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Development of Suitable Strengthening Methods for Thin Steel Roof Battens Subject to Pull-through Failures

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**ABSTRACT:** Thin-walled steel roof batten to rafter or truss connection failures were increasingly observed in the form of a localised pull-through failure in the batten bottom flanges during recent extreme wind events. Therefore an extensive research study was conducted to investigate this local connection failure and, suitable test and design methods were developed to accurately determine the design pull-through capacities of roof battens. The study also showed that optimising the batten geometry is unlikely to increase the pull-through capacity of batten to rafter or truss connection as it essentially depends on the screw fastener head diameter, batten thickness and steel ultimate tensile strength. Hence the study was extended to develop suitable strengthening methods to delay or prevent this critical localised connection failure and thus enhance the pull-through capacity. This paper first presents the investigations of some current roof construction practices recommended and used by the roof batten manufacturers and builders and, then proposes the details of suitable strengthening methods. Detailed experimental investigations were undertaken for this purpose and, their results and discussions are presented in this paper. In addition, suitable capacity improvement factors are proposed for the strengthening methods to accurately determine the design pull-through capacities of roof batten to rafter or truss connections.

**KEYWORDS:** Cold-formed steel structures, Light gauge steel roofing systems, Steel roof battens, Wind uplift forces, Pull-through failures, Experimental study, Strengthening methods, Design rules

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1. Introduction

Light gauge steel roofing systems made of high strength (G550 and G500) and thin (0.42 to 1.20 mm) steel roof sheeting and battens (Fig. 1) are highly susceptible to premature failures during extreme wind events such as tropical cyclones, tornadoes and thunderstorms. Past wind damage and research investigations showed that roof sheeting to batten connections (Fig. 1) prematurely failed at their screw fastener connections and, caused substantial losses of roof sheeting (Morgan and Beck (1977) and Beck and Stevens (1979)). In most cases, pull-through failures of roof sheeting were observed in which the screw fasteners connecting roof sheeting to battens pulled through the thin steel roof sheeting as shown in Fig. 2. However, many research studies (Xu and Reardon (1993), Mahendran (1994, 1995a, 1997), Jancauskas et al. (1994), Xu (1995), Mahendran and Tang (1998), Mahendran and Mahaarachchi (2002) and Mahaarachchi and Mahendran (2004, 2009)) investigated the pull-through failures of roof sheeting, and developed suitable test and design methods to enhance the safety of these roof connections. In addition, the use of cyclone washers (Fig. 1) was identified as an effective strengthening method to further enhance the safety of roof sheeting to batten connections in extreme wind events (Xu and Reardon (1993) and Mahendran (1995b)).

However, roof failures continued to occur notably as observed during recent extreme wind events. Wind damage investigations (Henderson and Leitch (2005), Henderson et al. (2006) and Boughton and Falck (2007, 2008)) showed that the failure location has now moved to roof batten to rafter or truss connections (Fig. 1) and, hence substantial losses of both roof sheeting and battens were observed. They failed mostly in the form of a localised pull-through failure in which the screw fastener connecting roof battens to rafters or trusses pulled through the bottom flanges of roof batten as shown in Fig. 3. The wind uplift load acting on the batten top flange via roof sheeting to batten screw fastener connections created large stress concentrations in the batten bottom flange at the screw fastener head edge closer to the batten web (Fig. 3). This lead to a tearing failure around the screw fastener head edge in a semicircular shape and a complete disengagement of both roof sheeting and battens. This pull-through failure mode of roof battens significantly differs from the previously researched pull-through failure mode of roof sheeting, which is related to a splitting failure mechanism (Fig. 2). Therefore an extensive research study consisting of both experimental and numerical investigations was undertaken at Queensland University of Technology (QUT), and suitable
test and design methods were proposed to accurately determine the pull-through capacities of roof battens (Sivapathasundaram and Mahendran (2016a,b) and Sivapathasundaram (2016)).

The roof batten tests were first conducted using full scale air-box tests and three different types of small scale tests such as two-span batten tests, cantilever batten tests and short batten tests, and the results showed that small scale tests can be used to accurately simulate the pull-through failures of roof battens (Sivapathasundaram and Mahendran (2016a)). The main experimental study was then conducted using the two-span batten tests and short batten tests (Fig. 4) and, the effects of parameters such as screw fastener tightening, roof batten geometry, batten thickness, steel grade, screw fastener head size and screw fastener location on the pull-through capacity of roof battens were investigated in detail (Sivapathasundaram and Mahendran (2016b)). The pull-through capacity from the short batten tests was determined by dividing the total failure load (Instron machine load) by the number of fasteners (two) whilst the pull-through capacity from the two-span batten tests was determined by accurately measuring the middle support reaction using a small K180 load cell (Fig. 4). The pull-through capacity design rules were first developed using experimental results for high strength (G550 and G500) and low strength (G300) steel roof battens (Sivapathasundaram and Mahendran (2016b)) and, then finally by also combining both experimental and finite element analysis results (Sivapathasundaram (2016)).

