6598	4.87	4.67	6493	2
				8972			8005	12
				2558			-	
				747			648	15
				952			892	7
				2062			1843	12
								12

Table 5.8 Capacity Difference Between 500 Series and HiTeks 2

					Load Predicted Based on Tang's			
		HITeks			500 Series			
Thread Form Pitch		Diameter d (mm)			Diameter d (mm)			
(/inch)	p (mm)	Nominal	Measured	Load(N/f)	Nominal	Measured	Load(N/f)	Diff (%)
				479			401	20
				681			571	19
				1495			1352	11
				4324			4451	-3
				4586			4292	7
24	1.06	5.43	5.36	7136	5.43	5.36	7452	-4
				9432			9187	3
				2906			-	
				820			744	10
				1011			1024	-1
				2366			2115	12
								7

From these tables each screw fastener type gives different strength regardless of the same thread pitch and diameter. Type 17 Screws give 15% more strength than HiTeks Screws and HiTeks Screws give 10% more strength than 500 Series Screws.

From parametric studies above, the preliminary assumption for governing thickness in pull-out failure mode is invalid. This is because in thick steel, the contact area between the battens and the screw is more than 1x length of the screw pitch, thus it will give additional strength to the failure load. Further investigation should be conducted to improve the understanding of the two failure modes in pull-out.

5.2.5 Effect of Cladding Thickness

Tables 5.1 to 5.4 and Figures 5.2 to 5.5 show the effect of thickness t together with other parameters. They included 4 ultimate tensile stresses (320 MPa, 480 MPa, 520 MPa, and 550 MPa) and 7 different thicknesses (0.4 mm, 0.6 mm, 1.0 mm, 1.6 mm, 1.9 mm, 2.4 , 3.0 mm). The increase of cladding thickness also significantly enhances the cladding strength. However, the fastener sizes may have to be increased to prevent fastener fracture.

5.3. Development of Design Formulae

The fastener load at failure depends on a number of parameters. These include the ultimate strength, cladding thickness, screw diameter, and screw pitch. Considering the number of parameters affecting the fastener failure load it is difficult to derive accurate formulae based on simple curve fitting methods. Therefore, the fastener failure load interactions with those parameters were first analysed using Buckingham's Pi theorem. Buckingham's Pi Theorem allows rearranging n variables in a given system into n-j dimensionless parameters, designated by Greek letter, Π,where "j" is the fundamental dimension of the n variables.

If a relationship is expressed by a functional relationship:

$\Phi(q_1, q_2, q_3, \ldots q_n) = 0$ **eq. 5.1**

Where, q_1, q_2, q_3,……q_n are the numerical values of all variables pertinent to the problem.

Then the dimensionless ratios will form a new functional relationship given by:

$\Phi(\Pi_1, \Pi_2, \Pi_3, \ldots \Pi_n) = 0$ **eq. 5.2**

The method of determining the Π parameters is as follows:

The first step is to select the dependent variable (q_1) as a function of the independent variables $q_2 \ldots q_n$ In Equation 5.1 The variables should be written in terms of fundamental dimensions. Then the repeating variables are selected. These variables must contain the j dimensions of the problem, and the dependent quantity should not be selected as a repeating variable. The Π parameters are then written in terms of fundamental dimensions. Then the repeating variables are selected. These variables must contain the j dimensions of the problem, and the dependant quantity should not be selected as a repeating variable. The Π parameters are then written in terms of fundamental dimensions (M, L, T) and substituted for the corresponding functions of repeating variables. Equation 5.2 is then written, keeping the same number of independent parameters. That is Π_1, the dependant variable and $\Pi_1 \ldots \Pi_{n-j}$ the independent variables. Finally, the terms $\Pi_1 \ldots \Pi_{n-j}$ can be recombined to arrive at a more meaningful relationship than if just the individual terms were used.

As the fastener load at failure F_{ou} depends on the cladding thickness, ultimate tensile stress, screw diameter, and screw pitch, the following functional relationship is deduced from the above variables.

$\Phi(F_{ou}, f_u, t, d, p) = 0$ **eq. 5.3**

Table 5.9 Physical Quantities and Dimensional Formula

Physical Quantity	Symbol	Dimensional Formula
Fastener Load at Failure	F_{ou}	$M\,L\,T^{-2}$
Ultimate Tensile Stress	f_u	$M\,L^{-1}\,T^{-2}$
Steel Thickness	t	L
Screw Diameter	d	L
Screw Pitch	p	L

The dimensional formulae of the above variables are as follows. Number of variables in Equation 5.3, n, is equal to 5 and the fundamental dimension j is 3 as shown in table 5.9 Therefore the number of dimensionless quantities (n-j) is 2.

$\Phi\ (\Pi_1, \Pi_2) = 0$ **eq. 5.4**

Where $\Pi_{1,}\ \Pi_2$ are the dimensionless groups.

To arrange the parameter, investigations to understand the correlation between each variable were conducted. Figures 5.6 to 5.11 show the relationships between each variable (d, t, and p)

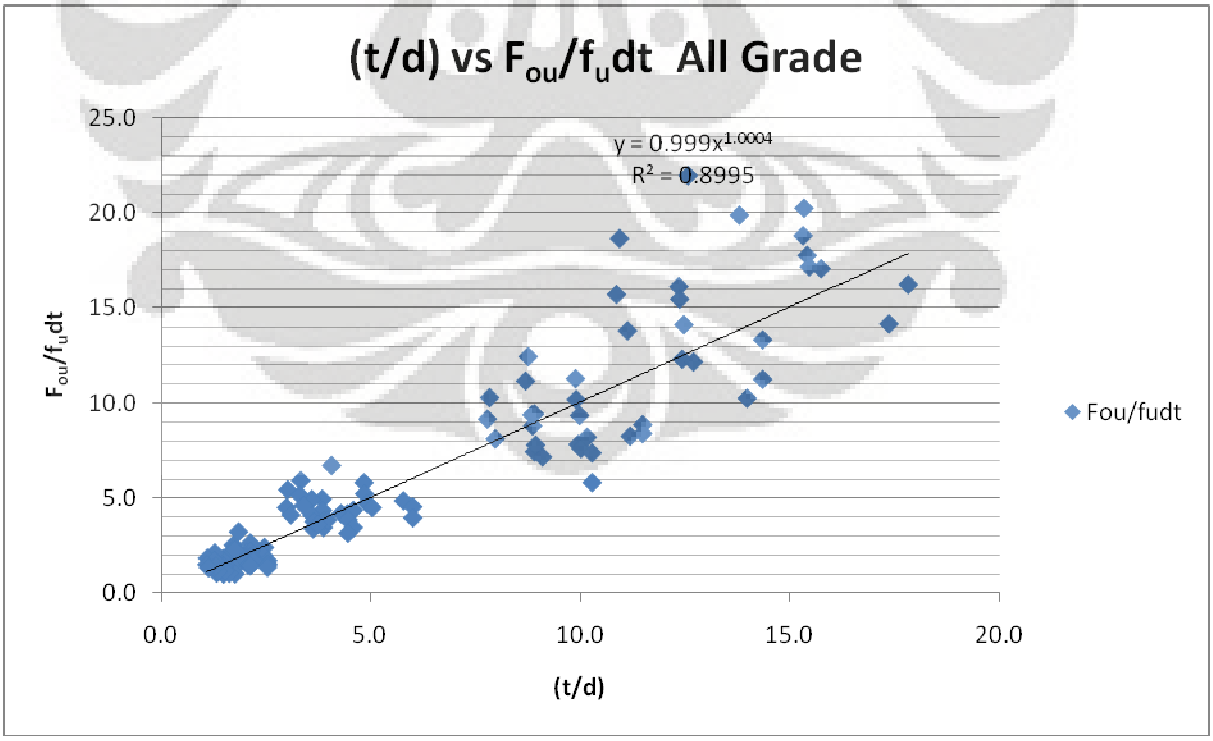


Figure 5.6 Relationship Between Screw Diameter and Cladding Thickness (t/d)

