Design of Thin Steel Roof Battens Subject to Pull-through Failures

Mayooran Sivapathasundaram
Department of Civil Engineering
University of Jaffna
Sri Lanka
mayoo@eng.jfn.ac.lk

Mahen Mahendran
School of Civil and Environmental Engineering
Queensland University of Technology
Australia
m.mahendran@qut.edu.au

***Abstract* –The use of thin steel roof battens for roof structures has been increased notably around the world. However, the occurrences of more intense and frequent storms due to climate changes have been a major cause of significant roof failures. Recent wind damage studies have highlighted that such severe roof failures occur predominantly in the form of localized pull-through failures of thin steel roof battens. Although recent research studies have developed suitable design methods, they have not considered very thin steel roof battens (<0.5 mm). Hence this research is aimed to assess the suitability of current design equations for the design of very thin steel roof battens subject to pull-through failures. A series of pull-through failure tests of roof battens was conducted for this purpose under simulated static wind uplift load and this paper presents the details and results from this study.**

Keywords – Thin steel roof batten, high wind uplift load, pull-through failure, design equation

I. INTRODUCTION

The use of thin steel roof battens (0.42 – 1.2 mm thicknesses and G550 – G500 grades) for roof structures has been increased notably around the world due to many benefits such as lightweight, high strength and low cost (Fig. 1). The bottom flanges of the top hat shaped roof batten is fastened to the roof purlin below using screw fasteners and, its top flange is connected to the roof cladding using a screw fastener. However, the occurrences of more intense and frequent storms due to climate changes have been a major cause of significant roof failures. Recent wind damage studies [1, 2] have highlighted that such severe roof failures occur predominantly in the form of localized pull-through failures of thin steel roof battens. In the pull-through failures, the screw fastener heads pull through the bottom flanges of thin steel roof battens (Fig. 2). Although recent research studies [3-8] have developed suitable design methods, they have not considered the very thin steel roof battens (<0.5 mm), for example, 0.42 and 0.48 mm thick G550 steel battens. Since the ductility of these very thin steels is notably lower than the thick G550 steels, it is vital to examine the behaviour of pull-through failures. Hence this research is aimed to assess the suitability of current design equations for the design of very thin steel roof battens subject to pull-through failures. A series of pull-through failure tests of roof battens was conducted for this purpose under simulated static wind uplift load and, this paper presents the details and results from this study.

II. REVIEW OF CURRENT DESIGN EQUATIONS

The current cold-formed steel design standards such as AS/NZS 4600: 2018 [9] and AISI S100: 2016 [10] present the same design equation (Eq. (1)) to determine the pull-through failure load (P_{nov}) of roof battens while Eurocode 3 Part 1-3: 2006 [11] presents a slightly different design equation (Eq. (2)). However, both Eqs. (1) and (2) exclude very thin steel thicknesses of 0.42 and 0.48 mm.

$$P_{nov} = 1.5\ t\ d\ f_u \qquad (1)$$

where t – thickness of sheet in contact with screw head, d – the screw head diameter as washers are not used with roof battens ($d \leqslant 20$ mm) and f_u – the tensile strength of the sheet in contact with the screw head in MPa.

$$P_{nov} = t\ d\ f_u \qquad (2)$$

where t – thickness of the thinner connected part or sheet ($0.5 \leqslant t \leqslant 1.5$ mm), d – as defined for Eq. (1) and f_u – ultimate tensile strength of the thinnest sheet next to the screw head ($f_u \leqslant 550$ MPa).

Since the pull-through failure modes of thin steel roof battens associated with a tearing fracture (Fig. 2) differ significantly from the pull-through failure modes of roof cladding associated with a splitting fracture, new pull-through capacity equations (Eqs. (3) and (4)) were developed recently [3-8]. AS/NZS 4600 [9] has now included them for the determination of the pull-through failure load of thin steel roof battens.

