Oct 19th, 12:00 AM

Cyclic Pull-out Strength of Steel Roof and Wall Cladding Systems

Mahen Mahendran

Dhammika Mahaarachchi

Fifteenth International Specialty Conference on Cold-Formed Steel Structures
St. Louis, Missouri U.S.A., October 19-20, 2000

Cyclic Pull-out Strength of Steel Roof and Wall Cladding Systems

M. Mahendran[1] and D. Mahaarachchi[2]

Summary

When crest-fixed thin steel roof cladding systems are subjected to wind uplift, local pull-through or pull-out failures occur prematurely at their screwed connections. During high wind events such as storms and cyclones these localised failures then lead to severe damage to buildings and their contents. In recent times, the use of thin steel battens/purlins has increased considerably. This has made the pull-out failures more critical in the design of steel cladding systems. Recent research has developed a design formula for the static pull-out strength of steel cladding systems. However, the effects of fluctuating wind uplift loading that occurs during high wind events are not known. Therefore a series of constant amplitude cyclic tests has been undertaken on connections between steel battens made of different thicknesses and steel grades, and screw fasteners with varying diameter and pitch. This paper presents the details of these cyclic tests and the results.

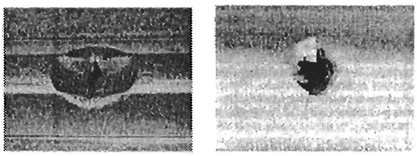
1. Introduction

Extreme wind events such as hurricanes and storms often cause severe damage to a large number of low-rise buildings (housing, schools, industrial, commercial, and farm buildings). Damage investigations following these extreme wind events have always shown that disengagement of steel roof and wall cladding systems has occurred because of local failures of screwed connections under wind uplift or suction loading (see Figure 1). The steel sheeting is made of thin high strength steels (0.42 mm base metal thickness and minimum yield stress 550 MPa) and is intermittently crest-fixed. Such profiled steel sheeting often pulls through the screw heads (Figure 1a) owing to the large stress concentrations around the fastener holes under wind uplift/suction loading (Mahendran, 1994). When subjected to sustained and strongly fluctuating hurricane wind forces, the roof claddings suffer from low cycle fatigue cracking in the vicinity of fastener holes at rather lower load levels (Beck and Stevens, 1979, Mahendran, 1990a). This also leads to a pull-through failure as shown in Figure 1b. Both static and fatigue type pull-through failures lead to rapid disengagement of all roof and wall claddings, causing severe damage to the entire building. The local pull-through failure phenomenon has been investigated by many researchers in the past and as a result a wealth of information is available (Mahendran, 1990a,b, 1994, Xu and Reardon, 1993, Beck and Stevens, 1979).

In recent times, very thin high-strength steel battens of various shapes have been used in housing, industrial and commercial buildings and this appears to be the fastest growing method in roof construction. These cladding systems can then suffer from another type of local failure when the screw fasteners pull-out of the steel battens, purlins or girts (see Figure 2). Such a pull-out failure also leads to a rapid

[1] Associate Professor of Civil Engineering & Director, [2] PhD Research Scholar, Physical Infrastructure Centre, School of Civil Engineering, Queensland University of Technology, Australia

disengagement of roof and wall claddings, causing severe damage to the entire building. It is important the entire roof/wall cladding system be safe under high wind events. Traditionally timber purlins and battens have been used in buildings and hence pull-out failures have not been a common occurrence or a problem. This situation has changed because of the increasing use of high strength thin steel battens and purlins in roof and wall construction. Therefore it is very important to investigate the static and fatigue pull-out behaviour of these steel cladding systems. Mahendran and Tang (1998) have investigated the static pull-out behaviour of connections for a range of commonly used screw fasteners and steel purlins, girts, and battens. It is likely that sustained fluctuating wind loading conditions during storms could lead to premature fatigue pull-out failure in a similar manner to pull-through failures. Therefore a series of constant amplitude cyclic tests has been undertaken on connections between steel battens made of different thicknesses and steel grades, and screw fasteners with varying diameter and pitch. This paper presents the details of this investigation and its results.



