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Kathekeyan, Myuran, Mahendran, Mahen, & Sivapathasundaram, Mayooran
(2017)
Effect of loading rate on the pull-through capacities of cold-formed steel roof battens.
In Jonsson, J (Ed.) *Proceedings of the 8th European Conference on Steel and Composite Structures (ce/papers, Volume 1, Issue 2-3).*
Wilhelm Ernst und Sohn, Germany, pp. 1697-1706.

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https://doi.org/10.1002/cepa.213

EFFECT OF LOADING RATE ON THE PULL-THROUGH CAPACITIES OF COLD-FORMED STEEL ROOF BATTENS

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ABSTRACT

Localised connection failure is the main shortcoming of cold-formed steel roofing systems subjected to high wind suction loads. Pull-through failure in the vicinity of roof batten to rafter connection is the major connection failure observed during recent high wind events. Both static and fatigue pull-through failures occur based on the type of wind loads (static or cyclic loads). The loading rate to be used in the static and cyclic pull-through failure tests is a moot point as the wind loading frequency can vary during wind events such as storms and cyclones. Therefore, it is necessary to understand the effect of wind loading frequency/rate on the pull-through failures of steel roof battens. This paper investigates the influence of loading rate on both static and fatigue pull-through capacities of steel roof battens by means of a series of static and cyclic tests conducted at various loading rates/frequencies. Initially, tests were conducted on roof battens made of two steel grades (G300 and G550) and two thicknesses (0.8 and 1 mm). The results showed a significant improvement in the pull-through capacities during tests using higher loading rates. They also showed that the current static and cyclic pull-through design rules/guidelines do not include the effect of loading rate. Secondly, to understand the influence of loading rate on the pull-through capacity of battens, the effect of loading rate on the mechanical properties of steels was investigated using 40 tensile coupon tests. The effect of loading rate on both the tensile strength of steel used and the pull-through capacity of roof batten was then compared. Using the results of comparison, the reasons for the increase in the static pull-through capacity of roof battens with loading rate are discussed and, a recommendation is made in relation to the loading rate to be used with the new Low High Low (LHL) cyclic test. This paper presents the details and results of this study.

Keywords: Cold-formed steel roof battens, Pull-through failures, Loading rate, LHL test

1 INTRODUCTION

In order to design a safer and economical roof structure, the effects of loading rate on the pull-through capacity of Cold-formed Steel (CFS) roof batten to rafter connection must be known. The actual wind loading on roof members, as recorded in [1, 2], indicates that it is much faster than that recommended in the standard test guidelines and previous studies [3-6]. As CFS (the material used to produce roof battens) seems to have strain rate sensitivity, there is a possibility for enhanced static pull-through capacities in the real case compared to the pull-through capacities predicted using the existing design equations. Also, the strain rate sensitivity could lead to either conservative or unsafe batten pull-through design in cyclic load applications. Therefore, a proper understanding of strain rate sensitivity of CFS roof battens is crucial for safe and optimised batten design, and this topic is discussed in this paper.

Current design criteria for static pull-through failures [7, 8] are based on the results of static pull-through tests conducted using quasi-static loading at 1 mm/min rate as recommended in [3]. However, some research studies [9-11] have considered different loading rates (2.54-51.0 mm/min) to determine the static wind uplift capacities of some other roof members/connections. This shows the inconsistency in using loading rates, which could affect the test results. A similar issue has been noted in cyclic load tests also. The Low-High-Low (LHL) cyclic test recommended by National

Construction Code of Australia (NCC) [12] suggests applying cyclic loads at a frequency less than 3 Hz. This is much faster compared to the loading rates recommended for static tests, and the fatigue capacities could be different for different frequencies within the recommended frequency range due to the strain rate sensitivity of CFS. Therefore, by considering all the available loading rates in severe wind events, static pull-through capacities of roof battens in the loading rate range of 1-300 mm/min and cyclic pull-through capacities in the loading frequency range of 1-3 Hz are required to investigate and determine the level of loading/strain rate sensitivity of CFS roof battens. This paper presents the details and results of a series of static and cyclic tests and discusses the loading rate sensitivity of CFS roof battens.

2 CURRENT STATIC AND CYCLIC CAPACITY DESIGN RULES

Sivapathasundaram and Mahendran [7, 8] investigated the suitability of pull-through capacity equations in the Australian [13], American [14] and European [15] standards and showed that those equations failed to calculate the capacities of roof battens due to symmetric fastener assembly (double fasteners), non-axial loading and varying batten geometry with loading history [16]. Therefore they developed improved equations for the prediction of design static pull-through capacity (ϕF_{ov}) as shown next.