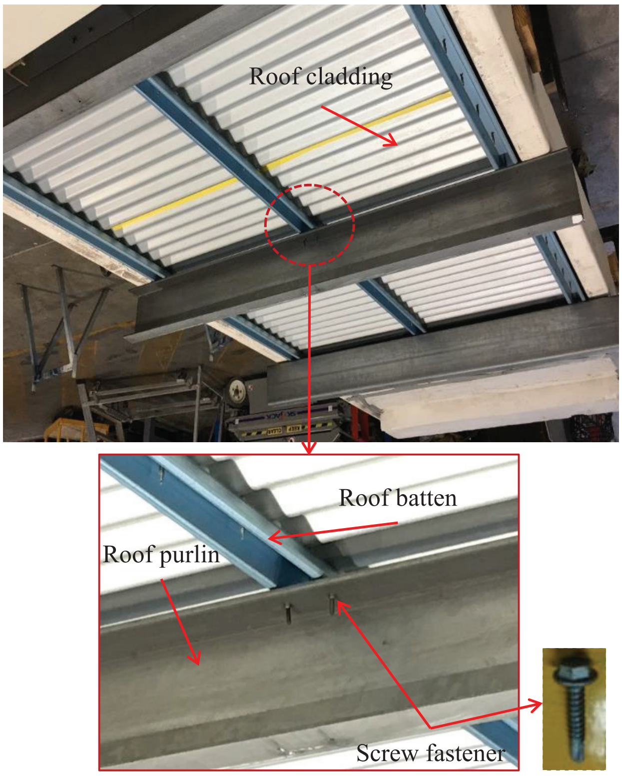


Fig. 1. Typical Thin Steel Roof Structure

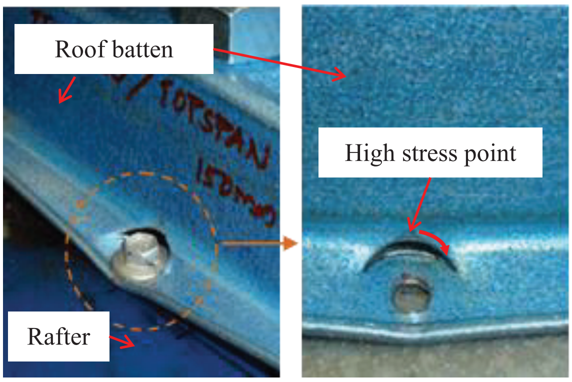


Fig. 2. Pull-through Failures of Steel Roof Batten

High strength steel roof battens (G500 and G550):

$$P_{nov} = 8.68\ t^2\ f_u \quad (3)$$

Low strength steel roof battens (G300):

$$P_{nov} = 3.07\ t^{1.4}\ d^{0.6}\ f_u \quad (4)$$

Recent research studies [3-8] considered most of the commonly used roof battens around the world, made of both high and low strength steels (G550/G500 0.55 to 1.15 mm and G300 0.55 to 1.0 mm) and a range of screw fasteners (10g to 14g). They investigated the effects of many critical parameters such as screw fastener tightening, roof batten geometry, roof batten thickness, steel grade, screw fastener head size and screw fastener location on the pull-through failure load. However, Eqs. (3) and (4) developed by them did not consider the thinner steel roof battens (G550 0.42 and 0.48 mm roof battens). G550 0.48 mm roof battens are recommended for use as either roof battens or ceiling battens. Although G550 0.42 mm roof battens are recommended predominantly for use as ceiling battens, they can also be used as roof battens. Since the pull-through failures are more critical in these very thin steel battens, the applicability of the new design equations was evaluated in this study. Since the level of ductility is highly reduced in thinner high strength steels, it was deemed important to determine whether such a loss in ductility affects the pull-through failure loads and modes notably. In order to investigate the above shortcomings in the currently available pull-through capacity equations [9], a series of static pull-through tests was conducted.