(a) Static (b) Fatigue

Figure 1. Pull-through Failure

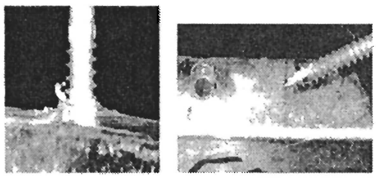


Figure 2. Pull-out Failure

2. Current Design Methods

The American (AISI, 1996), Australian (SA, 1996) and European provisions (Eurocode, 1992) include design formulae for mechanically fastened screw connections in tension as shown by the following equations. They apply to many different screw connections and fastener details. Therefore, these design formulae imply a greater degree of conservatism. The pull-out capacity, F_{ou} is calculated as follows.

American and Australian $\quad F_{ou} = 0.85\ t\ d\ f_u \quad$ 1(a)

European $\quad F_{ou} = 0.65\ t\ d\ f_y \quad$ 1(b)

where t = thickness of member, d = nominal screw diameter, f_u = ultimate tensile strength of steel and f_y = yield stress of steel.

The design pull-out capacity is obtained by using a capacity reduction factor of 0.5 to Equations 1(a) and 1(b). 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. These design equations were developed for conventional fasteners and thicker mild steel. At present the American and Australian codes recommend the use of 75% of the specified minimum strength for high-strength steel such as G550 with a yield stress greater than 550 MPa and a thickness less than 0.9 mm. This is to allow for the reduced ductility of these steels. Since the design formulae are considered to be conservative, the design for the pull-out failure of screwed connections in tension is at present mainly based on laboratory experiments.

In the past, different test methods such as the U-tension, cross-tension and plate methods, have been used for testing screw connections in tension (Mahendran and Tang, 1998). However, the Australian provisions (SA, 1996) have recommended the cross-tension method. Based on the test results using this method, Macindoe et al. (1995) modified the predictive equations to better model the observed behaviour. The following equation gives the modified formula for pull-out strength, F_{ou}. It includes the term $f_u^{0.5}$ in this equation as it was considered to eliminate the need for the use of 75% of the specified minimum strength for G550 steels with thickness less than 0.9 mm. But their work is not specific to roof and wall cladding systems.

$$F_{ou} = 35\sqrt{(t^{2.2} d f_u)} \qquad (2)$$

where t, d and f_u are as defined for Equation 1(a)

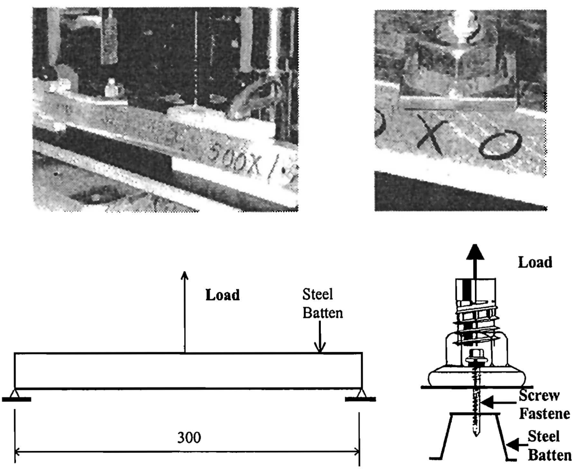


Figure 3. Test Set-up for the determination of Pull-out Strength
(Mahendran and Tang, 1998)

Mahendran and Tang (1998) developed an improved design formula for the pull-out strength of steel cladding systems used in Australia. Their formula was based on test results obtained from an appropriate small scale test method for steel cladding systems (Figure 3). The accuracy of this small scale test method was first validated by comparison with two-span cladding test results. Mahendran and Tang's formula calculates the pull-out strength F_{ou} of the connections in terms of the thickness of steel member (t in mm) and ultimate strength of steel (f_u in MPa), the thread diameter (d in mm) and the pitch (p in mm) of screw fasteners as shown next.

$$F_{ou} = k\, d\, p^{0.2}\, t^{1.3}\, f_u \tag{3}$$

where k = 0.7 for thinner sections made of G250, G500, and G550 steel of thickness t < 1.5 mm; k = 0.8 for thicker sections made of G450 steel of thickness $1.5 \leq t \leq 3$ mm and k = 0.75 for all sections made of G250, G450, G500, and G550 steel of thickness $t \leq 3.0$ mm.