For G550 steel roof battens:
$$\Phi\ F_{ov} = \Phi\ 8.68\ t^2 f_u \tag{1}$$

and, For G300 steel roof battens:
$$\Phi\ F_{ov} = \Phi\ 3.07\ t^{1.4} d^{0.6} f_u \tag{2}$$

where,
t - Thickness of the sheet in contact with the screw head ($0.55 < t < 1.15$ mm)
d - Greater of the screw head and the washer diameter ($11 < d < 14.5$ mm)
f_u - Measured ultimate tensile strength
ϕ - Capacity reduction factor = 0.6

However, it should be noted that the effect of cyclic wind loading was not included in *Eqs. (1)* and *(2)*. To design roof battens against fatigue pull-through failures, NCC [12] recommends a Low-High-Low (LHL) cyclic test method for low-medium rise building roofs in cyclone prone areas. This is a laboratory based test which simulates the real fluctuating cyclonic wind loading using a series of seven fatigue loading sequences, at a frequency less than 3 Hz, as listed in *Table 1*.

Table 1. LHL cyclic test pressure sequences [12]

Sequence	Number of cycles	Cyclic loads
A	4500	0 to 0.45 P_t
B	600	0 to 0.6 P_t
C	80	0 to 0.8 P_t
D	1	0 to 1.0 P_t
E	80	0 to 0.8 P_t
F	600	0 to 0.6 P_t
G	4500	0 to 0.45 P_t

Where, P_t is the ultimate limit state wind pressure

3 EXPERIMENTAL STUDY

3.1 General

This experimental study included two phases. The first phase is a series of static and cyclic pull-through tests to investigate the influence of loading rate on the pull-through capacities of CFS roof batten to rafter connections. The second phase is a series of tensile coupon tests to investigate the influence of loading rate on the battens' base material, CFS.

In order to represent the majority of industrial roof battens in this study, a total of four different CFS sheets of two different grades (G550 and G300 – minimum yield strengths of 550 and 300 MPa) and two different thicknesses (0.75/0.80 and 0.95/1.00 mm) were used in this study. For each steel sheet, a minimum of 10 tensile coupon tests and 13 static pull-through tests were conducted. In order to conduct the pull-through tests, battens were made using the steel sheets by a hydraulic press brake machine in the University workshop (QUT). In addition to the static pull-through and tensile coupon tests, 10 constant amplitude and 10 multi-level cyclic tests (LHL) were also conducted to study the effect of loading rate on the cyclic pull-through capacity. In addition to QUT battens, two industrial battens (TS4055 and TS4075) were also included in the cyclic test series.

3.2 Phase 1 tests - Batten pull-through tests

A series of static and cyclic (constant and multi-level amplitude tests) tests were conducted in the Phase 1 test series for all battens. Static pull-through tests were conducted on 200 mm long short-batten as recommended in [17]. On the other hand, cyclic tests were conducted on 1 m long two-span battens (span of 450 mm) as recommended in [18, 19]. The short batten and two-span batten test assemblies are shown in *Fig. 1 (a)* and *(b),* respectively. The short batten tests were conducted under two different loading rates (1mm/min quasi-static and 300 mm/min dynamic loading) by considering the loading rates recommended in the test standards/guidelines [3-5]. Similarly, two-span batten tests were conducted under three different cyclic frequencies (0.8, 1.0 and 1.5 Hz).