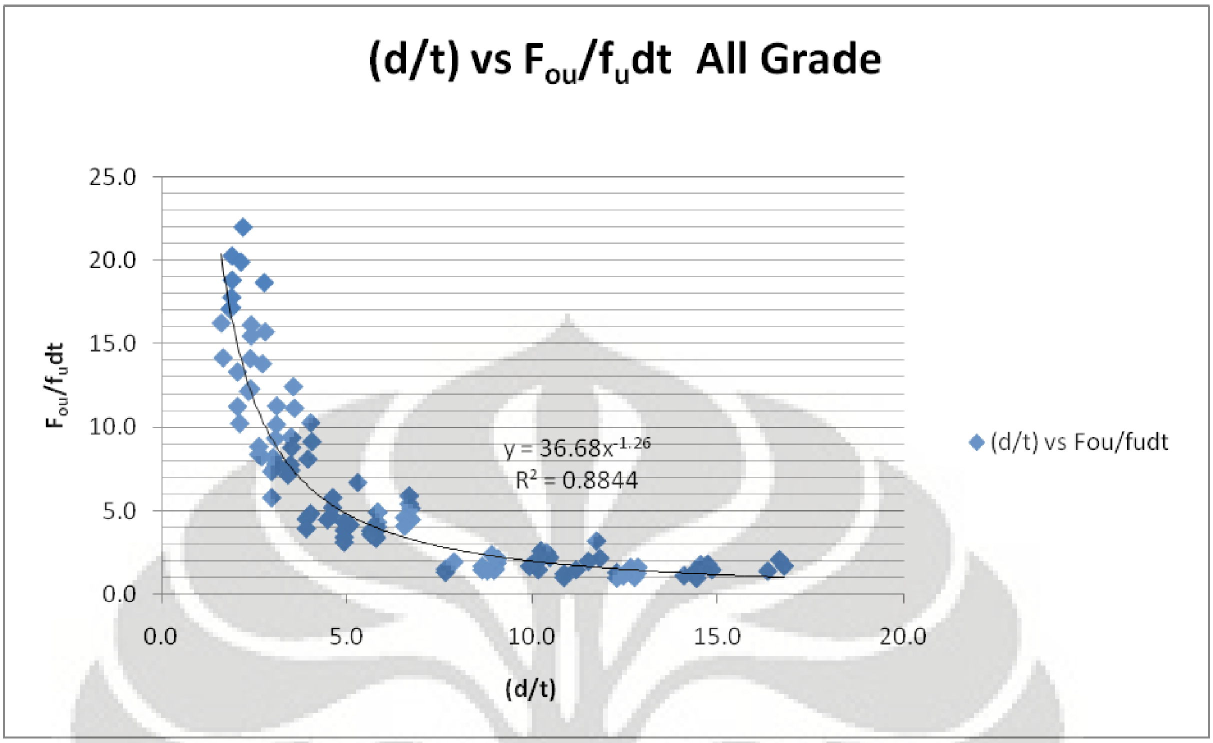


Figure 5.7 **Relationship Between Screw Diameter and Cladding Thickness (d/t)**

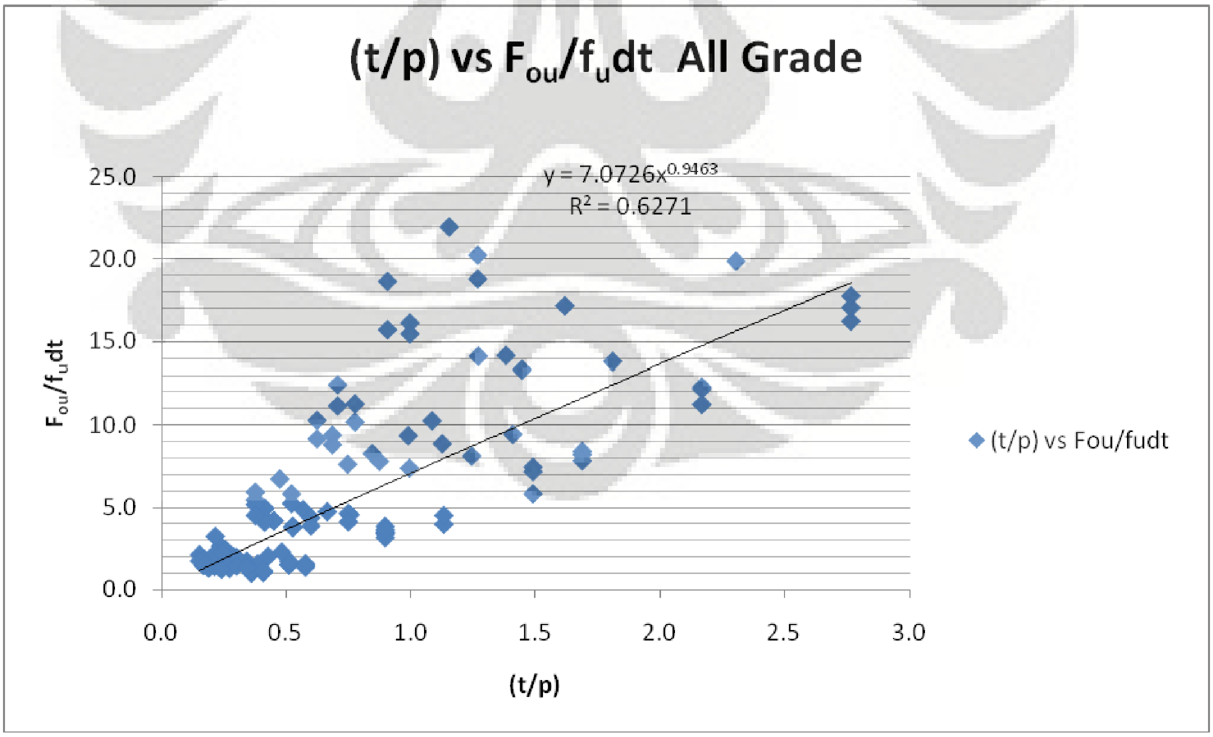


Figure 5.8 **Relationship Between Screw Pitch and Cladding Thickness (t/p)**

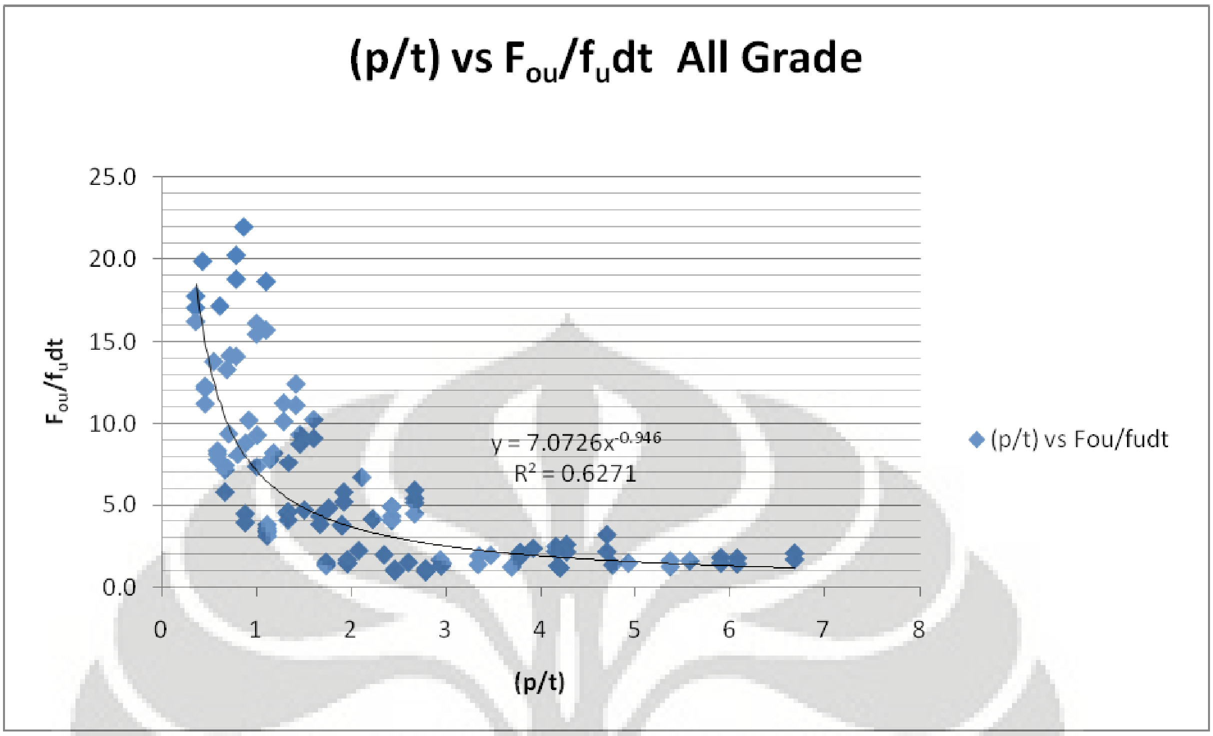


Figure 5.9 **Relationship Between Screw Pitch and Cladding Thickness (p/t)**

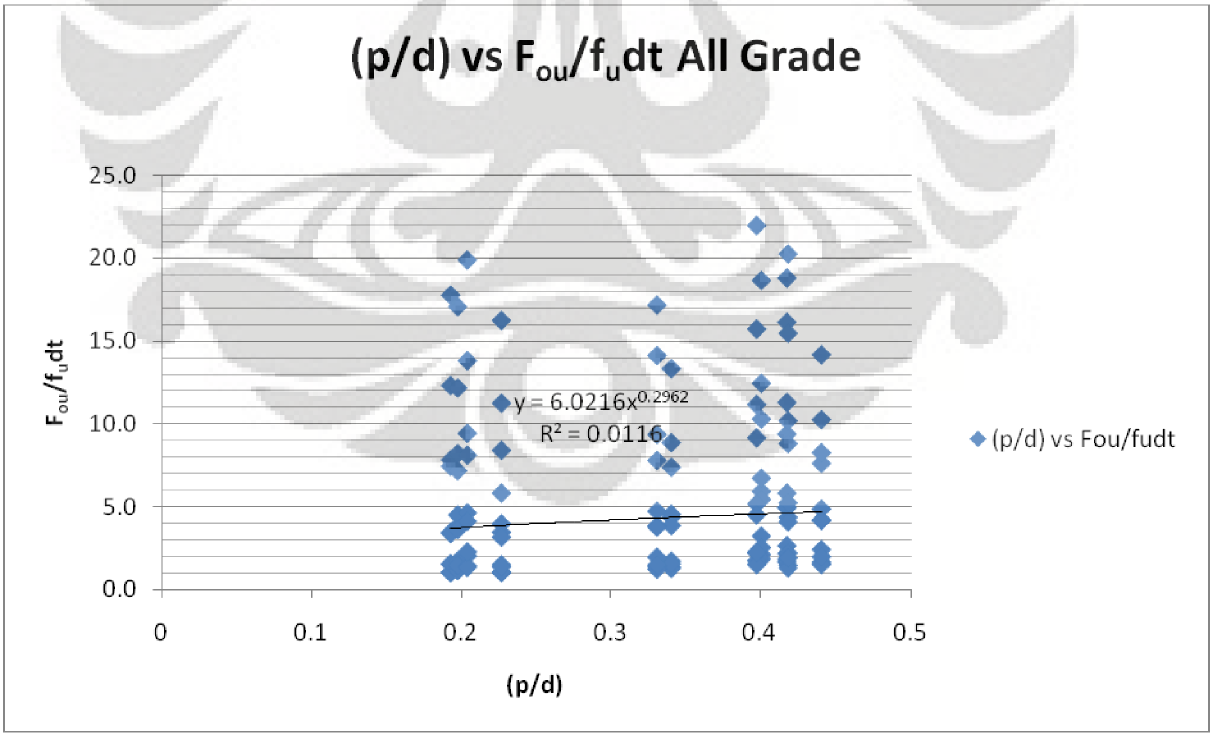


Figure 5.10 **Relationship Between Screw Pitch and Screw Diameter (p/d)**

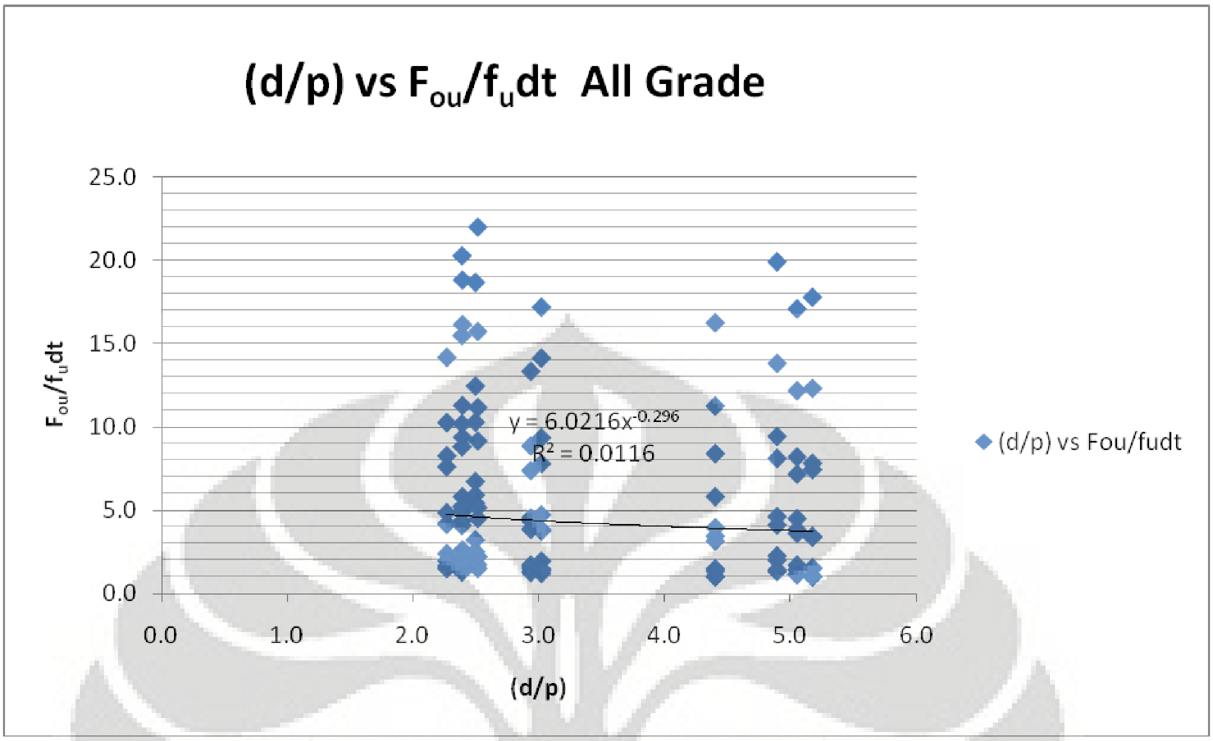


Figure 5.11 **Relationship Between Screw Pitch and Screw Diameter (d/p)**

Choosing t as repeating variables, the following dimensionless quantities can be derived.

$$\Pi_1 = \frac{F_{ou}}{f_u\ dt} \qquad \Pi_2 = \frac{d \times p}{t^2} \qquad \text{or} \qquad \Pi_2 = \frac{d}{t} \times \frac{p}{t} \qquad \textbf{eq. 5.5}$$

From the above dimensionless groups, the following relationship can be written. The fastener load at failure F_{ou} is obtained as

$$F_{ou} = f_u\ dt \quad f\left(\frac{d \times p}{t^2}\right) \qquad F_{ou} = f_u\ dt \quad f\left(\left(\frac{d}{t}\right)\left(\frac{p}{t}\right)\right) \qquad \textbf{eq. 5.6}$$

Even though Buckingham's Pi Theorem can derive non-dimensional quantities, it does have a few problems. If the variables introduced really do not affect the phenomenon, the solutions will end up with too many variables. Similarly if important variables are omitted, the solution may reach an impasse or may lead to an erroneous or incomplete result. Figures 5.12 to 5.13 show the relationships between the derived Π parameters (Π 1 to Π 2).