Mahendran and Tang's modified formula appears to better model the pull-out strength than the current design formula. Unlike the current design formula (Equation 1a), all the parameters on which the strength is dependent were included in this formula and it is not necessary to use the 75% of specified tensile strength of G550 steel of thickness less than 0.9 mm. However, none of these formulae allows for the effects of fluctuating wind loading. Fatigue caused by wind fluctuations can significantly reduce the pull-out failure load and should be accounted for in the evaluation of roofing systems (Baskaran et al., 1997). Therefore this investigation considers the cyclic wind load conditions and their effects on pull-out strength of steel roof and wall cladding systems.

3. Experimental Investigation

Although the use of a two-span cladding test assembly is the preferred method to simulate a wind uplift pressure, it is time consuming and expensive. Since pull-out failures are localised around the screw holes (see Figure 2), Mahendran and Tang (1998) used an appropriate small scale test method, which has been validated using two-span cladding test results. Therefore a similar small scale test set-up was used in this investigation, but with constant amplitude cyclic loading conditions as shown in Figure 4.

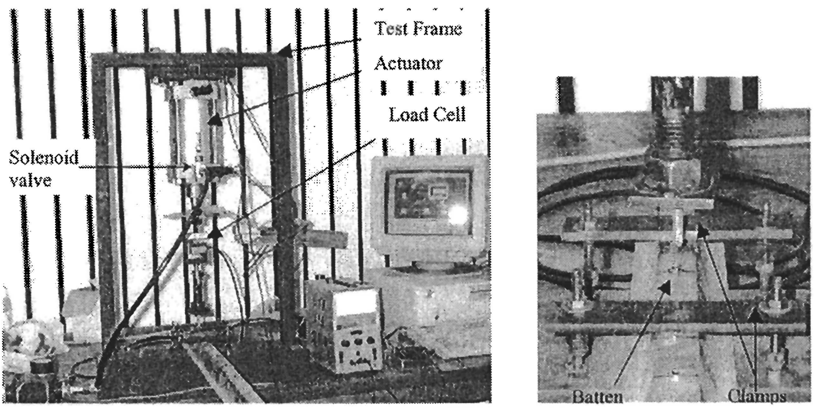


Figure 4. Experimental Set Up

The test battens used in this investigation are commonly used in the Australian building industry. Two different steel grades and thicknesses were chosen for this investigation. Figure 5 and Table 1 give the details of these steel battens. Similarly, a range of commonly used self-drilling screw fasteners with varying diameter and pitch were used in this investigation. Two different pitches, screw diameters and screw types were chosen. Figure 6 and Table 2 show the details of these screw fasteners. In the static pull-out test series, Mahendran and Tang (1998) considered a larger range of steel grades and thicknesses and screw fasteners. However, in this investigation on cyclic pull-out testing, only a subset of them was considered for two reasons: Fatigue effects were expected to be similar for other combinations of steel battens and screw fasteners; The number of tests may become excessive as at least five cyclic tests had to be conducted for each combination.

Table 1. Details of Steel Battens

Steel Grade	BMT (mm)		Yield Stress f_y (MPa)		Ultimate stress f_u (MPa)	
	Nominal	Measured	Nominal	Measured	Nominal	Measured
G250	0.40	0.38	250	358	320	415
G250	1.00	0.95	250	332	320	390
G550	0.42	0.43	550	717	550	721
G550	0.95	0.95	550	639	550	655

Table 2. Details of Screw Fasteners

Screw type	Gauge	Thread Diameter		Thread form (per Inch)	Thread pitch p (mm)
		Nominal	Measured		
HiTeks	10-16	4.87	4.67	16	1.59
HiTeks	14-10	6.41	6.39	10	2.54
HiTeks	14-20	6.41	6.22	20	1.27
Type 17	14-10	6.41	6.34	10	2.54