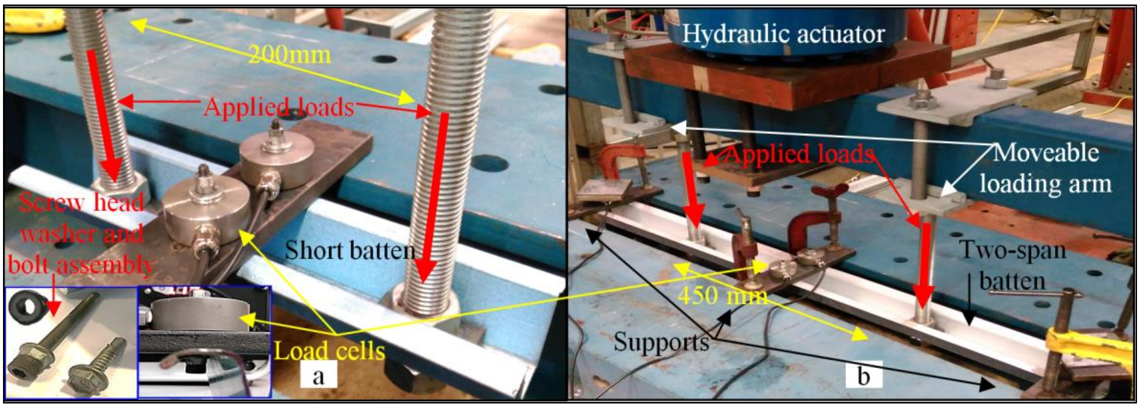

Fig. 1. a) Short-batten test; (b) Two-span batten test

Test battens were fixed in the test set-up as shown in *Fig. 1 (a)* and *(b),* and the static and cyclic wind loadings were simulated by a 100 kN hydraulic actuator. The LHL loading was applied according to *Table 1*. In order to overcome pull-out failures in the critical middle support of the short and two-span battens, "Unbrako" bolts and nuts with a simulated screw head washer (*Fig. 1a*) were used as an alternative to metal Tek screws. A constant torque of 2.5N/m was used to tighten the bolts, and additional lock nuts were used to prevent nut loosening, especially in cyclic tests. The pull-through failure capacity was obtained by measuring the fastener reaction using 15 kN washer load cells (K-180) as shown in *Fig. 1 (a)* and *(b).* Static pull-through tests were continued until the first tearing occurred and the cyclic tests were continued until both middle support screws completely pulled through the batten. The displacement between the critical middle support (failure location) and the loading point was recorded in both static and cyclic tests, and the number of cycles until complete failure was recorded in the cyclic tests to obtain the fatigue life of test battens.

3.3 Phase 2 tests - Tensile coupon tests

Tensile coupon tests were included in the Phase 2 test series to investigate the loading rate sensitivity (commonly known as strain rate sensitivity) of CFS sheets, and thereby understanding the performance of CFS roof battens to different loading rates. Dog-bone shaped coupons were machined according to [20] (*Fig. 2*) and tested in a 100 kN Mechanical Testing System (MTS) for five loading rates varying from 1 to 300 mm/min. Strains were measured using both a 50 mm extensometer and a non-contact video extensometer. A typical tensile coupon is shown in *Fig. 2*.

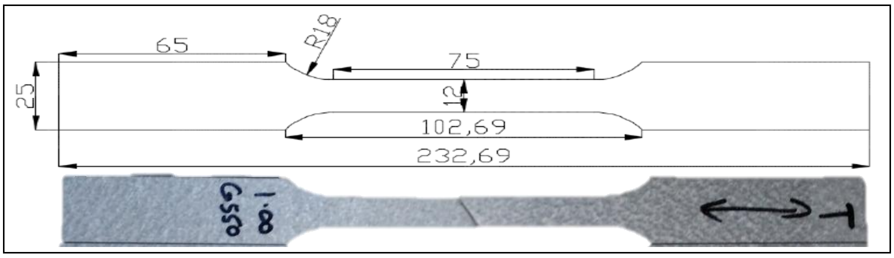

Fig. 2. Dog-bone shaped tensile coupon

4 TEST RESULTS AND DISCUSSION

4.1 Static pull-through tests

The static pull-through test results from Phase-1 tests to investigate the influence of loading rate on the static pull-through capacities of roof battens are listed in *Table 2*, while a graphical representation of quasi-static and dynamic pull-through test results of a G550-0.75 mm batten is shown in *Fig. 3*. The average static pull-through capacities obtained from the tests with 1 mm/min loading rate closely agreed with the pull-through capacities obtained from a previous study [7]. Such results are also included in *Table 2*.

Table 2. Static pull-through capacities of roof battens obtained from short batten tests

Batten	Loading rate (mm/min)	Pull-through capacity per fastener - F_{ov} (kN)	Average F_{ov}	F_{ov} based on [7]	$\frac{F_{ov-300}}{F_{ov-1}}$	COV
G550-0.75mm	1	3.1, 3.6, 3.8	3.48	3.56	1.13	0.10
	300	3.4, 3.6, 3.6, 3.7, 3.9, 4.0, 4.1, 4.2, 4.3, 4.3, 4.4	3.93			0.09
G550-0.95mm	1	4.9, 5.1, 5.3, 5.4, 5.4, 5.4	5.22	4.60	1.15	0.04
	300	5.5, 5.6, 5.7, 5.7, 6.0, 6.0, 6.1, 6.2, 6.4, 6.8	5.99			0.07
G300-0.80mm	1	3.2, 3.3, 3.3, 3.9, 4.0, 4.0	3.60	3.70	1.18	0.10
	300	4.0, 4.2, 4.2, 4.2, 4.3, 4.4, 4.4	4.23			0.03
G300-1.00mm	1	4.1, 4.4, 4.7, 4.8, 5.0, 5.0	4.65	4.55	1.20	0.08
	300	5.2, 5.3, 5.5, 5.7, 5.7, 5.7, 5.9	5.56			0.04