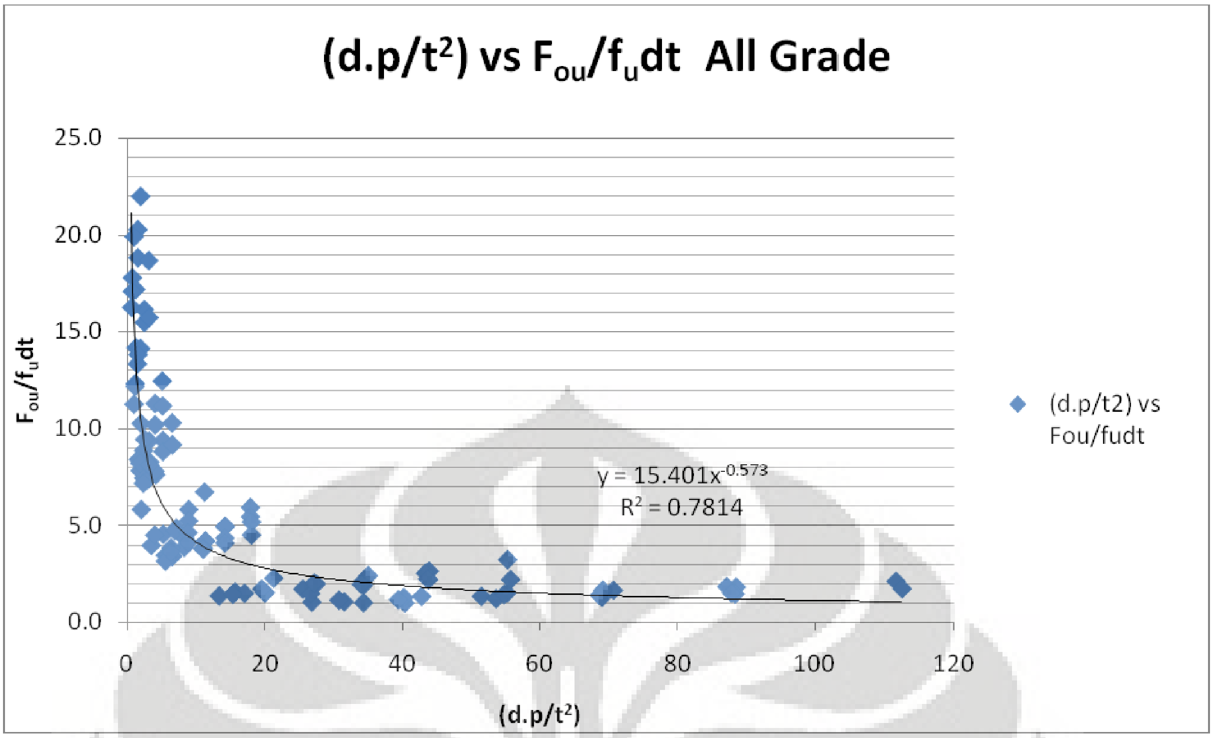


Figure 5.12 Relationship Between $\dfrac{F_{ou}}{f_u\ dt}$ and $\dfrac{d \times p}{t^2}$ for All Steel Grade

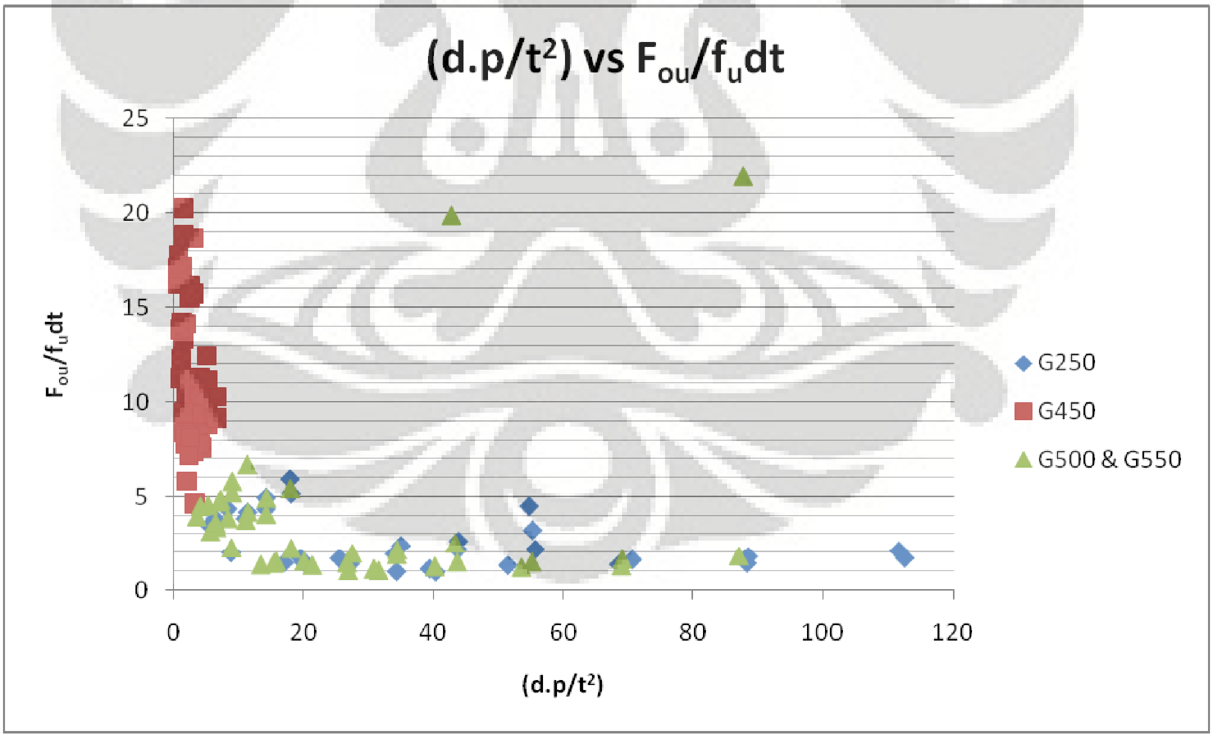


Figure 5.13 Relationship Between $\dfrac{F_{ou}}{f_u\ dt}$ and $\dfrac{d \times p}{t^2}$ Based on Each Steel Grade

It is observed that there is little correlation among these derived Π parameters. This can be explained by the fact that the behaviour of crest-fixed steel cladding is complicated and deriving a simple relationship is difficult. Figures 5.6 to 5.13 were used as a rough guideline to derive the dimensionless group (Π). Therefore, attempts were made to combine the above dimensionless quantities with nonlinear interactions considering the possible meaningful interactions of the geometric parameters. It is clear that the fastener load at failure depends on the contact area between cladding and screw thread. When the thickness of cladding is increased it is obvious that the number of thread inside that section will also be increased. Therefore, the fastener failure load is considered the function of the above ratio. Rearranging these parameters will lead to the following.

$$\Pi_1 = \alpha\left(\mu + \varphi\,\Pi_2\right)^{\beta} \qquad \textbf{eq. 5.7}$$

Substituting the relevant parameters, this equation can be rearranged as

$$F_{ou} = \alpha\left(\mu + \varphi\,\frac{d}{t}\right)^{\beta}\left(\delta + \rho\,\frac{p}{t}\right)^{\omega} dt\; f_u \qquad \textbf{eq. 5.8}$$

Power, multiplication, and summation coefficients in the above equation are determined by considering all the parameters simultaneously. The “Premium Solver 8.0” in Microsoft Excel 2007, which is based on the method of least squares and linear programming, was used to obtain the best equation that fits the experimental results. Finally the expression for the fastener failure load can be written as

$$F_{ou} = k\left(\frac{d}{t}\right)^{-0.3}\left(\frac{p}{t}\right)^{0.3} dt\; f_u \qquad \textbf{eq. 5.9}$$

Where:

Where:	k	= Thickness coefficient
	t	= Thickness of cladding member
	d	= Screw diameter
	p	= Screw pitch
	F_u	= Ultimate tensile strength of steel

Table 5.10 Test to Predicted Values Based Using the Simplified Nondimensional New Design Formula and Measured Properties

Grade (MPa)	t (mm)	k	Mean	COV
G250, G550	t < 0.9	2.4	1.01	0.19
G250, G500, G550	0.9 < t < 1.5	6.2	0.99	0.12
G450	1.5 < t < 2	12.5	1.01	0.13
G450	2 < t < 3	22.5	0.99	0.15

As seen in the results in Table 5.10, the mean Test to Predicted values are very close to 1.0 for all coefficient which reveal the adequacy of the new design formula in predicting the pull-out failure loads. The values of K were adjusted to give the best agreement with test results in order to recommend a capacity factor of 0.5 used by the American and Australian Codes (AISI, 1989, SAA, 1994). This is considered acceptable as the coefficients of variation are still within 0.19 and the mean values varied between 0.99 and 1.01 (see Table 5.10).

The fastener failure load from equation 5.9 is for all kind of screws with all steel grades and steel thickness. In this study, the ultimate tensile strength (f_u) was used instead of the yield strength, because the use of ultimate tensile strength gives a better correlation between the actual and predicted results than the yield strength (f_y) (Tang, 1998).

5.4 Capacity Reduction Factors

The design equations already in the codes and the proposed equations that mentioned in this chapter could predict average pull-out strengths based on the limited number of test data. The actual pull-out strength of a real connection can be considerably less than the value predicted by these equations because of the expected variations in material, fabrication, and loading effects. Therefore a capacity reduction factor commonly used in design codes should be recommended for the pull-out strength predicted by these equations.

