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Pull-through Capacity Design Rules for Steel Roof Battens under Wind Uplift Load

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Abstract

Steel buildings constructed using thin and high strength cold-formed steel roof sheeting and battens often suffer from roof failures during severe wind events such as storms, tornadoes and cyclones. Premature roof connection failures have been identified as the main reason for such roof failures. Among them, the screw connection between roof batten and truss or rafter suffers from a localised pull-through failure that can lead to the removal of the entire roof structure by high wind events. Therefore suitable design rules are urgently needed to ensure the structural safety of these roof batten screw fastener connections under high wind uplift loads. This paper presents the details of suitable design rules developed based on a detailed experimental study of roof battens subject to static wind uplift loads.

Introduction

Steel roof structures constructed using thin (0.42 to 1.20 mm) and high strength (G550 and G500) cold-formed steel roof sheeting and battens (Figure 1) often suffer from severe roof failures during high wind events such as tropical cyclones, tornadoes and thunderstorms. These roof failures have occurred primarily due to the premature failures of roof connections.

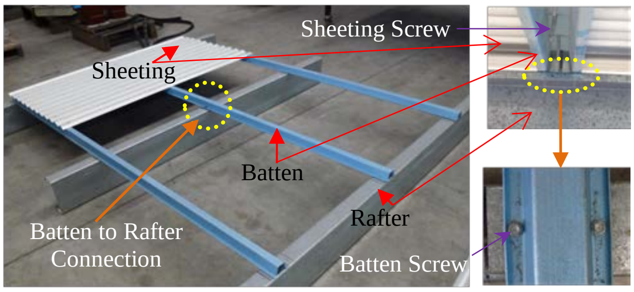


Figure 1. Light Gauge Steel Roofing System and Roof Batten to Rafter or Truss Connection

In the past, roof connection failures have often been observed at their screw connections between roof sheeting and battens. The screw fastener head pulled through the thin roof sheeting (pull-through failure) in many instances whilst the screw fastener also pulled out from the thin batten (pull-out failure) in other cases. Past research investigations carried out on these roof sheeting screw fastener connection failures (Mahendran 1990a,b, 1994, 1995, 1997; Xu and Reardon, 1993; Xu, 1995; Mahendran and Tang, 1998; Mahendran and Mahaarachchi, 2002 and Mahaarachchi and Mahendran, 2004, 2009) have contributed to the understanding of these localised connection failures and the development of suitable design capacity equations. In addition, the use of cyclone washers with screw fasteners has also improved the situation. Recent wind storm events appear to show that the safety of roof sheeting connections has significantly improved in the new buildings. However roof failures have continued to occur as shown by some of the recent wind events (Boughton and Falck, 2007, 2008). The screw connections between roof battens and the truss or rafter (Figure 1) are now the critical failure locations during high wind uplift loading situations. They fail mostly in the form of localised pull-through failures in which the screw fastener head pulls through the batten bottom flange as shown Figure 2.

Figure 2. Pull-through Failures of Roof Battens

The roof batten pull-through failure mode associated with a tearing fracture of the bottom flange of battens seems to be more specific and differs from the previously investigated pull-through failure of roof sheeting. Since there are no suitable design rules available at present to determine the roof batten pull-through capacity satisfactorily, the need to develop suitable design rules has become quite important. Therefore a detailed experimental study of roof battens was conducted under static wind uplift loading to derive suitable design rules that can be used to determine the critical steel roof batten pull-through capacities.

Experimental Study

The experimental study was undertaken using both full scale air-box tests and small scale tests. As there was an inevitable need to conduct a large number of tests in relation to many critical parameters such as roof batten thickness and geometry, steel grade, screw fastener types and sizes, and screw tightening, the difficulties related to investigating all of these parameters using full scale air-box tests were realised. As a solution to this problem, suitable small scale test methods were proposed. However, their abilities in accurately simulating the roof batten pull-through failures had to be ensured by evaluating the pull-through failure loads and modes obtained from these different types of tests. As the first step, a detailed roof batten test series was undertaken using commercially available steel roof battens in order to establish suitable small test methods that can be used to conduct a large number of roof batten tests required in this research.