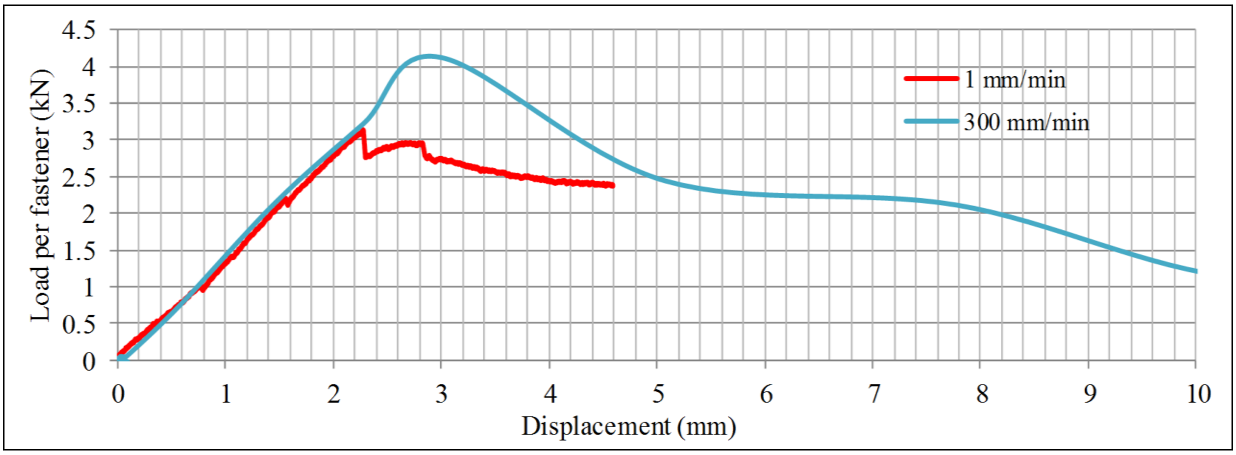

Fig. 3. Load versus displacement curve of G550-0.75 mm battens

As seen in *Table 2* and *Fig. 3*, there is a significant increment in the static pull-through capacity when 300 mm/min dynamic loading is applied compared to 1 mm/min quasi static loading. This must be due to the “Dislocation Motion Mechanism”, i.e. the high strain rate reduces the time available for movement of existing dislocations in the material [21-23]. This behaviour is commonly known as strain rate sensitivity, which is generally more significant in low grade steels than in high grade steels [23-25]. This can also be noted in *Table 2*, where G300 steel pull-through test results showed increments in the range of 18-20% whilst G550 steel tests showed increments in the range of 13-15%. As many battens in the industry are made of high strength steel (G550) and the pull-through capacity increment for the high strength steel is considerably small, the effect of loading rate on static pull-through failure can be neglected and the design *Eq. (1)* can be used to conservatively design G550 battens. However, the effects of loading rate on the cyclic test results may not be negligible as a small change in the cyclic stress could significantly influence the fatigue life. Therefore, a series of constant and multi-level cyclic tests was also included in this study.

4.2 Cyclic pull-through tests

The test method available to design the roof battens in cyclone prone areas is the LHL cyclic test (*Table 1*) [12]. Therefore, a series of LHL cyclic tests was first conducted to identify the effect of loading rate. Generally, cyclic capacities of metals are less than their static capacities. Considering this, the maximum cyclic magnitude in LHL cyclic test (sequence D – 100% P_t) was initially taken as the respective batten's static capacity and then reduced until the required LHL cyclic capacity is achieved. It should be noted that the static pull-through capacities obtained from the 450 mm span two-span batten tests are slightly different to that obtained from 200 mm short batten tests. Such capacities were obtained from [26]. The middle cyclic sequence, D, was held for 10 seconds at the test sequence 'P_t' based on [12]. In addition to 10g metal tek screws, 12g screws were also included in the LHL cyclic tests. Tests were conducted at 1 Hz to obtain conservative results, and their results are listed in *Table 3*. A typical load and displacement versus fatigue life graph obtained from a LHL cyclic test of a G550-0.95mm-12g batten configuration with 100% P_t is given in *Fig. 4*.

Table. 3. Low-High-Low (LHL) cyclic test results

Test No	Batten configuration	P_t* (%)	Sequences survived	Crack status	Test status
T-01	G550-0.75-10g	100	A-G	No/Hairline crack	Passed
T-02	G550-0.75-12g	100	A-G	Yes	Passed
T-03	G550-0.95-12g	100	A-G	No/Hairline crack	Passed
T-04	G300-0.80-10g	100	A-G	Yes	Passed
T-05	G550-0.95-10g	100	A-C	Complete failure	Failed
T-06	G550-0.95-10g	85	A-C	Complete failure	Failed
T-07	G550-0.95-10g	80	A-G	No	Passed
T-08	G300-1.00-10g	100	A-D	Complete failure	Failed
T-09	G300-1.00-10g	95	A-D	Complete failure	Failed
T-10	G300-1.00-10g	90	A-G	No	Passed