III. EXPERIMENTAL STUDY

Since recent research studies [3-8] have shown that small-scale tests can be satisfactorily used instead of expensive and time consuming full-scale air-box tests, 150 mm short batten tests and 300 mm span two-span batten tests were conducted in this study. Fig. 3 shows the two-span test set-up and the critical central support reactions, i.e. pull-through failure loads (per screw) were measured individually using small washer load cells. Fig. 4 shows the test set-up used in the short batten tests, in which, the pull-through failure load per screw was determined from the applied total load (Instron machine load). G550 0.42 and 0.48 mm roof battens (minimum yield strength of 550 MPa) of depths ranging from 22 to 40 mm and 10g screws (screw head diameter of 11 mm) were used in these tests. All the tests were conducted using an Instron testing machine under displacement control (1 mm/min). A minimum of three tests was conducted in each case based on AISI S905 [12]. Details of these short and two-span tests are available in [3-8].

IV. TEST RESULTS AND DISCUSSION

Fig. 5 shows the pull-through failure modes of thin steel roof battens. The bottom flange was found to tear around the edge of the screw head. The pull-through failure initiated at the hot stress point and continued to tear around the screw head edge as shown in Fig. 2. Both two-span and short batten tests showed similar pull-through failure modes. Past research studies also showed similar failure modes for roof battens of thicknesses in the range

ISBN: 978-624-6150-05-1

of 0.55 to 1.15 mm [3-8]. This highlights that the pull-through failure behaviour of roof battens has not changed for very thin steel roof battens with 0.42 and 0.48 mm thicknesses. Hence the applicability of pull-through capacity design equations developed for roof battens (Eqs. (3) and (4)) was assessed using the test results obtained in this study.

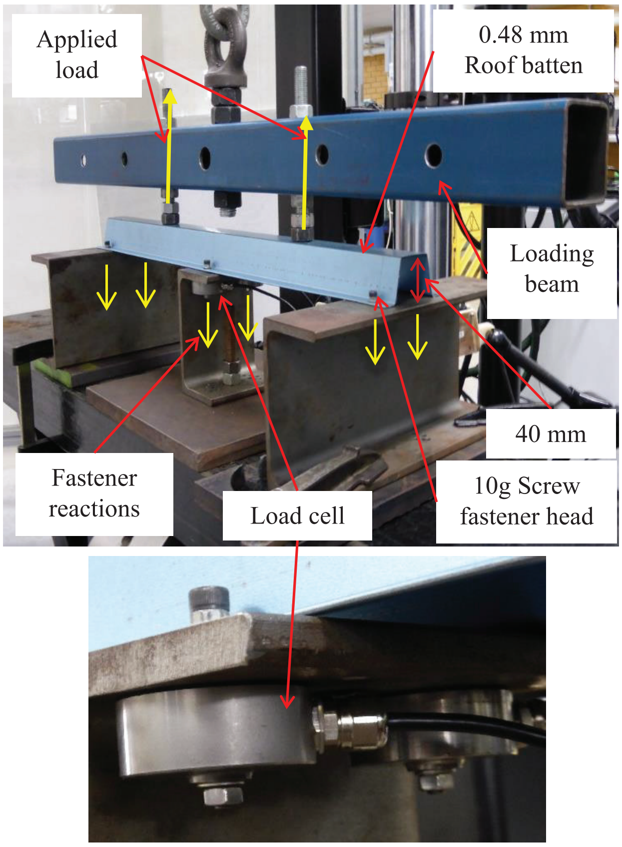


Fig. 3. Two-span Roof Batten Test Set-up

Figs. 6 and 7 show the typical applied load versus displacement curves obtained from the two-span and short roof batten tests. Table I presents the pull-through failure loads from the G550 0.42 mm two-span and short batten tests. The mean pull-through failure loads of 1270.2 N and 1281.3 N from the two-span tests and short batten tests agree well and their failure modes were identical. Hence the overall average pull-through failure load of 1275.7 N was used in the comparisons. Table I also presents the pull-through failure loads from the G550 0.48 mm two-span and short batten tests. The comparison made between the two mean pull-through failure loads (1586.8 and 1752.6 N) shows a difference of 10.5%, possibly due to unexpected experimental variations (eccentric loading and uneven load sharing between the screws). Therefore, the overall average pull-through failure load of 1669.7 N was used in the comparisons. With reduced batten thickness, the pull-through failure loads have also been reduced, but the main question is whether the pull-through capacity equations can predict the failure loads of these very thin roof battens.