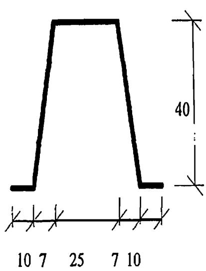


Figure 5. Test Batten

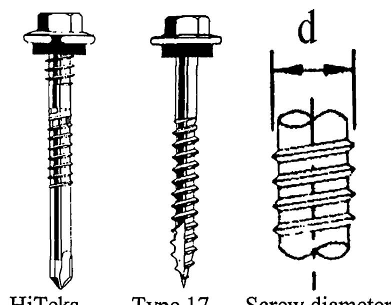


Figure 6. Screw Fasteners

A specially made test frame was used to assemble the test batten and the loading actuator. The test batten was clamped to the base of the test frame at a distance of about 150 mm. As seen in Figures 3 and 4, a computer-controlled pneumatic actuator was used to apply the constant amplitude cyclic loading to the screw fastener heads using a special arrangement. These fasteners with a hexagonal head and a neoprene sealing washer were fixed to the test battens in a similar manner to that used in the building industry. Special precautions were taken during the installation process to ensure all screws were centred at the battens, set perpendicular to the plane of the batten and driven inside the batten to a constant length. A series of cyclic pull-out tests was then conducted for a range of combinations of steel battens and screw fasteners until a pull-out failure occurred.

Table 3. Cyclic Test Program

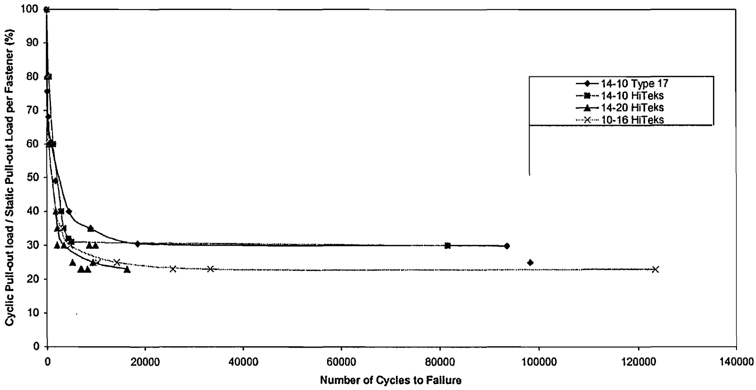
Steel Batten		Screw Fastener		Static Pull-out Failure Load (N/fastener)	Cyclic Load Ranges* as a Percentage of Static Pull-out Failure Load
Steel Grade	Nominal thickness	Type	Gauge		
G550	0.42	Type 17	14-10	1321	25, 30, 30.5, 31, 33, 35, 40, 49, 53, 61, 68, 76
		HiTeks	14-10	1079	30, 31, 32, 35, 40, 60, 80
			14-20	959	23, 25, 30, 35, 40, 60, 80
			10-16	913	23, 25, 30, 35, 40, 60, 80
G550	0.95	Type 17	14-10	3558	20, 25, 30, 35, 40, 50, 60, 70, 75, 80
		HiTeks	14-10	2944	25, 30, 35, 40, 60, 70, 80,
			14-20	2692	25, 30, 35, 40, 50, 60, 80
			10-16	2524	25, 30, 35, 40, 50, 60, 80
G250	0.40	Type 17	14-10	874	35, 37, 40, 50, 60, 80
		HiTeks	14-10	716	30, 35, 40, 50, 60, 80
			14-20	590	40, 50, 60, 80
			10-16	554	60, 80
G250	1.0	Type 17	14-10	2306	30, 35, 40, 50, 60, 80
		HiTeks	14-10	2012	30, 32, 35, 40, 50, 60, 80
			14-20	1800	30, 35, 37, 40, 50, 60, 80
			10-16	1696	30, 35, 37, 40, 60, 80