This research (Sivapathasundaram and Mahendran (2016a,b) and Sivapathasundaram (2016)) also showed that optimising the batten geometry is unlikely to increase the pull-through capacity of batten to rafter or truss connection as it essentially depends on the screw head diameter, batten thickness and steel ultimate tensile strength. Hence this paper is aimed at developing suitable strengthening methods to delay or prevent this critical localised connection failure and thus enhance the pull-through capacity. This paper first presents the investigations of some current roof construction practices recommended and used by the roof batten manufacturers and builders and, then presents the details of suitable strengthening methods. Experimental investigations were undertaken for this purpose and, the results and discussions of these investigations are presented in this paper. In addition, suitable capacity improvement factors are proposed for the strengthening methods to accurately determine the design pull-through capacities of roof batten to rafter or truss connections.
2. Currently Used Strengthening Methods

Three different strengthening (fastening) methods were first considered in this study to enhance the pull-through capacity of thin steel roof battens. They are: four screw fastener connections, rectangular shaped screw fastener head connections and raised head bolt connections. A series of roof batten tests was conducted to investigate the effects of these strengthening methods on the pull-through capacity of roof battens and, their details are presented next.

2.1 Four Screw Fastener Connection Tests

At present, many roof batten manufacturers recommend using four screw fastener connections (two screw fasteners on each bottom flange side) (Fig. 5) instead of typical two screw fastener connections (one screw fastener on each bottom flange side) (Figs. 1 and 4) to improve the roof batten performance under high wind uplift loads. However, it is not known yet whether this strengthening method can double the pull-through capacities of roof battens as anticipated. Therefore a series of roof batten tests with four screw fastener connections was conducted using the short batten test set-up shown in Fig. 5. These tests were conducted using 150 mm long batten specimens and four screw fastener connections in the batten bottom flanges.

The roof batten tests with four screw fastener connections were first conducted using 10 gauge screw fasteners (screw head diameter of 11 mm) and two types of industrial roof battens made of G550 steel (Topspan 4055 with a base metal thickness (BMT) of 0.55 mm and batten height of 40 mm and Topspan 4075 with a BMT of 0.75 mm and batten height of 40 mm) to investigate the effect of spacing between two screw fasteners on each of the batten bottom flanges (Fig. 5). Screw fastener spacings of 20, 25 and 30 mm (centre to centre) were chosen for this purpose. The same screw fastener arrangement used in the main experimental study (Fig. 4) was used to fasten the roof battens to the ‘C’ section rafter below (Sivapathasundaram and Mahendran (2016a,b)). The tensile load was applied on the top flange until the screw fastener heads pulled through the roof batten bottom flanges (Fig. 5). Fig. 6 shows the pull-through failure modes observed in these roof batten tests, which were similar to the pull-through failure modes observed in those undertaken with two screw fastener connections (Fig. 3).
The benefit of using four screw fastener connections over two screw fastener connections was assessed by comparing the total failure loads. Fig. 7 shows the typical applied load versus displacement of the loading point (batten top flange) curves obtained from these tests. Although all the tests showed a clear peak failure load, they indicated a few minor load drops before the peak failure load was reached. However, since the levels of load drop were very small, the final peak failure loads were considered in the comparisons. Three tests were conducted in each case. Table 1 presents the test results and the comparisons made for Topspan 4055 and 4075 roof battens. For example, Topspan 4055 roof batten tests conducted with four 10 gauge screw fastener connections and a screw fastener spacing of 20 mm provided a mean total failure load of 6.79 kN whilst Topspan 4055 roof batten tests conducted with two 10 gauge screw fastener connections provided a mean total failure load of 4.02 kN (Sivapathasundaram and Mahendran (2016a)). Hence the total capacity improvement factor of using four screw fastener connections over two screw fastener connections is 1.69. Although the capacity improvement factor is slightly increased for 25 mm screw fastener spacing (by 12.2% to 1.89), it is reduced to 1.76 for 30 mm screw fastener spacing. This comparison highlights that the effect of screw fastener spacing on the pull-through capacity of roof battens is insignificant and inconsistent. Topspan 4075 test results show slightly lower capacity improvement factors (1.51, 1.58 and 1.57 for screw fastener spacings of 20, 25 and 30 mm, respectively). However, they also show that the effect of screw fastener spacing is not significant (less than 5%) compared to the experimental variations commonly observed in the roof batten tests.