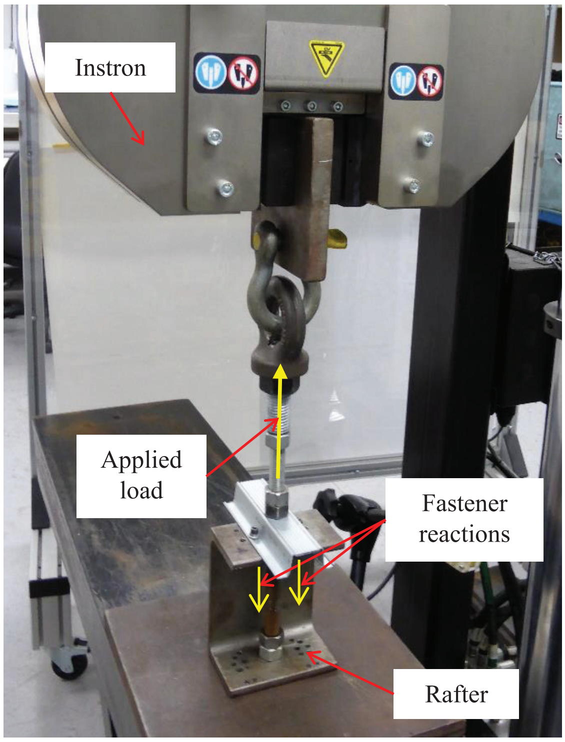
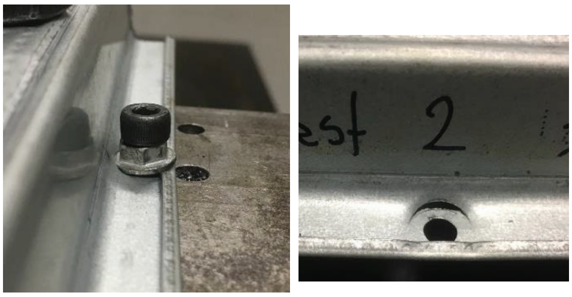


Fig. 4. Short Batten Test Set-up

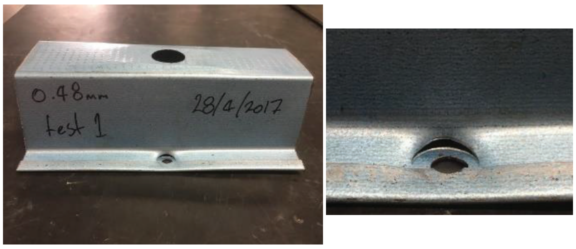
For this purpose, the test pull-through failure loads were first compared with the pull-through capacities calculated using the currently available design equations (Eqs. (1) to (3)). Table II presents these comparisons, where most of the cases show significant levels of overestimations (ratios of 0.45 and 0.51) by Eqs. (1) and (2) given in AISI S100 [10] and Eurocode 3 Part 1-3 [11]. However, the recently developed Eq. (3) predicts a capacity closer to the mean test pull-through failure load of G550 0.42 mm roof batten (only 8% difference and also conservative). Despite the difference of 8% for the overall average pull-through failure load, the lowest pull-through failure loads obtained from the tests (1161.2, 1193.7 and 1179.8 N) only show small differences (<1.2%). Therefore, Eq. (3) can be used to accurately determine the pull-through failure loads of G550 0.42 mm roof battens. The comparison in Table II also shows that the average test pull-through failure load of G550 0.48 mm roof batten is 11% higher than the predicted pull-through capacity. However, the minimum test pull-through failure load of 1485.7 N shows only a difference of