The American Cold-Formed Steel Structures Code (AISI, 1992) recommends a statistical model for the determination of capacity reduction factors from testing. This model accounts for the variations in material, fabrication and load effect. A modified version of this model with conservative values was recommended by Pekoz (1992) for screwed connections. This model is to be used in the draft Australian Cold-formed Steel Structures Code (Macindoe et al., 1995). Based on this model, the capacity reduction factor $\varnothing$ is given by the following equation.

$$\phi = 1.5\ M_m\ F_m\ P_m\ e^{-\beta o\sqrt{V_m^{\ 2}+V_f^{\ 2}+C_p\ V_p^{\ 2}+V_q^{\ 2}}}$$ **eq.5.14**

Where: M_m, V_m = Mean and Coefficient of Variation of the Material Factor

= 1.1, 0.1

(This is the ratio of actual material property to that specified)

F_m, V_f = Mean and Coefficient of Variation of the Fabrication Factor

= 1.1, 0.1

(This is the ratio of actual geometric property (eg: t) to that specified)

V_q = Coefficient of Variation of Load Effect = 0.21

β_o = Target Reliability Index = 3.5 for connections

C_p = Correction Factor depending on the number of tests N = (N-1)/(N-3)

P_m = Mean Value of the Tested to Predicted Load Ratio

V_p = Coefficient of Variation of the Tested to Predicted Load Ratio

N = Number of Tests

The last two values Pm and Vp have to be determined from experiments. Other values are taken from the American code and are considered to be conservative for most connections. Macindoe et al., (1995) used the same values his investigation. The substitution of these assumed values leads to the following equation.

$$\phi = 1.65\ P_m\ e^{-\beta o\sqrt{0.0641+C_p\ V_p^{\ 2}}}$$ **eq. 5.15**

Equation 5.15 was used to calculate the factor for all design formulae (eq 5.11 to eq 5.13). The P_m and V_p used were based on specified properties. Since measured tensile strength of the steel from which the test specimens were made was larger than the specified value, the ∅ must be reduced by a ratio of the specified to measured tensile strength. Table 5.10 Show these calculations and the final ∅factor included a correction factor for yield. Based on these formulas, the ∅factor were greater than 0.5, thus these formulas were acceptable. Although steel and screw fasteners used in this investigation were obtained from particular manufacturers, results should be equally applicable to other steels and screw fasteners provided they comply with the respective specifications for the grades of steels and fasteners used in this investigation.

				Error (%)		Reduction Factor		Yield	
	K	MEAN	COV	MAX	MIN	First	FINAL ∅	Correction	N
GENERAL FORMULAE									
G250 + G550 (t < 0.9 mm)	2.4	1.01	0.19	37.12	-34.12	0.712	0.556	0.780	232
G250 + G500 + G550 (0.9 mm < t < 1.5 mm)	6.2	0.99	0.12	18.47	-20.29	0.683	0.560	0.820	150
G450 (1.5 mm < t < 2 mm)	12.5	1.01	0.13	28.58	-23.58	0.699	0.580	0.830	112
G450 (2 mm < t < 3 mm)	22.5	0.99	0.15	28.29	-0.34375	0.689	0.572	0.830	98

Table 5.11 Final Result (COV, Mean, ∅)

6.0 CONCLUSION AND RECOMMENDATIONS

Analysis of the experimental results showed that the current design formula for the pull-out strength might not be suitable for the screw fasteners and thin high strength steels considered in this investigation. This design formula gave conservative results only for thicker ($1.5 < t < 3.0$ mm), softer grade steels. However, a smaller capacity reduction factor of 0.4 may allow the use of current design formula for pull-out strengths. A modified design formula recommended by Macindoe et al. (1995) appears to be more suitable than the current design formula. Furthermore a new simplified design formula recommended by Tang (1998) give a more accurate prediction than Macindoe et al. (1995).

A simple design formula those models the pull-out failure more accurately has been developed for the battens, purlins and girts used in the Australian building industry. This formula has been developed in terms of not only the thickness and ultimate tensile strength of steel and the thread diameter of the screw fastener, but also the pitch of screw fasteners.

The new nondimensional formula give the mean Test to Predicted values close to 1.0 for all thickness coefficients which reveal the adequacy of the new formula in predicting the pull-out failure loads. The mean Test to Predicted value is fairly constant across all steel thickness.

For this improved formula a capacity reduction factor of 0.5 as given in the American and draft Cold-formed Steel Structures codes was found to be acceptable. This can be applied as the coefficients of variation are still within 0.19 and the mean values varied between 0.99 and 1.01.

Future research is required to further improve the understanding of the structural performance of profiled steel claddings made of high strength steels. Following is an outlines of some recommendations for future research.

The assumptions made based on steel thickness to screw pitch to differentiate the two failure mode in pull-out failure cannot be applied and further investigation in this problem is needed to improve the formulae.

Each type of screw gives different failure load despite their same size in diameter and pitch thickness. Based on this, there must be another factor that differentiates their capacity to withstand tensile force. Assumption for this case is each type of screw gives a different amount of contact area between the screw thread and cladding. Further research that includes Major diameter, Minor diameter, and Thread Angle of the screws is needed to improve the understanding of the screw behaviour.

For cladding properties itself, the dimension of cladding screw hole also need to be measured to give the exact different between cladding screw hole diameter and screw diameter itself. Another factor is the ductility of the steel cladding. In some cases, pull-out failure also occurs when cladding already in fatigue condition. Tang's experiments used a wide range of cladding thickness (0.4 mm – 3 mm) and they gives different ductility that will affect their resistance to withstand fatigue failure.

Nowadays computer software have been able to model the cladding behaviour, thus using modelling software such as FORTRAN and ABAQUS is recommended to increase the data that can be used to further analyse the behaviour of steel cladding under wind uplift/suction loading.

Based on the lack of several variables mentioned above, it is almost impossible to produce 100% accurate formulae to predict pull-out failure under wind uplift loading, nonetheless the simplified non dimensional design formulae that have been developed in previous chapter is acceptable since it's satisfied all the criteria needed.

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APPENDIX A

HITEKS Screw Fasteners

SCREWS PROPERTIES					PURLINS PROPERTIES												
HITEKS	Diameter d(mm)		Thread Pitch		Thickness t(mm)		Grade				Failure Load						
							Specified		Measured								
	Nominal	Measured	(/inch)	p (mm)	Nominal	Measured	fy(MPa)	fu (MPa)	fy(MPa)	fu (MPa)	Experimental Record					Mean (N/f)	Std. Dev
10-16*25	4.87	4.67	16	1.59	0.4	0.38	250	320	358	415	563	565	548	590	505	554.2	31.4
					0.6	0.54			359	399	660	618	735	710	678	680.2	45.2
					1	0.95			332	390	1698	1655	1750	1620	1755	1695.6	58.9
					1.6	1.58	450	480	584	604	4290	4730	3850	4640	4740	4450.0	382.2
					1.9	1.79			497	560	5530	4870	4920	4310	5150	4956.0	445.3
					2.4	2.3			465	587	7750	7760	7560	8050	7960	7816.0	192.7
					3	2.93			450	553	-	-	-	-	-	-	-
					1.2	1.2	500	520	635	647	2810	2940	2960	3070	2890	2934.0	95.6
					0.42	0.43	550	550	717	721	918	803	988	888	970	913.4	73.5
					0.6	0.61			696	703	1320	1055	1075	1048	925	1084.6	144.2
					0.95	0.95			639	655	2380	2570	2640	2510	2520	2524.0	95.6
10-24*25	4.87	4.67	24	1.06	0.4	0.38	250	320	358	415	475	345	400	418	445	416.6	49.0
					0.6	0.54			359	399	548	578	643	603	593	593.0	34.8
					1	0.95			332	390	1343	1315	1323	1365	1370	1343.2	24.5
					1.6	1.58	450	480	584	604	3610	3290	3560	3100	3980	3508.0	335.4
					1.9	1.79			497	560	4750	4610	4600	4870	4660	4698.0	113.0
					2.4	2.3			465	587	7150	6720	6000	6450	6670	6598.0	419.6
					3	2.93			450	553	8650	9010	8930	8900	9370	8972.0	260.0
					1.2	1.2	500	520	635	647	2650	2720	2790	2190	2440	2558.0	243.9
					0.42	0.43	550	550	717	721	715	758	793	648	743	522.4	54.5
					0.6	0.61			696	703	930	918	1030	990	890	951.6	57.0
					0.95	0.95			639	655	2100	1890	2100	2100	2120	2062.0	96.5