* - Minimum cyclic load = zero

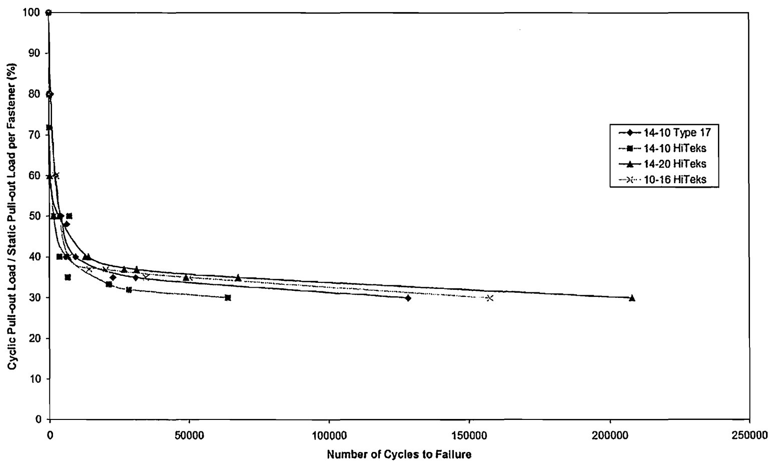
The pneumatic actuator was supplied with compressed air at a regulated pressure. Cyclic loading to the test batten was produced by an air control system in which a process timer operated the actuator. This system was connected to a data acquisition and process control system, which facilitated real time monitoring, integration and processing of test data. The applied load to the screw head was measured by a load cell connected in series with the actuator as shown in Figure 4, and was continuously monitored through a graphic display on the computer. It also had a self-triggering system to stop the system at failure and save the data automatically. By controlling the regulated air supply, the applied cyclic loading was produced at the desired rate. In most of the tests, the loading frequency was maintained at 3 Hz. For each combination of test batten and screw fastener, constant amplitude cyclic load tests were conducted with a load range from about zero to various percentages of its static pull-out load (see Table 3). This resulted in a total of 175 cyclic tests. The cyclic load ranges were based on static test results reported in Mahendran and Tang (1998) and Tang (1998), and are included in Table 3. In each test, the cyclic loading was continued until the screw fastener pulled-out from the battens and the corresponding number of cycles was recorded.

4. Experimental Results and Discussion

Typical experimental results are presented as Cyclic Pull-out failure load (as a percentage of static pull-out failure load per fastener) versus number of cycles to failure in Figures 7 (a) to (d). Figures 7 (a) and (b) illustrate the variations in the cyclic behaviour of each steel batten type (steel grade and thickness) due to the use of different screw fasteners whereas Figures 7 (c) and (d) illustrate these variations when different steel batten types are used for the same screw fastener. All the results clearly demonstrate the presence of fatigue effects as the pull-out failures occurred after only a few cycles of loading at much lower load levels than the static pull-out failure loads.