The current roof batten manual (Lysaght (2012)) recommends a screw fastener spacing of 20 mm for four screw fasteners connections. This is likely to be based on the minimum width of commonly used rafters and truss top chords. Hence a screw fastener spacing of 20 mm (centre to centre) was chosen for the remaining tests in this study. This screw fastener spacing requires a total flat width of 31 mm (ie. 20 + (11/2) + (11/2) mm) for 10 gauge screw fastener connections and, hence it can be used even with smaller rafter sizes (for example, Z/C Section 10010 with a total width of 51 mm (Lysaght (2014))). It should also be noted that 20 mm screw fastener spacing gave the lowest capacity improvement factors for both Topspan 4055 and 4075 roof battens (Table 1). This screw fastener spacing cannot be reduced further (for example, 15 mm) as the larger 12 gauge screw fasteners (screw fastener head diameter of 14.5 mm) cannot be used with smaller rafters.
The benefit of using four screw fastener connections over conventional two screw fastener connections was then evaluated using a series of roof batten tests with 12 gauge screw fastener connections. The roof batten tests were conducted using two industrial roof battens made of G550 steel, Topspan 6160 with a BMT of 0.60 mm and batten height of 61 mm and Topspan 6175 with a BMT of 0.75 mm and batten height of 61 mm. These roof battens were chosen since the previously used Topspan 4055 and 4075 battens do not provide adequate bottom flange width (bottom flange width of 12 mm (Sivapathasundaram and Mahendran (2016a))) to locate the larger 12 gauge screw fasteners. Fig. 8(a) shows the test set-up used for these tests whilst Fig. 8(b) shows a typical pull-through failure mode observed in these tests. These pull-through failure modes were similar to the previously observed pull-through failure modes in Topspan 4055 and 4075 roof batten tests with four 10 gauge screw fastener connections. The roof batten tests with two 12 gauge screw fasteners were also conducted using Topspan 6160 and 6175 roof battens for comparison purposes. Three tests were conducted in each case for two screw fastener connection tests whilst four tests were conducted in each case for four screw fastener connection tests.

Table 2 presents the test results and comparisons made between these four and two 12 gauge screw fastener tests using Topspan 6160 and 6175 roof battens. They provide total capacity improvement factors of 1.54 and 1.51 for Topspan 6160 and 6175 roof battens, respectively. The capacity improvement factor of 1.51 obtained for Topspan 6175 roof batten with 12 gauge screw fastener connections agrees well with the factor of 1.51 obtained for Topspan 4075 roof batten with 10 gauge screw fastener connections for the same screw fastener spacing of 20 mm (Tables 1 and 2). This finding indicates that screw fastener diameter (from 10 gauge to 12 gauge) does not significantly affect the capacity improvement factor. Although Topspan 4055 roof batten tests with 10 gauge screw fastener connections provide an improvement factor of 1.69 for 20 mm screw fastener spacing, Topspan 6160 roof batten tests with 12 gauge screw fastener connections provide a capacity improvement factor of 1.54. The latter would have been reduced further to 1.44 if the total failure load of 8.18 kN from Test 3 (which is almost twice the total failure load from two screw fastener tests, ie. closer to an ideal case) was excluded in the calculation (Table 2). This observation also highlights that although there is a possibility of achieving an improvement factor closer to 2, it is unlikely in real conditions. In other words, all the four screw fasteners do not equally share the applied load. The first pull-through failure mode is always initiated by a tearing fracture of thin steel batten bottom flange around the edge of the screw fastener head that
carries the highest load among the four screw fasteners. This requires the remaining three screw fasteners to equally share most of the total applied load. However, since this is unlikely, the entire connection fails rapidly without the ability to carry any additional loads. This highlights that the premature failure of one screw fastener connection triggers the complete failure of a four screw fastener connection. Equal load sharing among all four screw fasteners is applicable only until the first pull-through failure.

Although the roof battens made of high strength steels (G550 and G500) are predominantly used in Australia, the roof battens made of low strength steels (G300) are commonly used in Europe and many other countries. Therefore, appropriate roof batten specimens were fabricated at the Queensland University of Technology (QUT) workshop using both high strength (G550) and low strength (G300) steels and, a series of roof batten tests was undertaken. Four screw fastener connection tests (Fig. 9) were conducted using 10 gauge screw fasteners and six types of steel roof battens such as G550 0.55, 0.75 & 0.95 mm roof battens and G300 0.55, 0.80 & 1.00 mm roof battens in addition to the two screw fastener connection tests (Fig. 4(b)). Figs. 10(a) and 10(b) show the typical applied load versus displacement of the loading point (batten top flange) curves obtained from the four screw fastener tests conducted using G550 0.55 mm and G300 1.00 mm steel roof battens, respectively. The pull-through failure modes observed are shown in Figs. 11 and 12, respectively, for G550 and G300 steel roof battens. They were similar to the pull-through failure modes observed for two screw fastener connections (Fig. 3(b)).

Table 3 presents the details of the comparisons made for the abovementioned G550 and G300 steel roof battens. For example, G550 0.55 mm roof batten tests with four screw fastener connections gave a mean total failure load of 5.17 kN whilst G550 0.55 mm roof batten tests with two screw fastener connections gave a mean total failure load of 4.14 kN (Sivapathasundaram and Mahendran (2016b)). Hence the capacity improvement factor for four screw fastener connections over two screw fastener connection is 1.25. The other G550 steel roof battens (0.75 and 0.95 mm) provided improvement factors of 1.36 and 1.24, respectively. Based on these values, an improvement factor of 1.20 can be considered in the design of G550 steel roof battens. Based on the factors of 1.76, 1.67 and 1.66 obtained for G300 0.55, 0.80 and 1.00 mm steel roof battens, an improvement factor of 1.60 can be considered in the design of G300 steel roof battens. These findings again portray an important fact that the use of four screw fastener connections instead of conventional two
screw fastener connections does not double the failure loads as anticipated. Hence suitably
reduced capacity improvement factors are needed based on the test results reported in this
section.