ISBN: 978-624-6150-05-1

1.6%. In addition, all these differences are on the safe side. Therefore, considering the possible experimental variations observed in the pull-through failure tests of roof battens, it is concluded that Eq. (3) developed for high strength steel roof battens can be used to accurately determine the pull-through capacities of very thin G550 0.42 and 0.48 mm roof battens. This also confirms that the reduced ductility in G550 0.42 and 0.48 mm steels has not affected the static pull-through failure behaviour in comparison with other higher strength steel roof battens (G550/G500 0.55-1.15 mm) reported in previous studies [3-8].



(a)



(b)

Fig. 5. Pull-through Failure Modes of (a) 0.42 mm Batten and (b) 0.48 mm Batten

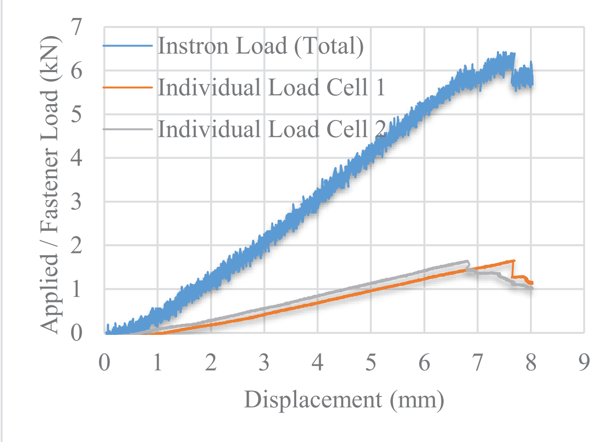


Fig. 6. Applied/Fastener Load versus Displacement Curves from Two-span Batten Tests Conducted using 0.48 mm Roof Battens and 10g Screw Connections.

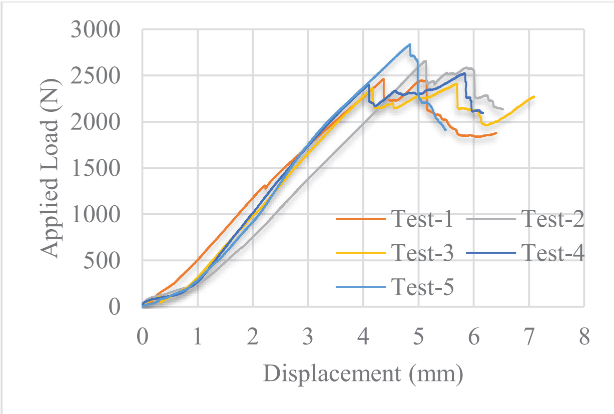


Fig. 7. Applied Load versus Displacement Curves from Short Batten Tests Undertaken using 0.42 mm Roof Battens and 10g Screw Connections.

TABLE I. PULL-THROUGH FAILURE LOADS OBTAINED FROM TWO-SPAN AND SHORT BATTEN TESTS

Batten type	Test Type	Pull-through Failure Load (N)							COV
		Test-1	Test-2	Test-3	Test-4	Test-5	Test-6	Average	
0.42 mm	Two-span	1161.2	1306.9	1342.5	…	…	…	1270.2	0.08
0.42 mm	Short	1231.0	1329.5	1193.7	1233.0	1419.4	…	1281.3	0.07
0.48 mm	Two-span	1485.7	1625.8	1648.9	…	…	…	1586.8	0.06
0.48 mm	Short	1631.7	1790.5	1658.6	1851.6	1830.5		1752.6	0.06

ISBN: 978-624-6150-05-1

TABLE II. COMPARISON OF PULL-THROUGH FAILURE LOADS OF 0.42 AND 0.48 MM BATTENS WITH EQS. (1) TO (3).