*- % of static pull-through failure load

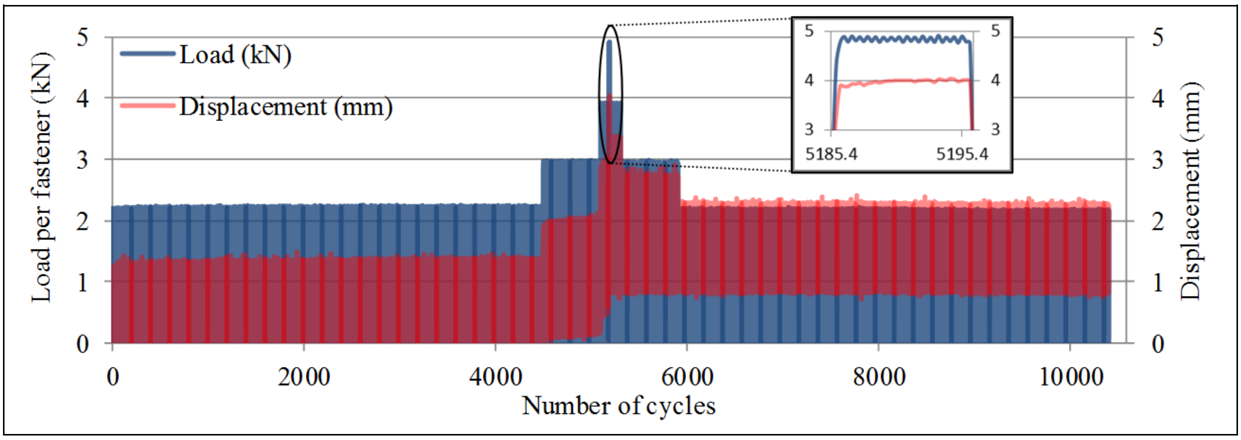

Fig. 4. LHL cyclic test of a G550-0.95mm-12g batten with 100% P_t (T-03)

According to *Table 3*, all the LHL cyclic tests with 100% P_t, except G550-0.95 mm-10g and G300-1.00 mm-10g, showed that the battens may have fatigue capacities that could survive the design cyclones with maximum P_t equal to or slightly more than the respective batten's static capacity. It is unusual as even if the battens have excellent fatigue capacities, they should not have survived the middle sequence, which is equal to the respective batten's static pull-through capacity. This unusual behaviour should be due to the loading rate sensitivity, which increased the F_{ov-300} in short batten tests. However, a similar behaviour was observed in an industrial roof batten, TS4075, but believed to be due to the differences between the failure definitions in static and LHL cyclic tests [19]. The static pull-through failure is defined based on the first tearing whereas the fatigue failure is based on complete separation of batten from rafter/truss (crack initiation (N_i) and crack propagation). Thus, there could be additional fatigue life during crack growth, although the crack has initiated during the first few cycles. However, this has been proved wrong by means of a constant amplitude cyclic test performed on a G550-0.75 mm batten under a cyclic load varying from 10 N to batten's static capacity at 1 Hz. The test result, as shown in *Fig. 5*, indicates that the crack did not initiate until about 285 cycles and it took only another 10 cycles to completely pull-through. Therefore, it is confirmed that the loading rate sensitivity is the solo reason for the unusual behaviour.

The loading rate in which the middle sequence-D should be loaded is not specifically defined in the LHL cyclic test guideline [12]. Therefore, it was loaded at 1 Hz, i.e. P_t was reached in 0.5 Seconds. According to *Fig. 3*, G550-0.75 batten's deformation corresponding to its static pull-through failure load is about 2.5 mm. As P_t was taken as the batten's static capacity, in LHL sequence-D, the batten has to deform about 2.5 mm in 0.5 Seconds, i.e. (2.5/0.5)*60 = 300 mm/min. Hence, it can be predicted that G550-0.75-10g batten in a LHL cyclic test will survive up to P_t equal to 1.13 F_{ov-1} (see Table 2). Similarly, G300-0.8-10g batten will survive up to P_t equal to 1.18 F_{ov-1}. However, it should be noted that these failures are expected to occur during sequence-D, in static failure mode, as their LHL cyclic capacities are greater than their static capacities. However there is a possibility for failure, in fatigue mode, before sequence D if their LHL cyclic capacity is between 1 – 1.13 F_{ov-1} for G550-75-10g batten and 1 – 1.18 F_{ov-1} for G300-0.8-10g batten configuration. This is not valid for G550-0.95-10g and G300-1.0-10g battens as their LHL cyclic capacities are less than their static capacities, i.e. 0.8, 0.9 F_{ov-1}, respectively (Table 3). Considering the above discussion and the fact that static load tests use 1 mm/min loading rate, this study recommends the use of 1mm/min loading rate for sequence-D in the LHL cyclic test with 10 seconds hold period.