2.2 Rectangular Shaped Screw Fastener Head Connection Tests

Although the roof batten tests conducted using four screw fastener connections showed
significant improvements for G300 steel roof battens (above 65% in all the cases), they only
showed increments in the range of 24 to 36% for G550 steel roof battens. Therefore, some
other strengthening methods were attempted in this study to improve the pull-through failure
capacity of G550 steel roof battens. As a first attempt, since increasing the screw fastener
head size (from 10 gauge to 12 gauge) did not significantly increase the pull-through
capacities of G550 steel roof battens (Sivapathasundaram and Mahendran (2016b)), roof
batten tests were conducted using 10 mm × 15 mm rectangular shaped screw fastener heads
(Fig. 13). The width of 10 mm was chosen based on the minimum bottom flange width of 12
mm whilst the length of 15 mm was chosen based on the size of the larger screw fastener
head (12 gauge screw fastener head diameter of 14.5 mm). The tests were conducted using
G550 0.55 and 0.75 mm steel roof battens. G550 0.75 mm steel roof batten test showed a
pull-through failure mode whilst G550 0.55 mm steel roof batten test showed a pull-through
failure mode and a splitting failure mode at the bottom flange to web corner (Fig. 14). The
pull-through failure loads of 3.38 and 4.97 kN were determined for G550 0.55 and 0.75 mm
steel roof battens, respectively, ie. improvements of 63.3% and 39.6%.

Although this fastening method gave a higher strength improvement for G550 steel roof
battens compared to the four screw fastener connections, specific screw drivers are needed to
install them properly in the bottom flanges (without damaging the batten web due to the
rotation of the rectangular screw fastener head). In addition to this practical concern, the use
of this particular fastener arrangement indicated the possibilities of localised failure moving
to the web to bottom flange corner in the form of a splitting failure (Fig. 14). Further, there is
a larger variation in the strength improvement, ie. 39.6 vs. 63.3% for 0.75 and 0.55 mm G550
steel roof battens.
2.3 Raised Fastener Head Connection Tests

Since the pull-through failure of roof sheeting is caused by screw fastener head pulling through the screw fastener hole (Fig. 2) compared to the pull-through failure of roof batten caused by screw head pulling around the screw head edge (Fig. 3), some roof batten tests were also attempted using fasteners with raised screw heads (Fig. 15). The tests were conducted using G550 0.75 and 0.95 mm steel roof battens. Despite the expectation that the use of raised fastener heads may change the failure mode to be similar to that observed with roof sheeting connections and possibly lead to higher failure loads, the tests showed a different ultimate failure mode in which the fastener shank caused an edge tearing failure (Fig. 16). Since the raised fastener head was not in full contact with the bottom flange to form a firm connection (ie. typical roof batten to rafter or truss connection), the failure mode observed in these tests was dominated by shear forces in the fastener instead of tensile forces. Since the edge distance was small (ie. 7.5 mm, between the fastener hole and the closest edge of the bottom flange), it was governed by a shear action and associated failure. The failure loads (per screw fastener) of 2.80 and 3.76 kN were determined for G550 0.75 and 0.95 mm roof battens, respectively. Since these failure loads are significantly lower than the pull-through failure loads obtained using 10 gauge screw fastener connections from the previous tests (ie. 2.80 versus 3.56 kN and 3.76 versus 4.60 kN) (Sivaphasundaram and Mahendran (2016b)), it is recommended that this type of fastener connections is not used with roof battens.

3. Proposed Strengthening Method

Since the prevention of localised connection failures with the use of an effective fastening method can eventually lead to other forms of member failures (ie. bending failures), they were also considered in developing a reliable strengthening method. A suitable solution was to strengthen the entire roof batten section at the batten to rafter or truss connections. Hence it was decided to use 150 mm long roof battens as brackets at the roof batten to rafter or truss connections (Fig. 17) and conduct two-span batten tests to determine whether this proposed strengthening method can significantly improve the pull-through capacity due to the presence of two bottom flanges. It can also eliminate or delay other failures such as the splitting failures at the web to bottom flange corner (Fig. 14) and the bending failure of battens.
In the two-span batten tests, two industrial battens, namely, Topspan 6160 and 6175 battens were used with 10 gauge screw fastener connections. These battens are made of G550 steel and have an overall height of 61 mm, top flange width of 36.5 mm, bottom flange width of 14 mm, but have different BMTs of 0.60 and 0.75 mm (Lysaght (2012)). A span of 900 mm was used in these two-span batten tests. Two tests were first conducted for each of these battens without including the bracket, and then with a 150 mm long bracket at the critical central support connection (Fig. 17).

The tests were conducted using an inverted batten test set-up and a Moog hydraulic loading system at a loading rate of 1 mm/minute (Fig. 18). This test set-up is considered equivalent to the normal two-span batten test set-up discussed in Sivapathasundaram and Mahendran (2016a,b). The loads were applied at two mid-span points in the downward direction until pull-through failures occurred at both fasteners of the critical central support. The critical central support fastener loads (ie. pull-through failure loads) were measured using the individual fastener load measurement (IFLM) system based on two small K180 load cells (Fig. 18).