HITEKS Screw Fasteners

SCREWS PROPERTIES					PURLINS PROPERTIES												
HITEKS	Diameter d(mm)		Thread Pitch		Thickness t(mm)		Grade				Failure Load						
							Specified		Measured								
	Nominal	Measured	(/inch)	p (mm)	Nominal	Measured	fy(MPa)	fu (MPa)	fy(MPa)	fu (MPa)	Experimental Record					Mean (N/f)	Std. Dev
12-11*50	5.43	5.52	11	2.31	0.4	0.38	250	320	358	415	575	663	635	563	580	603.2	43.4
					0.6	0.54			359	399	930	823	853	865	885	871.2	39.8
					1	0.95			332	390	1765	1493	1735	1760	1718	1694.2	114.1
					1.6	1.58	450	480	584	604	5240	5340	5300	5360	5320	5312.0	46.0
					1.9	1.79			497	560	6280	6150	5820	5540	5070	4810.0	487.3
					2.4	2.3			465	587	8860	9430	9520	8070	9490	9074.0	623.0
					3	2.93			450	553	11320	10920	11580	11180	10960	11192.0	271.5
					1.2	1.2	500	520	635	647	3160	3440	3610	3280	3390	3376.0	169.5
					0.42	0.43	550	550	717	721	1038	933	853	890	945	665.6	69.7
					0.6	0.61			696	703	1328	1343	1258	1448	1310	1337.4	69.7
					0.95	0.95			639	655	2600	2310	2720	2770	2950	2670.0	237.4
12-14*45	5.43	5.47	14	1.81	0.4	0.38	250	320	358	415	463	600	635	558	625	576.2	69.9
					0.6	0.54			359	399	735	788	830	848	675	775.2	70.9
					1	0.95			332	390	1590	1123	1445	1615	1695	1493.6	226.0
					1.6	1.58	450	480	584	604	4830	4410	4600	4870	4790	4700.0	192.4
					1.9	1.79			497	560	4830	5260	5450	5380	5230	5230.0	240.7
					2.4	2.3			465	587	8210	8340	8250	8070	8540	8282.0	174.0
					3	2.93			450	553	8800	9580	10150	8410	10500	9488.0	881.2
					1.2	1.2	500	520	635	647	2920	3110	3170	3070	3000	3054.0	97.1
					0.42	0.43	550	550	717	721	858	958	875	840	833	623.4	50.4
					0.6	0.61			696	703	818	1260	938	1178	985	1035.8	180.3
					0.95	0.95			639	655	2470	2500	2520	2450	2360	2460.0	62.0
12-24*30	5.43	5.36	24	1.06	0.4	0.38	250	320	358	415	478	538	470	438	473	479.4	36.3
					0.6	0.54			359	399	628	700	678	690	710	681.2	32.0
					1	0.95			332	390	1453	1553	1530	1425	1515	1495.2	54.0
					1.6	1.58	450	480	584	604	4350	4440	4390	3960	4480	4324.0	209.4
					1.9	1.79			497	560	4740	4480	4420	4790	4500	4586.0	167.0
					2.4	2.3			465	587	6720	7020	7330	7510	7100	7136.0	302.2
					3	2.93			450	553	9300	9210	9530	9120	10000	9432.0	352.2
					1.2	1.2	500	520	635	647	2940	2830	2890	2840	3030	2906.0	82.0
					0.42	0.43	550	550	717	721	853	850	813	773	885	695.7	42.9
					0.6	0.61			696	703	940	1048	1035	870	1163	1011.2	111.8
					0.95	0.95			639	655	2410	2400	2240	2370	2410	2366.0	72.3

HITEKS Screw Fasteners

SCREWS PROPERTIES					PURLINS PROPERTIES												
HITEKS	Diameter d(mm)		Thread Pitch		Thickness t(mm)		Grade				Failure Load						
							Specified		Measured								
	Nominal	Measured	(/inch)	p (mm)	Nominal	Measured	fy(MPa)	fu (MPa)	fy(MPa)	fu (MPa)	Experimental Record					Mean (N/f)	Std. Dev
14-10*50	6.41	6.39	10	2.54	0.4	0.38	250	320	358	415	640	748	670	763	760	716.2	57.1
					0.6	0.54			359	399	950	870	1023	855	678	875.2	129.2
					1	0.95			332	390	1995	2160	1755	2083	2065	2011.6	155.0
					1.6	1.58	450	480	584	604	5290	5630	5930	5500	5270	5524.0	272.0
					1.9	1.79			497	560	6670	5840	5680	6280	6750	6244.0	479.6
					2.4	2.3			465	587	9020	9750	9910	8680	8740	9220.0	574.2
					3	2.93			450	553	11300	12000	13050	12500	11850	12140.0	664.6
					1.2	1.2	500	520	635	647	-	-	-	-	-	-	-
					0.42	0.43	550	550	717	721	1228	1060	1055	1033	1020	1079.2	84.8
					0.6	0.61			696	703	1580	1440	1713	1748	1360	1568.2	168.2
					0.95	0.95			639	655	2610	3120	2790	3170	3030	2944.0	237.0
14-20*45	6.41	6.22	20	1.27	0.4	0.38	250	320	358	415	558	595	623	543	633	590.4	39.4
					0.6	0.54			359	399	775	835	785	840	773	801.6	33.1
					1	0.95			332	390	1698	1710	1880	1938	1773	1799.8	105.7
					1.6	1.58	450	480	584	604	5040	4400	5210	5140	4680	4894.0	343.3
					1.9	1.79			497	560	4870	5030	5810	5510	5150	5274.0	381.2
					2.4	2.3			465	587	7720	7850	8410	8110	8400	8098.0	313.5
					3	2.93			450	553	11100	11050	11100	10650	11050	10990.0	191.7
					1.2	1.2	500	520	635	647	-	-	-	-	-	-	-
					0.42	0.43	550	550	717	721	928	978	1095	825	968	958.8	97.3
					0.6	0.61			696	703	1598	1605	1580	1470	1698	1590.2	81.3
					0.95	0.95			639	655	2800	2550	2810	2690	2610	2692.0	114.5

500 Series Screw Fasteners

SCREWS PROPERTIES					PURLINS PROPERTIES												
500 S	Diameter d(mm)		Thread Pitch		Thickness t(mm)		Grade				Failure Load						
							Specified		Measured								
	Nominal	Measured	(/inch)	p (mm)	Nominal	Measured	fy(MPa)	fu (MPa)	fy(MPa)	fu (MPa)	Experimental Record					Mean (N/f)	Std. Dev
12-24*50	5.43	5.49	24	1.06	0.4	0.38	250	320	358	415	410	393	413	385	458	411.8	28.3
					0.6	0.54			359	399	668	548	615	613	543	597.4	52.3
					1	0.95			332	390	1368	1423	1368	1338	1210	1341.4	79.6
					1.6	1.58	450	480	584	604	4330	4610	4510	4550	4440	4488.0	107.8
					1.9	1.79			497	560	4290	4630	4510	4010	4440	4376.0	238.7
					2.4	2.3			465	587	6800	6840	7180	6870	8400	7218.0	677.7
					3	2.93			450	553	9760	10080	9050	10160	10050	9820.0	456.2
					1.2	1.2	500	520	635	647	-	-	-	-	-	-	-
					0.42	0.43	550	550	717	721	800	733	698	768	780	755.8	40.5
					0.6	0.61			696	703	1055	1015	1140	1160	1085	1091.0	59.7
					0.95	0.95			639	655	2040	2380	2000	2210	2410	2208.0	188.3