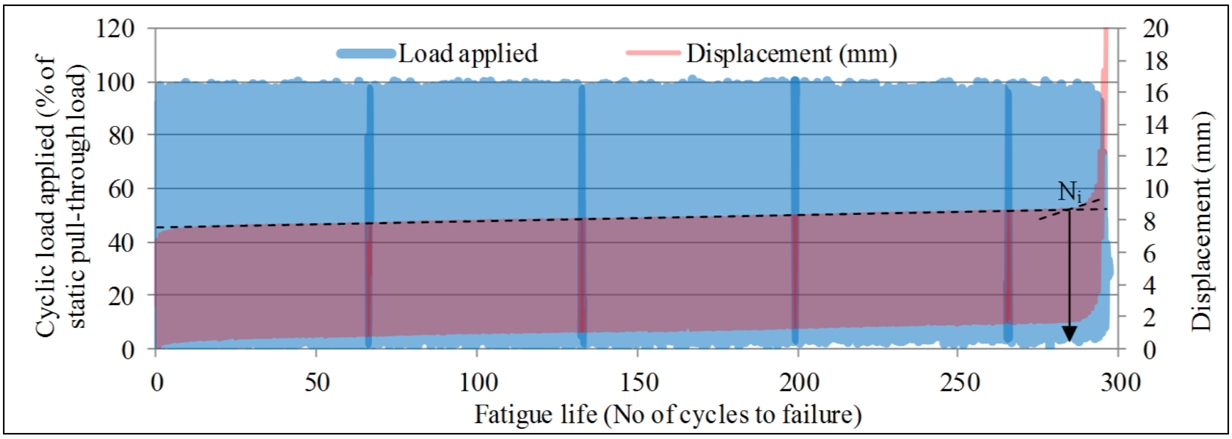

Fig. 5. Load and displacement versus fatigue life graph of a cyclic test of G550-0.75 mm batten at 100% of F_{ov}

Finally, the influence of loading rate on the constant amplitude cyclic tests was investigated by means of constant amplitude cyclic tests conducted at different cyclic frequencies. These tests were carried out on two different industrial roof battens (TS4055 and TS4075) under two different cyclic magnitudes (80% and 65% of the respective batten's static pull-through capacity) and three different frequencies (0.8, 1.0 and 1.5 Hz). The peak cyclic deformations were recorded along with the number of cycles, and are presented in *Figs. 6* and *7.*

According to *Figs. 6* and *7*, both battens gained a longer fatigue life with faster loading rates. Also, unlike in static pull-through tests, fatigue tests have resulted in higher increments in the number of cycles to failure (more than 50% for both 80% and 65% cyclic tests). This supports the argument that the CFS roof battens are sensitive to loading rates and their sensitivity in cyclic pull-through tests are more significant than in static pull-through tests. Therefore, it should be noted that this loading rate effect on the cyclic tests will significantly affect the LHL cyclic tests conducted at different loading frequencies (any frequencies less than 3 Hz as recommended in [12]). Therefore, with the intention of getting conservative results, this study suggests a frequency of 1 Hz for LHL cyclic tests, which is commonly considered as the lower bound to simulate cyclonic wind loads.

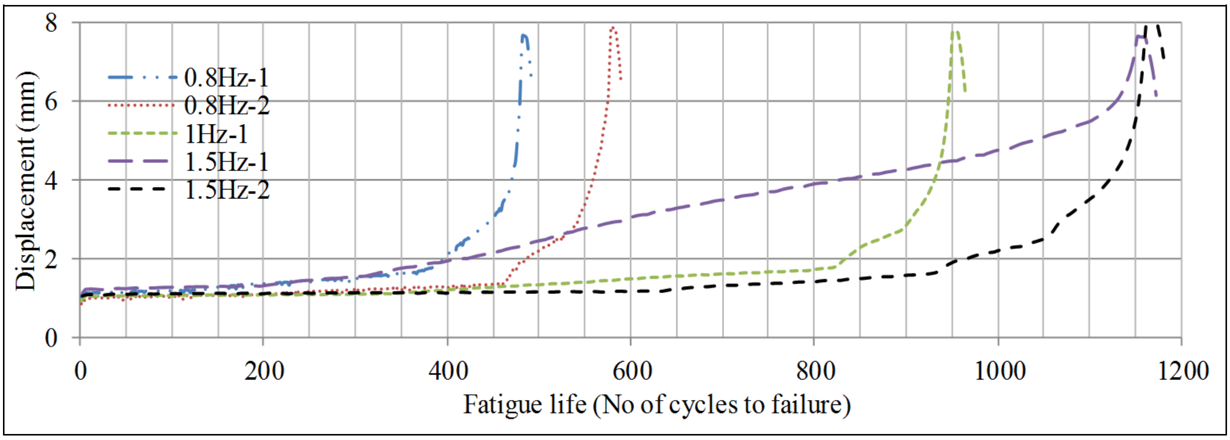

Fig. 6. Displacement versus fatigue life graph of a cyclic test of TS4055 roof batten at 80% of F_{ov}