The tests conducted without brackets showed typical pull-through failure modes of roof battens (Fig. 19). However, the tests conducted with brackets showed member failure modes of roof battens at the loading points (mid-span). Since the use of bracket at the critical central support delayed the pull-through failure mode, it caused the member to fail at mid-span. Although the screw fastener head initiated a typical pull-through failure mode in the bracket section at the critical central support, it was not able to completely pull through both the bracket and the main roof batten due to the occurrences of member failures. Fig. 20 shows these failure modes observed in the tests conducted with brackets.

Despite the fact that a complete pull-through failure mode was not observed in the tests conducted with brackets, the critical central support reaction at the member failure point was considered in the failure load comparisons. The central support fastener loads at failure were determined by averaging the individual fastener load measurements (IFLM) and simple calculations based on the total failure loads. Table 4 presents the failure loads determined using these two different methods. There is good agreement between them except in one case (Topspan 6175 - Test 1) in which the pull-through failure load obtained using IFLM was significantly lower than the pull-through failure load obtained using the total failure load.
Since the total failure loads were close for similar tests (ie. Topspan 6175 - Tests 1 and 2), it was considered that this variation might have occurred due to some unknown experimental variations and thus the central support fastener load at failure calculated using the total failure loads were considered in the analyses, ie. 1.375/4 × total failure load.

As seen in Table 4, the average central support fastener load of 3.76 kN at failure for Topspan 6160 battens with brackets is 54.5% higher than that of the same battens without brackets (2.43 kN). Similarly, the average central support fastener load of 5.26 kN for Topspan 6175 battens with brackets is 58.5% higher than that of the same battens without brackets (3.32 kN). These two comparisons indicate that the use of bracket at the critical central support of a two-span batten system delays the typical pull-through failure mode with a consistent strength enhancement of more than 50%.

4. Discussions

4.1 Four Screw Fastener Connections

Topspan 4055 and 4075 roof batten tests with 10 gauge screw fastener connections provided total capacity improvement factors of 1.69 and 1.51 whilst Topspan 6160 and 6175 roof batten tests with 12 gauge screw fastener connections provided total capacity improvement factors of 1.54 and 1.51 for 20 mm screw fastener spacing. Based on these factors obtained for Topspan roof battens, a capacity improvement factor of 1.50 can be considered. However, QUT roof batten tests with 10 gauge screw fastener connections provided a capacity improvement factor of 1.20 for 20 mm screw fastener spacing. Both Topspan (4055 and 4075) and QUT roof battens were similar in geometry with the same BMT and steel grade (G550) except the differences in the manufacturing method (roll forming versus press braking), web to top/bottom flange corner radii and top flange surface type (knurled versus flat). The rolled safety lips in the Topspan 4055 and 4075 roof battens (Fig. 6) were also not included in the QUT roof battens (Fig. 9) to simplify the press braking process in the university workshop. Although the Topspan 6160 and 6175 roof battens do not include such rolled safety lips, they include edge stiffeners in the bottom flanges (Fig. 8). In addition, they include two small longitudinal grooves in the bottom flanges to ease the fastener installation process. However, their top flange surfaces were flat as QUT roof battens.
Since the Topspan 4075 and 6175 roof battens provided the same capacity improvement factor of 1.51, it appears that the differences in the geometry, lip type (rolled or edge stiffener), top flange (knurled or flat) and bottom flange (flat or with longitudinal grooves) do not significantly affect the improvement factor of a four screw connection. Hence the main differences between the Topspan and QUT roof battens are the manufacturing method (press braking) and the unstiffened bottom flanges. Our preliminary QUT roof batten tests with two screw fastener connections confirmed that these differences do not affect the critical pull-through capacity significantly (Sivapathasundaram and Mahendran (2016a)). However, QUT roof batten tests with four screw fastener connections highlight that they slightly affect the redistribution of the applied load among the screw fasteners and the ultimate connection capacity. The abovementioned differences might have reduced the capacity improvement factor from 1.50 to 1.20 for QUT roof battens.

Since the roof battens without rolled safety lips or edge stiffeners are also manufactured and used widely in many parts of the world, the use of QUT roof battens was considered appropriate. Based on these discussions, it is recommended to design the high strength roof battens (G550) with stiffened bottom flanges (rolled safety lips or edge stiffeners) using a total capacity improvement factor of 1.50 whilst a factor of 1.20 must be used if they do not include such stiffeners. Since the low strength industrial battens (G300) do not have such stiffeners in the bottom flanges (Lindab (2015)), the capacity improvement factor of 1.60 obtained for QUT roof battens should be used. In addition, the comparisons made between low and high strength steel QUT roof battens also highlight the effect of ductility. High ductile roof battens (G300) improve the redistribution of applied load compared to low ductile roof battens (G550) (ie. improvement factors of 1.60 versus 1.20). However, it is unlikely to achieve a total capacity improvement factor of 2.0 as the ultimate pull-through failure mode is governed by a tearing fracture mode. The test results obtained by Laboube and Sokol (2002) and Li et al. (2013) for thin steel connections subjected to shear actions also confirm this. In summary, total capacity improvement factors of 1.20 and 1.60 can be used in the design of G550 and G300 steel roof battens when four screw connections are used.