Preliminary Roof Batten Tests

The steel roof battens are mostly used as multi-span systems, spanning between trusses or rafters. As it is very difficult to test multi-span roof panels in the laboratory, testing of two-span roof panels is considered adequate for research purposes. Since full-scale tests simulate more realistic roofing system behaviour under wind uplift forces, some full-scale tests were first undertaken using the air-box testing facility at the Queensland University of Technology (QUT). A two-span roof panel was fabricated using Topspan 4055 battens (thickness of 0.55 mm, height of 40 mm and flat bottom flange width of 11 mm) (Lysaght, 2012), 0.48 mm corrugated roof sheeting and 'C' section purlins (Figure 1). The roof panel was placed on top of the air-box and upside down in order to safely apply a suction air pressure on the roof sheeting. A suction air pump was then used to simulate the required uniform suction pressure on the roof panel. The suction pressure was slowly increased until a roof batten pull-through failure occurred at the critical roof batten to purlin connection, ie. at the central support as shown in Figure 1.

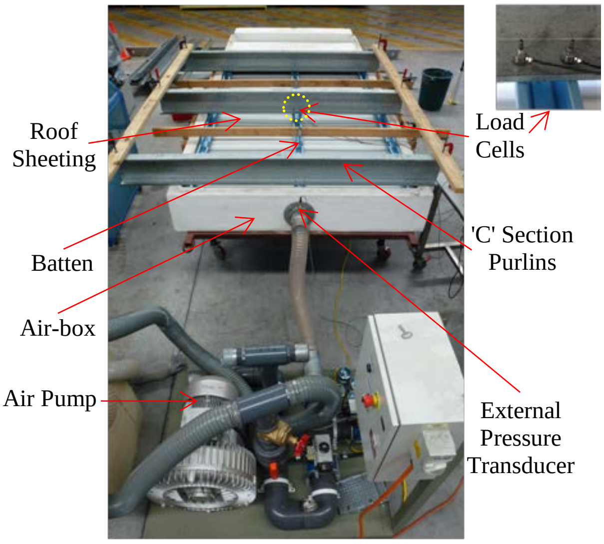


Figure 3. Full Scale Air-box Tests

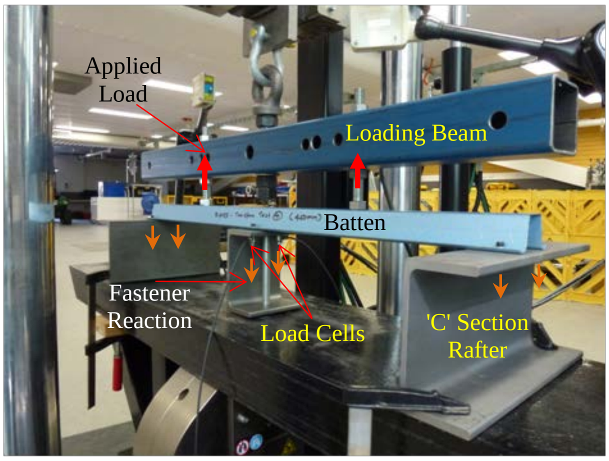


Figure 4. Two-span Batten Tests

The batten pull-through failure mode observed during the full scale test is shown in Figure 2 in which the screw fastener head had pulled through the thin bottom flanges of roof batten. This batten pull-though failure was initiated at the edge of the screw fastener head closest to the batten web and then it moved in either direction as shown in Figure 2. The suction pressure inside the air-box was measured using an external air pressure transducer while the roof batten pull-through failure load was estimated by multiplying the suction pressure at failure by the batten to purlin tributary area (batten span × batten spacing). This estimation method was validated by measuring the screw fastener reactions directly in the other full scale air-box test using small load cells as shown in Figure 3.