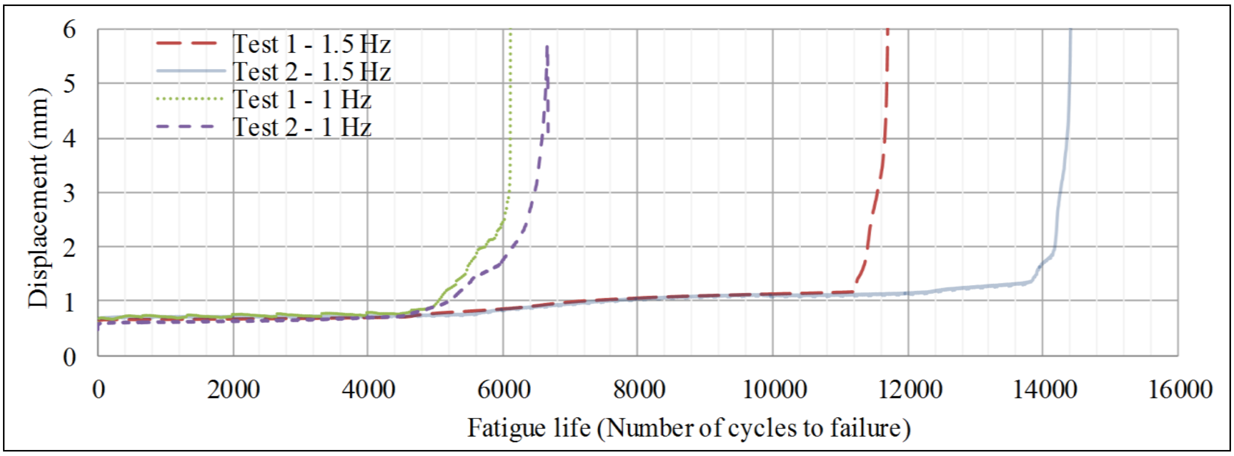

Fig. 7. Displacement versus fatigue life graph of a cyclic test of TS4075 roof batten at 65% of F_{ov}

4.3 Tensile coupon tests

A series of tensile coupon tests was included in Phase 2 tests to understand the influence of loading rate on the pull-through capacity of CFS roof battens through understanding the influence on the mechanical properties of CFS. This was investigated by means of 40 tensile coupon tests, and their results are listed in *Tables 4-7*. Typical stress-strain curves of G300-1 mm steel for loading rates in the range of 1 – 300 mm/min ($3x10^{-4}$ – 0.1 mm/mm/s) are given in *Fig. 8*.

According to *Tables 4-7* and *Fig. 8*, a significant increment is observed in the ultimate tensile stress, f_u, with increasing loading/strain rate. The increment pattern is almost similar to the F_{ov} increment pattern in the static pull-through tests conducted on 200 mm short battens (*Table 2*). Also, higher strain rate sensitivity has been noticed in low grade tensile coupons than in high grade coupons as observed in the short batten tests. These similarities observed in both tensile coupon and batten pull-through tests confirm that the increased f_u is the reason for the F_{ov} increment in the pull-through tests conducted with higher loading rates. As the pull-through capacity (F_{ov}) is directly proportional to the ultimate tensile strength (f_u) of the battens' base material [7], the increment in f_u and F_{ov} should be the same for the same loading rate. In order to verify this, tensile coupon tests and static pull-through tests conducted at 1 mm/min quasi-static and 300 mm/min dynamic loading rates were compared in *Table 8*.

Table 4. Coupon test results of G300-0.80 mm steel

Strain rate (mm/mm/s)	Loading rate (mm/min)	F_u	Average F_u	% increment
0.0003	1	378, 379	378	0.00
0.0167	50	390, 389	390	3.17
0.0333	100	391, 393	392	3.70
0.0667	200	396, 392	394	4.23
0.1000	300	396, 400	398	5.03

Table 5. Coupon test results of G300-1.00 mm steel

Strain rate (mm/mm/s)	Loading rate (mm/min)	F_u	Average F_u	% increment
0.0003	1	363, 369	366	0.00
0.0167	50	380, 381	380	3.77
0.0333	100	378, 382	380	3.74
0.0667	200	384, 389	386	5.48
0.1000	300	387, 387	387	5.75