Although the total failure load of the roof batten was used to determine the capacity improvement factors in order to assess the benefit of four screw fastener connections over two screw fastener connections, the pull-through failure loads were also determined for better understanding and comparison purposes. The pull-through failure load per screw fastener was
obtained by dividing the total failure load by the number of fasteners (four). Table 5 presents
the pull-through failure loads obtained from the main roof batten tests conducted using QUT
made roof battens and four screw fastener connections.

The pull-through failure loads obtained from these roof batten tests were lower than the pull-
through failure loads obtained from the roof batten tests conducted using two screw fastener
connections (Table 5). A capacity reduction factor of 0.60 can be considered for high strength
(G550) steel roof battens whilst a capacity reduction factor of 0.80 can be considered for low
strength (G300) steel roof battens. This observation indicates that the use of a group of screw
fasteners reduces the individual fastener failure loads. Since all four screw fasteners do not
share the loads equally in reality, they exhibit this contrasting behaviour. Since G300 steels
have greater ductility than G550 steels, G300 steel roof battens provide a higher factor than
G550 steel roof battens (0.80 versus 0.60). However, it should be noted that they still increase
the total connection capacities as a group. This finding due to the screw fastener group effect
was also observed by Laboube and Sokol (2002) in their tests of screw fastener connections
subjected to shear actions. Since their test results showed that the screw fastener connection
capacity is decreased with the number of screw fasteners in the connection (n), they
recommended an equation (Equation 1) to estimate the group effect factor (R). This equation
was found useful since the number of screw fasteners in the thin steel shear connections
varied from 1 to 9.

\[ R = (0.535 + 0.467/\sqrt{n}) \leq 1.0 \] (1)

Li et al. (2013) conducted an experimental study on screw fastener connections subjected to
shear actions and showed that the use of group effect factor recommended by Laboube and
Sokol (2002) eliminates the predictions of unconservative connection capacities. However,
since only a maximum of four screw fastener connections can be used in the roof batten
connections, a single group effect factor was considered adequate in this study. The group
effect factors obtained by Laboube and Sokol (2002) for four screw fastener connection tests
using normal ductility steel sheets ranged from 0.71 to 0.79, which compares well with the
G300 steel reduction factor of 0.80 from this research. Therefore it is recommended to
include group effect (reduction) factors (R) of 0.60 and 0.80 in the design rules recommended
in Sivapathasundaram and Mahendran (2016b) and Sivapathasundaram (2016) to accurately
determine the design pull-through capacity of high strength (G550) and low strength (G300)
steel roof battens with four screw fastener connections (Equations 2 and 3). More details of
the development of these design rules are presented in Sivapathasundaram (2016).

G550 and G500 steel roof battens:

\[ P_{nov} = 8.68 \ t^2 \ f_u \ R \]  

(2)

G300 steel roof battens:

\[ P_{nov} = 2.96 \ t^{1.39} \ d^{0.61} \ f_u \ R \]  

(3)

where \( P_{nov} \) - batten pull-through capacity, \( t \) - batten thickness, \( d \) - screw fastener head
diameter, \( f_u \) - ultimate tensile strength of steel, \( R = 1 \) for two screw fastener connections and
\( R = 0.60 \) (Equation 2) and \( R = 0.80 \) (Equation 3) for four screw fastener connections

4.2 Roof Battens with Brackets

Since the ultimate failure was due to the member failure in bending when the brackets were
used in the two-span batten tests, their suitability to other batten spans is not known. The
section moment capacities of Topspan 6160 and 6175 battens were 0.61 and 0.84 kNm based
on AS/NZS 4600 (2005). The mid-span failure bending moments were 0.77 and 1.08 kNm
for the tested Topspan 6160 and 6175 roof battens which compare reasonably well with the
estimated section moment capacities (0.61 and 0.84 kNm). These comparisons in general
show that the use of brackets at the central support has caused the batten failure to be
governed by the section moment capacity of batten instead of the pull-through capacity.

The test results and the section moment capacity calculations of the tested battens with and
without brackets show that their wind uplift capacity can be increased by delaying the pull-
through failures. Such improvements will be significant for shorter spans for which pull-
through failures are critical. The pull-through capacity of roof battens with brackets could not
be determined from the two-span batten tests as such failures did not occur. However, it can
be determined using suitable small scale test results without assuming it as twice the pull-
through failure load from the roof batten tests conducted without brackets. Therefore a set of
short batten tests was conducted using a test set-up shown in Fig. 21. Two Topspan 6160 roof
batten specimens (each 150 mm long) were placed on top of each other and, fastened to the
‘C’ section rafter below using two 10 gauge screw fastener connections. Since the bending
failure of roof batten is unlikely to occur with this short batten test set-up, the tensile load
applied on the batten top flange was continued until the screw fastener head pulled through the batten bottom flanges completely (ie. double bottom flanges).