Type 17 Screw Fasteners

SCREWS PROPERTIES					PURLINS PROPERTIES												
Type 17	Diameter d(mm)		Thread Pitch		Thickness t(mm)		Grade				Failure Load						
							Specified		Measured								
	Nominal	Measured	(/inch)	p (mm)	Nominal	Measured	fy(MPa)	fu (MPa)	fy(MPa)	fu (MPa)	Experimental Record					Mean (N/f)	Std. Dev
10-12*30	4.87	4.81	12	2.12	0.4	0.38	250	320	358	415	728	645	713	660	658	680.8	37.1
					0.6	0.54			359	399	940	870	1020	1013	938	956.2	61.9
					1	0.95			332	390	1523	1500	1660	1698	1745	1625.2	108.4
					1.6	1.58	450	480	584	604	3510	5040	5450	5140	3820	4592.0	866.6
					1.9	1.79			497	560	5050	4950	5310	4790	3710	3968.3	617.7
					2.4	2.3			465	587	6710	6040	6280	5020		6012.5	717.4
					3	2.93			450	553	7040	7650	7600	8270	8570	7826.0	602.2
					1.2	1.2	500	520	635	647	2690	3160	3190	3300	3340	3136.0	260.2
					0.42	0.43	550	550	717	721	1098	1155	1033	1018	1093	899.5	55.2
					0.6	0.61			696	703	1400	1385	1245	1488	1405	1384.6	87.8
					0.95	0.95			639	655	2610	2720	2670	2730	2960	2738.0	132.9
12-11*50	5.43	5.53	11	2.31	0.4	0.38	250	320	358	415	788	678	775	745	765	750.2	43.3
					0.6	0.54			359	399	988	1100	1090	1058	1008	1048.8	49.4
					1	0.95			332	390	1945	1883	1908	1933	1958	1925.4	30.0
					1.6	1.58	450	480	584	604	5690	5950	5610	5350	5700	5660.0	215.2
					1.9	1.79			497	560	6250	6320	5920	6750	6330	6314.0	295.7
					2.4	2.3			465	587	8440	10210	10120	9070		9460.0	854.5
					3	2.93			450	553	9750	10720	11730	9720	10030	10390.0	850.4
					1.2	1.2	500	520	635	647	3830	3650	3900	3810	3590	3756.0	130.3
					0.42	0.43	550	550	717	721	1213	1203	1198	1168	1098	840.0	46.7
					0.6	0.61			696	703	1520	1468	1488	1580	1518	1514.8	42.4
					0.95	0.95			639	655	3030	3180	3310	3300	3310	3226.0	122.6
14-10*50	6.41	6.34	10	2.54	0.4	0.38	250	320	358	415	820	863	970	910	808	874.2	66.9
					0.6	0.54			359	399	1350	1283	1245	1245	1298	1284.2	43.6
					1	0.95			332	390	2198	2355	2408	2223	2345	2305.8	90.7
					1.6	1.58	450	480	584	604	6100	6430	5810	6300	6390	6206.0	255.4
					1.9	1.79			497	560	6640	6870	7380	6840	7080	6962.0	280.9
					2.4	2.3			465	587	10910	10960	10610	10860	11380	10944.0	278.4
					3	2.93			450	553	-	-	-	-	-	-	-
					1.2	1.2	500	520	635	647	4330	4130	4440	4250	4550	4340.0	163.1
					0.42	0.43	550	550	717	721	1268	1295	1413	1440	1285	957.3	79.9
					0.6	0.61			696	703	1885	1805	1795	1700	1660	1769.0	89.5
					0.95	0.95			639	655	3560	3360	3670	3710	3490	3558.0	141.0

APPENDIX B

Very Thin Steel (t < 0.9 mm)

a	**-0.3**		**Max Error**	**37.12**
b	**0.3**		**Min Error**	**-34.13**
k	**2.4**		**Mean**	**1.02**
			COV	**0.20**

Parameters					**Analysis**						
d (mm)	**p (mm)**	**t (mm)**	**fu (Mpa)**	**F (N)**	**(d/t)**	**(p/t)**	**(d/t)^a**	**(p/t)^b**	**Load**	**Mean**	**Diff %**
5.49	1.06	0.54	399	597.4	10.17	1.96	0.50	1.22	584.66	1.02	-2.13
5.49	1.06	0.61	703	1091.0	9.00	1.74	0.52	1.18	1030.12	1.06	-5.58
4.81	2.12	0.38	415	680.8	12.66	5.58	0.47	1.67	778.96	0.87	14.42
4.81	2.12	0.54	399	956.2	8.91	3.93	0.52	1.51	748.93	1.28	-21.68
4.81	2.12	0.43	721	1084.2	11.19	4.93	0.48	1.61	1353.33	0.80	24.83
4.81	2.12	0.61	703	1384.6	7.89	3.48	0.54	1.45	1319.54	1.05	-4.70
5.53	2.31	0.38	415	750.2	14.55	6.08	0.45	1.72	766.52	0.98	2.18
5.53	2.31	0.54	399	1048.8	10.24	4.28	0.50	1.55	736.97	1.42	-29.73
5.53	2.31	0.43	721	1187.6	12.86	5.37	0.46	1.66	1331.72	0.89	12.14
5.53	2.31	0.61	703	1514.8	9.07	3.79	0.52	1.49	1298.47	1.17	-14.28
6.34	2.54	0.38	415	874.2	16.68	6.68	0.43	1.77	756.98	1.15	-13.41
6.34	2.54	0.43	721	1321.6	14.74	5.91	0.45	1.70	1315.13	1.00	-0.49
6.34	2.54	0.61	703	1769.0	10.39	4.16	0.50	1.53	1282.30	1.38	-27.51
4.67	1.59	0.38	415	554.2	12.29	4.18	0.47	1.54	720.91	0.77	30.08
4.67	1.59	0.54	399	680.2	8.65	2.94	0.52	1.38	693.12	0.98	1.90
4.67	1.59	0.43	721	913.4	10.86	3.70	0.49	1.48	1252.48	0.73	37.12
4.67	1.59	0.61	703	1084.6	7.66	2.61	0.54	1.33	1221.21	0.89	12.60
4.67	1.06	0.54	399	593.0	8.65	1.96	0.52	1.22	613.73	0.97	3.50
4.67	1.06	0.61	703	951.6	7.66	1.74	0.54	1.18	1081.34	0.88	13.63
5.52	2.31	0.38	415	603.2	14.53	6.08	0.45	1.72	766.94	0.79	27.15
5.52	2.31	0.54	399	871.2	10.22	4.28	0.50	1.55	737.37	1.18	-15.36
5.52	2.31	0.61	703	1337.4	9.05	3.79	0.52	1.49	1299.18	1.03	-2.86
5.47	1.81	0.38	415	576.2	14.39	4.76	0.45	1.60	714.77	0.81	24.05
5.47	1.81	0.54	399	775.2	10.13	3.35	0.50	1.44	687.21	1.13	-11.35
5.47	1.81	0.61	703	1035.8	8.97	2.97	0.52	1.39	1210.80	0.86	16.90
5.36	1.06	0.38	415	479.4	14.11	2.79	0.45	1.36	612.49	0.78	27.76
5.36	1.06	0.54	399	681.2	9.93	1.96	0.50	1.22	588.88	1.16	-13.55
5.36	1.06	0.43	721	819.5	12.47	2.47	0.47	1.31	1064.12	0.77	29.85
5.36	1.06	0.61	703	1011.2	8.79	1.74	0.52	1.18	1037.55	0.97	2.61
6.39	2.54	0.38	415	716.2	16.82	6.68	0.43	1.77	755.20	0.95	5.44
6.39	2.54	0.54	399	875.2	11.83	4.70	0.48	1.59	726.08	1.21	-17.04
6.39	2.54	0.43	721	1079.2	14.86	5.91	0.45	1.70	1312.04	0.82	21.58
6.39	2.54	0.61	703	1568.2	10.48	4.16	0.49	1.53	1279.28	1.23	-18.42
6.22	1.27	0.38	415	590.4	16.37	3.34	0.43	1.44	618.39	0.95	4.74
6.22	1.27	0.54	399	801.6	11.52	2.35	0.48	1.29	594.55	1.35	-25.83
6.22	1.27	0.43	721	958.8	14.47	2.95	0.45	1.38	1074.36	0.89	12.05
6.22	1.27	0.61	703	1590.2	10.20	2.08	0.50	1.25	1047.54	1.52	-34.13

Thin Steel (0.9 mm < t < 1.5 mm)

a	**-0.3**	**Max Error**	**18.47**
b	**0.3**	**Min Error**	**-20.30**
k	**22.5**	**Mean**	**1.00**
		COV	**0.12**