Since the full scale air-box test investigations identified that the roof batten pull-through failure is more localised to the screw fastener vicinity, three different types of small scale tests such as two-span batten tests (Figure 4), cantilever batten tests (Figure 5) and short batten tests (Figure 6) were proposed as alternative test methods. However, there is a need to establish whether they can accurately simulate the observed pull-through failures of roof battens. In the two-span tests, test roof battens were loaded at two mid-span points as shown in Figure 4. The loads in the screw fasteners at the critical central support where pull-through failure occurred were directly measured using small load cells.

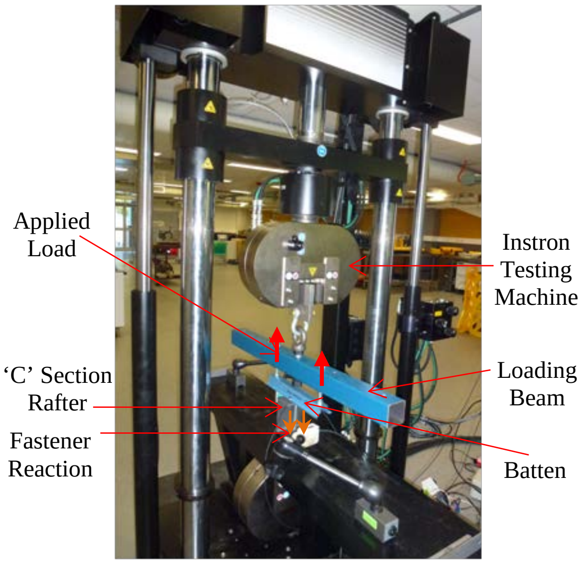


Figure 5. Cantilever Batten Tests

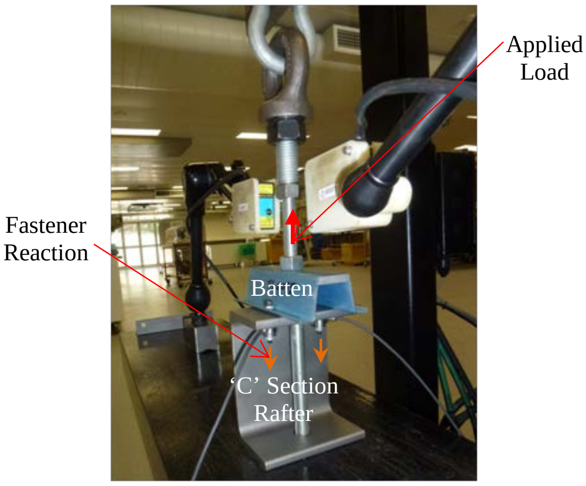


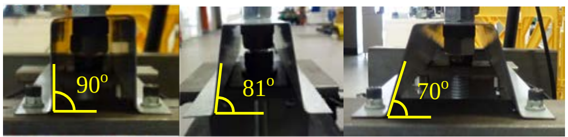
Figure 6. Short Batten Tests

A special fastener arrangement made of an Unbrako bolt with an actual screw fastener head as a washer and a small load cell was used in the small scale tests in which the fastener loads were accurately measured individually (Sivapathasundaram and Mahendran, 2014). Since the roof batten pull-through failure occurs under the actions of a screw fastener tensile load and a bending moment in the batten cross section, a second small scale test method based on a cantilever system (Figure 5) was considered in this research. Also since there were no significant differences observed between the two-span test results obtained for two different span values of 450 and 300 mm, a short batten test method shown in Figure 6 was also proposed and used in which the bending moment in the battens was not simulated. Comparison of pull-through failure loads from all the small scale tests and full scale air-box test showed that small scale test methods proposed in this research can be used to determine the pull-through failure load of roof battens. The observed pull-through failure mode was also identical. The accuracy of these tests was also verified using the cantilever batten and short batten tests conducted with actual screw fasteners that were installed using a torque adjustable Makita FS 2700 electric screw driver. Suitable estimation methods to determine the pull-through failure loads of roof battens from these small scale tests conducted with and without Individual Fastener Load Measurements and their details are presented in Sivapathasundaram and Mahendran (2014), which recommends the use of short batten test method with additional two-span batten tests for further confirmation.