The pull-through failure loads obtained from these tests were 4.09, 4.25 and 4.66 kN (mean of 4.33 kN and COV of 0.07). These failure loads were slightly lower than twice the pull-through failure loads obtained from the tests conducted using single batten specimens (2.17, 2.38 and 2.34 kN (mean of 2.30 kN and COV of 0.05)). These test results show a reduction of 11.7%, which contradicts another common assumption of anticipating twice the pull-through failure loads from the roof batten tests without brackets. However, it should be noted that this proposed strengthening method provides the highest possible level of enhancement of 88.3% for high strength (G550) steel roof battens subject to pull-through failures. Based on this understanding, pull-through failure loads of 4.29 and 5.86 kN were considered for Topspan 6160 and 6175 roof battens with brackets (double batten thickness), respectively.

The failure moments determined from the two-span tests and the estimated pull-through failure loads for Topspan 6160 and 6175 roof battens with brackets were then used to back calculate the critical span values where the transition of member (bending) failure to localised pull-through failure occurs. They show that the pull-through failures will only occur for Topspan 6160 and 6175 roof battens with brackets for spans less than 790 and 810 mm, respectively. This finding implies that a capacity improvement of 85% is achievable by employing the recommended strengthening method using 150 mm long brackets at the roof batten to rafter or truss connections for commonly used shorter roof batten spans (450 or 600 or 750 mm) that are very likely to be governed by localised pull-through failures. This proposed strengthening method can also be employed by overlapping the roof battens at the batten to rafter or truss connections. This will be significantly beneficial for large span applications since the number of required overlapping will be reasonable in such instances.

This will not only increase the critical pull-through capacities but also reduce the effect of higher bending moments at the batten to rafter or truss connections. However, the latter may not a preferable option for short span applications since the number of roof batten to rafter or truss connections (ie. overlapping of roof battens) is high. In such situations, the brackets can be effectively and efficiently used as recommended and discussed in this paper.
5. Conclusions

This paper has presented the details of three strengthening methods that can be used to enhance the roof batten performance under high wind uplift loads. A series of roof batten tests was conducted to investigate the pull-through failure behaviour of roof battens fastened using four screw fastener connections (two screw fastener connections per each bottom flange side), rectangular shaped screw fastener head connections and raised head bolt connections. The use of four screw fastener connections did not provide the expected twice the pull-through capacity of two screw fastener connections (varied from 1.25 to 1.76 in the tests). Hence other strengthening methods were considered to delay or eliminate the critical pull-through failures of roof battens. Based on the improved understanding and the knowledge gained from the detailed experimental investigations, a reliable strengthening method of using 150 mm long roof battens as brackets at the roof batten to rafter or truss connections is proposed. This method improves the roof batten performance under high wind uplift loads by minimising the possibilities of localised connection failures and other forms of member failures. Test results highlight that 85% capacity improvement is achievable for commonly used short batten spans that are likely to be governed by the critical pull-through failure. Suitable capacity improvement factors are proposed for the strengthening methods considered in this paper.

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Figure 1: Typical Thin-walled Steel Roof Structure and Connections
Figure 2: Roof Sheeting Pull-through Failures
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### Table 1. Comparison of Total Failure Loads Obtained from the Industrial Roof Batten Tests Conducted using Four and Two 10 Gauge Screw Fastener Connections

| Type of Roof Batten | Screw Fastener Spacing | Total Failure Load (kN) | Mean Total Failure Load (kN) | Capacity Improvement Factor |
|---------------------|-------------------------|-------------------------|------------------------------|----------------------------|
|                     |                         | Four Screw Fasteners Test No. | Four Screw Fasteners Test | Two Screw Fasteners Test |
|                     |                         | 1 | 2 | 3 | 1 | 2 | 3 | 4 |
| Topspan 4055        | 20 mm                   | 6.74 | 6.77 | 6.86 | 6.79 (0.01\textsuperscript{a}) | 4.02 | 1.69 |
|                     | 25 mm                   | 7.78 | 7.62 | 7.45 | 7.62 (0.02\textsuperscript{a}) | 4.02 | 1.89 |
|                     | 30 mm                   | 6.46 | 7.22 | 7.58 | 7.09 (0.08\textsuperscript{a}) | 4.02 | 1.76 |
| Topspan 4075        | 20 mm                   | 10.23 | 10.08 | 10.07 | 10.13 (0.01\textsuperscript{a}) | 6.70 | 1.51 |
|                     | 25 mm                   | 10.47 | 11.48 | 9.77 | 10.57 (0.08\textsuperscript{a}) | 6.70 | 1.58 |
|                     | 30 mm                   | 10.48 | 10.47 | 10.65 | 10.53 (0.01\textsuperscript{a}) | 6.70 | 1.57 |

Note: \textsuperscript{a}: Coefficient of Variation (COV) and \textsuperscript{b}: From Sivapathasundaram and Mahendran (2016a)