Parameters					Analysis						
d (mm)	**p (mm)**	**t (mm)**	**fu (Mpa)**	**F (N)**	**(d/t)**	**(p/t)**	**(d/t)^a**	**(p/t)^b**	**Load**	**Mean**	**Diff %**
5.49	1.06	0.95	390	1341.4	5.78	1.12	0.59	1.03	1476.31	0.91	10.06
5.49	1.06	0.95	655	2208.0	5.78	1.12	0.59	1.03	2479.44	0.89	12.29
4.81	2.12	0.95	390	1625.2	5.06	2.23	0.61	1.27	1891.10	0.86	16.36
4.81	2.12	0.95	655	2738.0	5.06	2.23	0.61	1.27	3176.07	0.86	16.00
5.53	2.31	0.95	390	1925.4	5.82	2.43	0.59	1.31	1860.90	1.03	-3.35
5.53	2.31	0.95	655	3226.0	5.82	2.43	0.59	1.31	3125.35	1.03	-3.12
6.34	2.54	0.95	390	2305.8	6.67	2.67	0.57	1.34	1837.72	1.25	-20.30
6.34	2.54	0.95	655	3558.0	6.67	2.67	0.57	1.34	3086.43	1.15	-13.25
4.67	1.59	0.95	390	1695.6	4.92	1.67	0.62	1.17	1750.17	0.97	3.22
4.67	1.59	0.95	655	2524.0	4.92	1.67	0.62	1.17	2939.39	0.86	16.46
4.67	1.06	0.95	390	1343.2	4.92	1.12	0.62	1.03	1549.72	0.87	15.38
5.52	2.31	0.95	390	1694.2	5.81	2.43	0.59	1.31	1861.91	0.91	9.90
5.52	2.31	0.95	655	2670.0	5.81	2.43	0.59	1.31	3127.05	0.85	17.12
5.47	1.81	0.95	390	1493.6	5.76	1.91	0.59	1.21	1735.26	0.86	16.18
5.47	1.81	0.95	655	2460.0	5.76	1.91	0.59	1.21	2914.34	0.84	18.47
5.36	1.06	0.95	390	1495.2	5.64	1.12	0.60	1.03	1486.96	1.01	-0.55
5.36	1.06	0.95	655	2366.0	5.64	1.12	0.60	1.03	2497.33	0.95	5.55
6.39	2.54	0.95	390	2011.6	6.73	2.67	0.56	1.34	1833.40	1.10	-8.86
6.39	2.54	0.95	655	2944.0	6.73	2.67	0.56	1.34	3079.16	0.96	4.59
6.22	1.27	0.95	390	1799.8	6.55	1.34	0.57	1.09	1501.28	1.20	-16.59
6.22	1.27	0.95	655	2692.0	6.55	1.34	0.57	1.09	2521.37	1.07	-6.34
4.81	2.12	1.2	647	3136.0	4.01	1.77	0.66	1.19	3137.28	1.00	0.04
4.67	1.59	1.2	647	2934.0	3.89	1.33	0.67	1.09	2903.49	1.01	-1.04
4.67	1.06	1.2	647	2558.0	3.89	0.88	0.67	0.96	2570.94	0.99	0.51
5.52	2.31	1.2	647	3376.0	4.60	1.93	0.63	1.22	3088.86	1.09	-8.51
5.47	1.81	1.2	647	3054.0	4.56	1.51	0.63	1.13	2878.75	1.06	-5.74
5.36	1.06	1.2	647	2906.0	4.47	0.88	0.64	0.96	2466.82	1.18	-15.11
5.53	2.31	1.2	647	3756.0	4.61	1.93	0.63	1.22	3087.18	1.22	-17.81

Thick Steel (2.0 mm < t < 3.0 mm)

a	**-0.3**	**Max Error**	**28.29**
b	**0.3**	**Min Error**	**-22.64**
k	**22.5**	**Mean**	**0.99**
		COV	**0.16**

Parameters					**Analysis**						
d (mm)	**p (mm)**	**t (mm)**	**fu (Mpa)**	**F (N)**	**(d/t)**	**(p/t)**	**(d/t)^a**	**(p/t)^b**	**Load**	**Mean**	**Diff %**
5.49	1.06	2.3	587	7218.0	2.39	0.46	0.77	0.79	8063.82	0.90	11.72
5.49	1.06	2.93	553	9820.0	1.87	0.36	0.83	0.74	7596.75	1.29	-22.64
4.81	2.12	2.93	553	7826.0	1.64	0.72	0.86	0.91	9731.17	0.80	24.34
5.53	2.31	2.3	587	9460.0	2.40	1.00	0.77	1.00	10164.52	0.93	7.45
5.53	2.31	2.93	553	10390.0	1.89	0.79	0.83	0.93	9575.77	1.09	-7.84
6.34	2.54	2.3	587	10944.0	2.76	1.10	0.74	1.03	10037.93	1.09	-8.28
4.67	1.59	2.3	587	7816.0	2.03	0.69	0.81	0.90	9559.71	0.82	22.31
4.67	1.06	2.3	587	6598.0	2.03	0.46	0.81	0.79	8464.81	0.78	28.29
4.67	1.06	2.93	553	8972.0	1.59	0.36	0.87	0.74	7974.52	1.13	-11.12
5.52	2.31	2.3	587	9074.0	2.40	1.00	0.77	1.00	10170.04	0.89	12.08
5.52	2.31	2.93	553	11192.0	1.88	0.79	0.83	0.93	9580.97	1.17	-14.39
5.47	1.81	2.3	587	8282.0	2.38	0.79	0.77	0.93	9478.25	0.87	14.44
5.47	1.81	2.93	553	9488.0	1.87	0.62	0.83	0.87	8929.25	1.06	-5.89
5.36	1.06	2.3	587	7136.0	2.33	0.46	0.78	0.79	8122.00	0.88	13.82
5.36	1.06	2.93	553	9432.0	1.83	0.36	0.83	0.74	7651.56	1.23	-18.88
6.39	2.54	2.3	587	9220.0	2.78	1.10	0.74	1.03	10014.30	0.92	8.61
6.22	1.27	2.3	587	8098.0	2.70	0.55	0.74	0.84	8200.20	0.99	1.26

Thick Steel (1.5 mm < t < 2.0 mm)

a	**-0.3**	**Max Error**	**28.59**
b	**0.3**	**Min Error**	**-23.58**
k	**12.5**	**Mean**	**1.01**
		COV	**0.13**

Parameters					Analysis						
d (mm)	**p (mm)**	**t (mm)**	**fu (Mpa)**	**F (N)**	**(d/t)**	**(p/t)**	**(d/t)^a**	**(p/t)^b**	**Load**	**Mean**	**Diff %**
5.49	1.06	1.58	604	4488.0	3.47	0.67	0.69	0.89	4609.64	0.97	2.71
5.49	1.06	1.79	560	4376.0	3.07	0.59	0.71	0.85	4273.84	1.02	-2.33
4.81	2.12	1.58	604	4592.0	3.04	1.34	0.72	1.09	5904.79	0.78	28.59
4.81	2.12	1.79	560	4620.0	2.69	1.18	0.74	1.05	5474.64	0.84	18.50
5.53	2.31	1.58	604	5660.0	3.50	1.46	0.69	1.12	5810.49	0.97	2.66
5.53	2.31	1.79	560	6314.0	3.09	1.29	0.71	1.08	5387.21	1.17	-14.68
6.34	2.54	1.58	604	6206.0	4.01	1.61	0.66	1.15	5738.13	1.08	-7.54
6.34	2.54	1.79	560	6962.0	3.54	1.42	0.68	1.11	5320.12	1.31	-23.58
4.67	1.59	1.58	604	4450.0	2.96	1.01	0.72	1.00	5464.76	0.81	22.80
4.67	1.59	1.79	560	4956.0	2.61	0.89	0.75	0.97	5066.66	0.98	2.23
4.67	1.06	1.79	560	4698.0	2.61	0.59	0.75	0.85	4486.37	1.05	-4.50
5.52	2.31	1.58	604	5312.0	3.49	1.46	0.69	1.12	5813.65	0.91	9.44
5.52	2.31	1.79	560	5696.7	3.08	1.29	0.71	1.08	5390.14	1.06	-5.38
5.47	1.81	1.58	604	4700.0	3.46	1.15	0.69	1.04	5418.19	0.87	15.28
5.47	1.81	1.79	560	5230.0	3.06	1.01	0.72	1.00	5023.49	1.04	-3.95
5.36	1.06	1.58	604	4324.0	3.39	0.67	0.69	0.89	4642.90	0.93	7.38
5.36	1.06	1.79	560	4586.0	2.99	0.59	0.72	0.85	4304.67	1.07	-6.13
6.39	2.54	1.58	604	5524.0	4.04	1.61	0.66	1.15	5724.62	0.96	3.63
6.39	2.54	1.79	560	6244.0	3.57	1.42	0.68	1.11	5307.60	1.18	-15.00
6.22	1.27	1.58	604	4894.0	3.94	0.80	0.66	0.94	4687.60	1.04	-4.22
6.22	1.27	1.79	560	5274.0	3.47	0.71	0.69	0.90	4346.12	1.21	-17.59