t (mm)	d (mm)	f_u (MPa)	0.75 f_u (MPa)	Measured f_u (MPa)	P_u (N)	P_u/ Eq. 1	P_u/ Eq. 1*	P_u/ Eq. 2	P_u/ Eq. 3
0.42	11	550	412.5	770.5	1275.7	0.33	0.45	0.50	1.08
0.48	11	550	412.5	755.3	1669.7	0.38	0.51	0.57	1.11

Note: * - Reduced ultimate tensile strength of 0.75 f_u is used

V. CONCLUSION

This paper has presented the details of an experimental study undertaken to assess the accuracy of the currently available pull-through capacity design equations for very thin roof battens made of G550 0.42 and 0.48 mm steels. The inadequacy of the design equations in some of the current cold-formed steel standards was first demonstrated. The comparisons of pull-through failure capacities showed that the pull-through capacity design equations developed and recommended for the cold-formed steel roof battens in the recent research studies [3-8] and included in AS/NZS 4600 [9] can be used to accurately determine the critical pull-through failure loads of these very thin (<0.5mm) steel battens.

ACKNOWLEDGMENT

The authors would like to appreciate the financial support provided by Australian Research Council (ARC) (DP120103366) and the testing and computing facilities provided by Queensland University of Technology (QUT).

REFERENCES

[1] Boughton, G.N. and Falck, D.J. (2007), “Tropical Cyclone George Damage to Buildings in the Port Hedland Area”, Technical Report 52, Cyclone Testing Station, James Cook University, Townsville, Australia.

[2] Boughton, G.N. and Falck, D.J. (2008), “Shoalwater and Roleystone WA Tornadoes Wind Damage to Buildings”, Technical Report 54, Cyclone Testing Station, James Cook University, Townsville, Australia.

[3] Sivapathasundaram, M. and Mahendran, M. (2016), “Development of Suitable Test Methods for the Screw Connections in Cold-formed Steel Roof Battens”, Journal of Structural Engineering, pp. 04016025-1:13.

[4] Sivapathasundaram, M. and Mahendran, M. (2016), “Experimental Studies of Thin-walled Steel Roof Battens Subject to Pull-through Failures, Engineering Structures”, 113, pp. 388-406.

[5] Sivapathasundaram, M. and Mahendran, M. (2016), “Development of Fragility Curves for Localized Pull-through Failures of Thin Steel Roof Battens”, Engineering Structures, 124, pp. 64-84.

[6] Sivapathasundaram, M. and Mahendran, M. (2016), “Development of Suitable Strengthening Methods for Thin Steel Roof Battens Subject to Pull-through Failures”, ASCE Journal of Architectural Engineering, Vol.24, Issue 2,

[7] Sivapathasundaram, M. and Mahendran, M. (2017), “Numerical Modeling of Thin-walled Steel Roof Battens Subject to Pull-through Failures”, Journal of Structural Engineering, pp. 04017014-1:17.

[8] Sivapathasundaram, M. and Mahendran, M. (2017), “Numerical Studies and Design of Thin Steel Roof Battens Subject to Pull-through Failures”, Engineering Structures, 146, pp. 54-74.

[9] Standards Australia (2018): “AS/NZS 4600, Cold-formed Steel Structures”, Sydney, Australia.

[10] American Iron and Steel Institute (AISI) (2016), “North American Specification for the Design of Cold-formed Steel Structural Members, AISI S100”, Washington, DC, USA.

[11] EN 1993-1-3 (Eurocode 3) (2006), “Design of Steel Structures - Part 1-3, General Rules - Supplementary Rules for Cold-formed Members and Sheeting”, European Committee for Standardization, Brussels, Belgium.

[12] American Iron and Steel Institute (AISI) (2013), “Test Standard for Cold-formed Steel Connections, AISI S905", Washington, DC, USA.