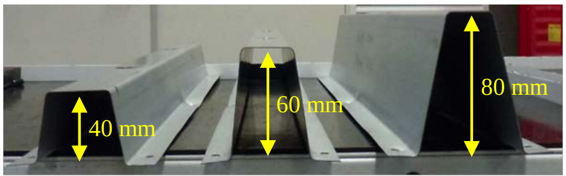
Main Roof Batten Tests

The success of using small scale test methods to simulate roof batten pull-through failures accurately have enabled us to conduct a large number of main roof batten tests in investigating the roof batten pull-through failure in relation to many critical parameters such as screw fastener tightening, roof batten height, web angle, steel grade, thickness, screw fastener head size and roof batten bottom flange width. The main roof batten tests were conducted in two phases to minimise the number of tests.

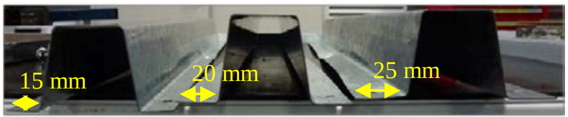
Phase 1 main tests were conducted for the parameters such as screw fastener tightening, roof batten height and web angle. Since their effects were not significant in relation to roof batten pull-through failure behaviour, some default values were assigned for them, which were used during Phase 2 main tests. Phase 2 main tests were undertaken to investigate the effects of the critical parameters such as steel grade, thickness, screw fastener head size and bottom flange width. Since the commercially available roof battens cannot be used for specific testing purposes, suitable steel batten specimens were fabricated at the QUT workshop as shown in Figure 7. Two different screw fastener tightening values (in terms of pretension values of 0.1 and 1.0 kN), three different batten heights (40, 60 and 80 mm) and three different batten web angles (70°, 81° and 90°) were considered in Phase 1 main tests. Thirty-six different batten configurations were used in Phase 2 main tests by combining two different steel grades (G550 and G300), three different steel thicknesses (0.55, 0.75/0.80, 0.95/1.00 mm), two different screw fastener head sizes (10g and 12g) and three different batten bottom flange widths (15, 20 and 25 mm). The test results obtained from the main test series and the estimation methods used to obtain them are presented in Sivapathasundaram and Mahendran (2014).



Web Angle (90°, 81°, 70°)



Height (40 mm, 60 mm, 80 mm)



Bottom Flange Width (15 mm, 20 mm, 25 mm)

Figure 7. Main Roof Batten Test Specimens (Sivapathasundaram and Mahendran, 2014)

Development of Suitable Design Rules

The pull-through capacities obtained from the experimental study were used for this purpose. Since the effects due to the critical parameters such as steel grade, thickness, screw head size and batten bottom flange width were identified as significant, they were considered in the development of suitable design rules. In addition to these four parameters, the elastic modulus of steel was also included in order to obtain appropriate dimensionless formulae. The basic dimensionless formula was obtained by dividing the pull-through failure load of roof batten by the product of steel thickness, screw fastener head diameter and ultimate tensile strength of steel. Two graphs were then plotted using the values obtained from this basic dimensionless formula against the values obtained from another two appropriate dimensionless formulae that relate the other two critical parameters (batten bottom flange width and elastic modulus of steel). These two suitable dimensionless formulae were identified using the curve fitting technique by joining some more critical parameters with them, in order to achieve lines of best fits.

The following design rules were derived by solving the mathematical relationships obtained from the graphs, and are proposed in this research to determine the pull-through capacity of roof battens under static wind uplift loading. Since the test results showed that high grade (G550) and low grade (G300) steels behave differently in relation to batten pull-through failures (Sivapathasundaram and Mahendran, 2014), the design rules were developed separately. The accuracy of these design equations in predicting the batten pull-through capacities was established by comparing its predictions with test results in Tables 1 and 2 for G550 and G300 steel battens, respectively.

Pull-through capacity of High grade (G550) steel roof battens:

$$F_{ov} = (360 \times t^{2.1} \times f_u^{1.6}) / (b^{0.05} \times d^{0.05} \times E^{0.6}) \qquad (1)$$

Pull-through capacity of low grade (G300) steel roof battens:

$$F_{ov} = (5.5 \times t^{1.4} \times d^{0.7} \times f_u^{1.1}) / (b^{0.1} \times E^{0.1}) \qquad (2)$$

where F_{ov} – pull-through capacity, t - roof batten thickness, d - screw fastener head diameter, f_u - ultimate tensile strength of steel, b - bottom flange width and E - elastic modulus of steel.