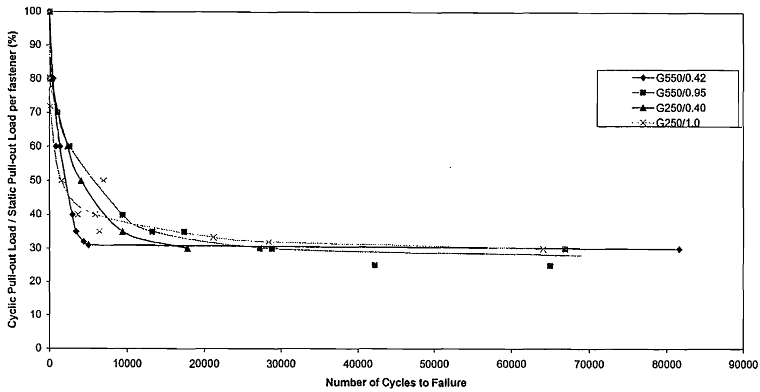


(a) 0.42 mm G550 Steel

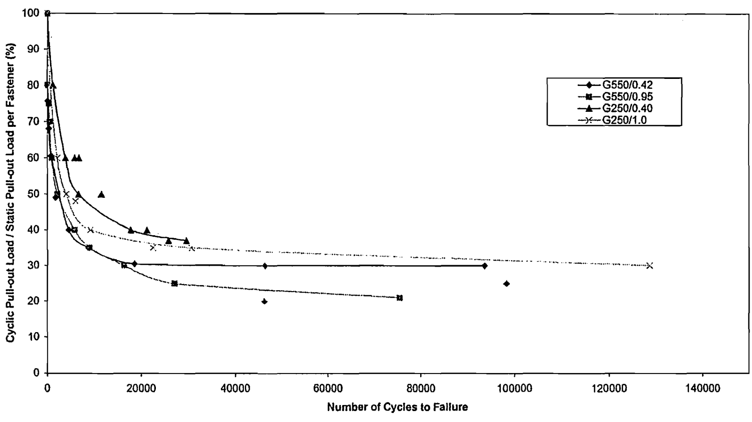


(b) 1.0 mm G250 Steel

Figure 7. Group of Fatigue Curves for Varying Steel and Screw Types



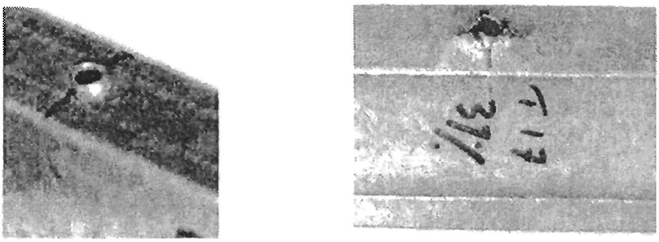
(c) No.14-10 HiTeks Screws



(d) No.14-10 Type 17 Screws

Figure 7. Group of Fatigue Curves for Varying Steel and Screw Types

In general, there were two modes of cyclic pull-out failure as shown in Figure 8. When the cyclic load was more than about 40 to 50% of the static pull-out failure load, the screw fasteners pulled out as the steel around the fastener holes was bent upwards after a limited number of cycles (< about 10,000) and there weren't any cracking around the fastener holes. The steel bending deformation around the hole was quite small for thicker steel battens. This type of failure was due to the slipping at the connections caused by the upward bending deformations of steel around the fastener hole and cyclic loading. This was particularly true for the thin steel as there wasn't much grip between the fastener and steel. Figure 8 (a) shows the typical failure mode in this case. At higher cyclic loads closer to the static pull-out failure load, the failure was essentially a slipping type failure as for the pure static failures. In summary, the first mode of failure was not an ideal fatigue type failure and occurred after a limited number of cycles. There was a rapid reduction in cyclic pull-out strength in all cases because of this type of failure mode.



(a) Failure due to slipping (b) Failure due to fatigue cracking

Figure 8. Typical Cyclic Pull-out Failure Modes

When the cyclic load was less than 40% of the static pull-out failure load, radial cracks appeared around the fastener holes for all grades and thicknesses of steel. These cracks started from the edge of the hole and propagated in all directions. This was due to the repeated deformation that occurs in the vicinity of fastener holes where high stress concentrations were present. Once these cracks propagated sufficiently to let the screw shaft pull-out, the failure occurred suddenly. The above observations were the same irrespective of the steel grade and thickness or the screw type or gauge. Figure 8 (b) shows the typical failure mode observed in this case.

The two contrasting segments of Figures 7(a) to (d) confirm the above discussions about the two types of failure. From these figures, the following observations can also be made.

- Type 17 screw fasteners appeared to give a better cyclic performance for thinner steels. But for thicker steels, no significant difference was observed when different types and sizes of fasteners were used.
- No.10-16 and 14-20 HiTeks screw fasteners appeared to lower the cyclic performance of thinner steels as the combination of smaller pitch and thinner steels did not provide a good resistance against pull-out failures.
- The cyclic performance of steel battens was similar when No.14-10 HiTeks screw fasteners were used, however, there were some differences between the different steel thicknesses and grades when other fasteners were used.
- The results from all the connections between the steel battens and screw fasteners considered in this investigation appear to indicate the presence of a fatigue limit in the range of 25 to 35% of the static pull-out failure load.

In addition to the results presented in Figures 7 (a) to (d), Table 4 also presents some of the results from the cyclic tests. It includes the loads below which the pull-out failure associated with fatigue cracking occurred. These loads indicate that this load is in the range of 40-50% of the static pull-out failure load. Table 4 also includes the level of cyclic load that caused a pull-out failure after a specified number of cycles as obtained from the fatigue curves.