### Table 2. Comparison of Total Failure Loads Obtained from the Industrial Roof Batten Tests Conducted using Four and Two 12 Gauge Screw Fastener Connections

| Test Type | Type of Roof Batten | Total Failure Load (kN) | Mean Total Failure Load (kN) | Capacity Improvement Factor |
|-----------|---------------------|-------------------------|------------------------------|----------------------------|
|           |                     | Test No. | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | |
| Two Screw Fastener Tests | Topspan 6160 | 4.13 | 4.44 | 4.68 | … | 4.42 (0.06\textsuperscript{a}) | … | … |
|           | Topspan 6175 | 7.98 | 7.62 | 8.40 | … | 8.00 (0.05\textsuperscript{a}) | … | … |
| Four Screw Fastener Tests | Topspan 6160 | 6.11 | 6.50 | 8.18 | 6.47 | … | 6.81 (0.14\textsuperscript{a}) | 1.54 |
|           | Topspan 6175 | 11.04 | 12.82 | 11.94 | 12.53 | … | 12.08 (0.06\textsuperscript{a}) | 1.51 |

Note: \textsuperscript{a}: Coefficient of Variation (COV)
Table 3. Comparison of Total Failure Loads Obtained from the QUT Roof Batten Tests Conducted using Four and Two 10 Gauge Screw Fastener Connections

| Type of Roof Batten | Total Failure Load (kN) | Mean Total Failure Load (kN) | Capacity Improvement Factor |
|---------------------|-------------------------|-----------------------------|---------------------------|
|                     | Four Screw Fasteners Test No. | Four Screw Fasteners Test | Two Screw Fasteners Test a |
|                     | 1 | 2 | 3 | | | |
| G550 0.55 mm | 4.96 | 5.28 | 5.28 | 5.17 | 4.14 | 1.25 |
| G550 0.75 mm | 9.48 | 9.04 | 10.53 | 9.68 | 7.12 | 1.36 |
| G550 0.95 mm | 11.04 | 11.24 | 12.04 | 11.44 | 9.20 | 1.24 |
| G300 0.55 mm | 6.92 | 6.96 | 9.08 | 7.65 | 4.36 | 1.76 |
| G300 0.80 mm | 12.28 | 11.68 | 13.08 | 12.35 | 7.40 | 1.67 |
| G300 1.00 mm | 15.40 | 14.68 | 15.28 | 15.12 | 9.10 | 1.66 |

Note: a: From Sivapathasundaram and Mahendran (2016b)

Table 4. Failure Loads Obtained from the Two-span Batten Tests Conducted with and without Brackets

| Test Type                | Central Support Fastener Load using IFLM (kN) | Total Failure Load (kN) | Central Support Fastener Load using Calculations (kN) | Average Fastener Load using Calculations (kN) |
|-------------------------|-----------------------------------------------|-------------------------|-------------------------------------------------------|---------------------------------------------|
| Topspan 6160 - Test 1  | 2.30                                          | 6.69                    | 2.30                                                  | 2.43                                        |
| Topspan 6160 - Test 2  | 2.52                                          | 7.46                    | 2.56                                                  |                                             |
| *Topspan 6160 - Test 1 | 3.45                                          | 10.80                   | 3.71                                                  | 3.76                                        |
| *Topspan 6160 - Test 2 | 4.04                                          | 11.06                   | 3.80                                                  |                                             |
| Topspan 6175 - Test 1  | 2.53                                          | 9.78                    | 3.36                                                  | 3.32                                        |
| Topspan 6175 - Test 2  | 3.16                                          | 9.52                    | 3.27                                                  |                                             |
| *Topspan 6175 - Test 1 | 4.74                                          | 15.23                   | 5.24                                                  | 5.26                                        |
| *Topspan 6175 - Test 2 | 5.27                                          | 15.37                   | 5.28                                                  |                                             |

Note: *: Tests were conducted with brackets
Table 5. Comparison of Pull-through Failure Loads Obtained from the QUT Roof Batten Tests Conducted using Four and Two 10 Gauge Screw Fastener Connections

| Type of Roof Batten | Pull-through Failure Load (kN) | Mean Pull-through Failure Load (kN) | Reduction Factor |
|---------------------|-------------------------------|-----------------------------------|-----------------|
|                     | Four Screw Fasteners Test No. | Four Screw Fasteners Test         | Two Screw Fasteners Test |                  |
|                     | 1    | 2    | 3    | 1    | 2    | 3    | a                  |
| G550 0.55 mm        | 1.24 | 1.32 | 1.32 | 1.29 | 2.07 | 0.62 |
| G550 0.75 mm        | 2.37 | 2.26 | 2.63 | 2.42 | 3.56 | 0.68 |
| G550 0.95 mm        | 2.76 | 2.81 | 3.01 | 2.86 | 4.60 | 0.62 |
| G300 0.55 mm        | 1.73 | 1.74 | 2.27 | 1.91 | 2.18 | 0.88 |
| G300 0.80 mm        | 3.07 | 2.92 | 3.27 | 3.09 | 3.70 | 0.83 |
| G300 1.00 mm        | 3.85 | 3.67 | 3.82 | 3.78 | 4.55 | 0.83 |

Note: a: From Sivapathasundaram and Mahendran (2016b)