Roof Batten Configuration (t × b × screw size)	F_{ov} from G550 Batten Tests	F_{ov} from Equation (1)	Ratio of Test to Predicted
0.55 × 15 × 10g	2.07	1.84	1.13
0.55 × 15 × 12g	2.08	1.81	1.15
0.55 × 20 × 10g	1.88	1.81	1.04
0.55 × 20 × 12g	1.82	1.78	1.02
0.55 × 25 × 10g	1.73	1.79	0.96
0.55 × 25 × 12g	1.62	1.76	0.92
0.75 × 15 × 10g	3.56	3.34	1.07
0.75 × 15 × 12g	3.46	3.29	1.05
0.75 × 20 × 10g	3.38	3.29	1.03
0.75 × 20 × 12g	3.19	3.24	0.98
0.75 × 25 × 10g	3.38	3.26	1.04
0.75 × 25 × 12g	3.12	3.21	0.97
0.95 × 15 × 10g	4.60	4.56	1.01
0.95 × 15 × 12g	4.32	4.49	0.96
0.95 × 20 × 10g	4.88	4.49	1.08
0.95 × 20 × 12g	4.07	4.43	0.92
0.95 × 25 × 10g	4.58	4.45	1.03
0.95 × 25 × 12g	4.34	4.38	0.99

Table 1. Comparison of predicted pull-through failure loads with test results for G550 steel roof battens

Roof Batten Configuration (t × b × screw size)	F_{ov} from G300 Batten Tests	F_{ov} from Equation (2)	Ratio of Test to Predicted
0.55 × 15 × 10g	2.18	1.98	1.10
0.55 × 15 × 12g	2.66	2.46	1.08
0.55 × 20 × 10g	2.10	1.93	1.09
0.55 × 20 × 12g	2.61	2.39	1.09
0.55 × 25 × 10g	1.87	1.88	0.99
0.55 × 25 × 12g	2.36	2.34	1.01
0.80 × 15 × 10g	3.70	3.34	1.11
0.80 × 15 × 12g	4.19	4.15	1.01
0.80 × 20 × 10g	3.48	3.25	1.07
0.80 × 20 × 12g	4.24	4.03	1.05
0.80 × 25 × 10g	3.14	3.17	0.99
0.80 × 25 × 12g	4.03	3.94	1.02
1.00 × 15 × 10g	4.55	4.34	1.05
1.00 × 15 × 12g	5.45	5.39	1.01
1.00 × 20 × 10g	4.39	4.22	1.04
1.00 × 20 × 12g	5.49	5.24	1.05
1.00 × 25 × 10g	4.48	4.12	1.09
1.00 × 25 × 12g	5.16	5.12	1.01

Table 2. Comparison of predicted pull-through failure loads with test results for G300 steel roof battens

The pull-through failure loads estimated using Equation (1) for high grade (G550) steel roof battens provide error margins of -13 to +9% whilst the pull-through failure loads estimated using Equation (2) for low grade (G300) steel roof battens provide error margins of -10 to +1 %. It should be noted that these variations were observed for a few tests only and the predicted pull-through failure loads compared well with test failure loads in most cases. This is acceptable considering the allowable experimental variation of ± 15 % in AISI (2013).

Conclusions

This paper has presented the details of suitable design rules developed to determine the pull-through capacity of steel roof battens under static wind uplift loads. Since high grade (G550) and low grade (G300) steel batten tests showed different pull-through failure behaviour, the design rules were developed separately. The design rules were developed in terms of the important critical parameters that highly influenced the roof batten pull-through failure. The accuracy of the developed design rules was verified by comparing their predictions with the experimental pull-through failure loads. A good agreement shows that the developed design rules can be used in the design of roof battens subject to pull-through failures under wind uplift loads.

Acknowledgments

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