Table 4. Cyclic Test Results

Steel Batten		Screw Fastener		P_{crack}^{*}	Cyclic Load that causes pull-out failure after the following Number of Cycles			
Grade	thickness	Type	Gauge		1000	2500	5000	10000
G550	0.42	Type 17	14-10	x	60	51	40	35
		Hiteks	14-10	x	66	45	31	31
		HiTeks	14-20	x	51	32	29	25
		HiTeks	10-16	x	51	36	30	28
	0.95	Type 17	14-10	x	60	49	42	35
		HiTeks	14-10	x	70	60	50	42
		HiTeks	14-20	40%	61	57	51	44
		HiTeks	10-16	40%	70	56	48	44
G250	0.4	Type 17	14-10	60%	60	50	42	33
		HiTeks	14-10	50%	72	59	46	33
		HiTeks	14-20	50%	70	57	50	46
	1.0	Type 17	14-10	40%	73	58	48	42
		HiTeks	14-10	40%	54	46	41	39
		HiTeks	14-20	40%	56	52	49	43
		HiTeks	10-16	40%	70	60	45	39

* - The amplitude of cyclic load below which fatigue cracks appeared.
x – not available

The design for hurricane wind loading conditions in Australia requires that the steel roof cladding systems pass a three-level low-high fatigue test sequence (SA, 1989). The three-level low-high fatigue test sequence includes the following loading: 8,000 cycles at 0.4 x ultimate design load (F_u), 2,000 cycles at 0.5 F_u and 200 cycles at 0.6 F_u. However, the design for the Northern Territory in Australia requires a more severe loading sequence made of 10,000 cycles at 0.67 F_u. These fatigue test sequences are considered to simulate hurricane wind load conditions on roofing systems. The results given in Table 4 can therefore be used by designers to determine the design pull-out failure load for hurricane wind loading conditions depending on the screw fastener and steel batten used. For multi-level fatigue test sequences, the use of an appropriate fatigue damage rule such as Miner's law is required to estimate the design pull-out failure load for hurricane wind conditions.

5. Design Method

Although the results in Section 4 can be used directly by designers of roof cladding systems, it is important that a simpler design method is developed to take into account the significant reduction to the pull-out strength caused by cyclic wind loading. For this purpose, all the cyclic test results obtained from this investigation were plotted in the same figure (Figure 9), and simple design equations (Equation 4) shown next were obtained as an approximate lower bound. These equations give the necessary reduction factor R (cyclic pull-out strength to static pull-out strength) as a function of the number of cycles to failure N_f.

$$\text{For } N_f \leq 2000, \quad R = 1 - 0.70\,(N_f/2000) \qquad (4a)$$
$$\text{For } N_f > 2000, \quad R = 0.30 \qquad (4b)$$

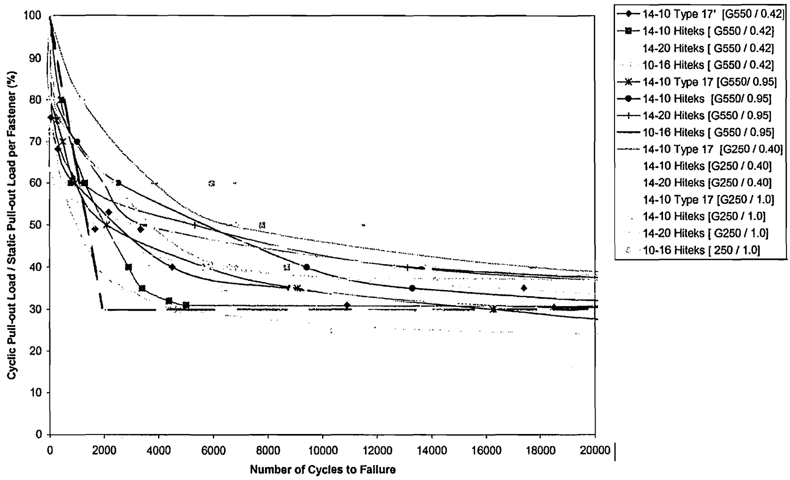


Figure 9. Fatigue Curves

Equation 4b is conservative for almost all cases whereas Equation 4a may be unconservative in some cases. However, the combination of these two equations is expected to provide conservative results for all types of connections. It is recommended that No.10-16 and No.14-20 screw fasteners are not used with thinner steels (0.40 and 0.42 mm), in which case, the applicability of recommended equations will not be limited.

The simple design equations recommended above can be used to allow for the reduction in pull-out strength due to fluctuating wind loading conditions. If the appropriate wind loading spectrum is known for the design wind event, they can be used in combination with the loading spectrum to determine the design pull-out load. A fatigue damage law such as Miner's law is required in these calculations for a wind loading spectrum with more than one load level. This approach may be considered too conservative as the simple design equations 4(a) and (b) are based on an approximate lower bound to all the test results. However, this can be improved by developing similar equations, but which are specific for a given combination of steel and fastener types based on its fatigue curves such as those shown in Figures 7 (a) to (d). The results given in Table 4 can also be used instead of the fatigue curves.

It is not known whether the use of Miner's law based on a linear damage model is adequate to determine the total fatigue damage caused by a wind loading spectrum. Therefore further fatigue tests are currently under way to determine this and to develop appropriate modifications if required.

Alternatively, a simpler, but more conservative design approach based on the observed fatigue limit can be used. Since this investigation indicated the presence of a fatigue limit of about 25 to 35% of the static pull-out failure load, it is recommended that a reduction factor of 0.3 can be used in the design of steel cladding systems to allow for the effects of wind loading fluctuations on pull-out strength.

6. Conclusions

An experimental investigation involving a large number of cyclic tests has been conducted on connections between steel battens made of different thicknesses and steel grades, and screw fasteners with varying diameter and pitch. The results have been used to quantify the effects of cyclic wind uplift loading on the pull-out strength of steel cladding systems and to develop simple design equations. This paper has presented the details of the investigations and the results.

7. References

American Iron and Steel Institute (AISI) (1996) Specification for the Design of Cold-formed Steel Structural Members, Washington, D.C.

Baskaran, A. and Dutt, Om. (1997) Performance of Roof Fasteners under Simulated Loading Condition, Journal of Wind Engineering, 72(3): 389-400.

Beck, V.R. and Stevens, L.K. (1979) Wind Loading Failures of Corrugated Roof Cladding, Civil Eng. Trans., IEAust; 21(1): 45-56.

Eurocode 3, (1992) Design of Steel Structures, Part 1.3 – Cold-formed Thin-gauge Members and Sheeting, Commission of European Communities, Brussels, Belgium.

Macindoe, L., Adams, J., and Phalm, L. (1995). Performance of Single Point Fasteners. Report to the CRC for Materials, Welding and Joining, CSIRO Div. of Building., Construction and Engineering., Melbourne, Australia.

Mahendran, M. (1990a) Fatigue Behaviour of Corrugated Roofing under Cyclic Wind Loading, Civil Eng Trans., IEAust; 32(4): 219-226.

Mahendran, M. (1990b) Static Behaviour of Corrugated Roofing under Simulated Wind Loading, Civil Eng Trans., IEAust; 32(4): 211-218.

Mahendran, M. (1994) Behaviour and Design of Crest-fixed Profiled Steel Roof Claddings Under High Wind Forces, Eng Struct; 16(5): 368-376.

Mahendran, M. and Tang, R.B. (1998) Pull-through Strength of High Tensile Steel Cladding Systems. Australian Journal of Struct. Eng; 2(1): 37-49.

Pekoz, T. (1990) Design of Cold-formed Steel Screw Connections, Proc. 10th Int. Speciality Conf. on Cold-formed Steel Structures, St. Louis, 576-587.

Standards Australia (SA) (1992) AS1562 Design and Installation of Sheet Roof and Wall Cladding, Part 1: Metal Standards, Sydney.

Standards Australia (SA)(1989) AS 1170. Loading Code Part 2: Wind Loads, Sydney.

Standards Australia (SA)(1996) AS 4600 Cold-formed Steel Structures Code, Sydney.

Tang, R.B. (1998) Local Failures of Steel Cladding Systems under Wind Uplift, ME Thesis, Queensland University of Technology, Brisbane, Australia.

Toma, A., Sedlacek, G. and Weynand, K. (1993) Connections in Cold-formed Steel, Thin-walled Structures, 16: 219-237.

Xu, Y.L. and Reardon, G.F. (1993) Test of Screw Fastened Profiled Roofing Sheets Subject to Simulated Wind Uplift. Eng. Struct; 15(6): 423-430.