Table 6. Coupon test results of G550-0.75 mm steel

Strain rate (mm/mm/s)	Loading rate (mm/min)	F_u	Average F_u	% increment
0.0003	1	664, 659	661	0.00
0.0167	50	670, 671	670	1.39
0.0333	100	664, 662	663	0.24
0.0667	200	682, 681	682	3.07
0.1000	300	674, 680	677	2.38

Table 7. Coupon test results of G550-0.95 mm steel

Strain rate (mm/mm/s)	Loading rate (mm/min)	F_u	Average F_u	% increment
0.0003	1	618, 612	615	0.00
0.0167	50	622, 618	620	0.81
0.0333	100	630, 623	627	1.95
0.0667	200	622, 630	626	1.79
0.1000	300	635, 623	629	2.28

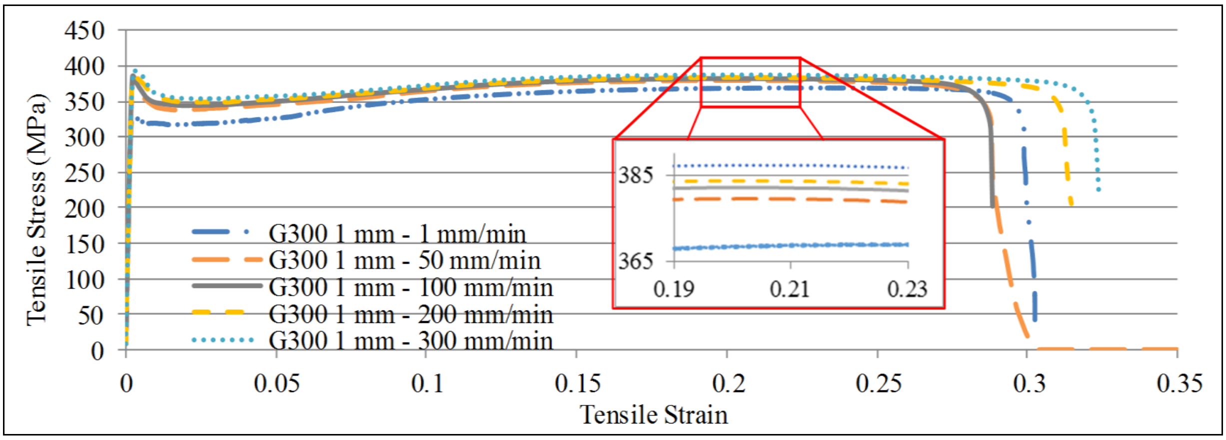

Fig. 8. Stress versus strain curve of G300-1 mm steel for loading rate range of 1-300 mm/min

Table 8. Results of Tests conducted at 1 mm/min quasi-static and 300 mm/min dynamic loading rates

Batten	Quasi-static loading (1 mm/min)		Dynamic loading (300 mm/min)		$A=F_{ov\text{-}300}/F_{ov\text{-}1}$	$B=f_{u\text{-}300}/f_{u\text{-}1}$	Factor $\{R=A/B\}$
	$F_{ov\text{-}1}$ (kN)	$f_{u\text{-}1}$ (MPa)	$F_{ov\text{-}300}$ (kN)	$f_{u\text{-}300}$ (MPa)			
G550-0.75mm	3.48	661	3.93	677	1.13	1.02	1.10
G550-0.95mm	5.22	615	5.99	629	1.15	1.02	1.12
G300-0.80mm	3.60	378	4.23	398	1.18	1.05	1.12
G300-1.00mm	4.65	366	5.56	387	1.20	1.06	1.13

According to *Table 8*, the increment in F_{ov} is not equal to the increment in f_u. This is considered to be due to the difference in the fracture modes observed in the tensile coupon and pull-through batten tests. However, a straight line relationship can be found (refer columns A, B and R). Therefore, in order to predict the pull-through capacity at 300 mm/min dynamic loading rate, the existing design equations can be used by including a factor, R. The modified capacity equations are given in *Eqs. (3)* and *(4)*, and R for 300 mm/min dynamic test ($R_{\text{-}300}$) is listed in the last column of *Table 8*. For simple use, $R_{\text{-}300}$ can be taken as 1.12 for all four battens. In a similar way, R can be obtained for a range of loading rates. However, more tests at various loading rates are needed to verify the equations to predict the pull-through capacities in the case of varying loading rates.

For G550 steel roof battens: $$\Phi\ F_{ov-300} = \Phi\ 8.68\ R_{300}\, t^2 f_{u-300} \qquad (3)$$

and, For G300 steel roof battens: $$\Phi\ F_{ov-300} = \Phi\ 3.07\ R_{300}\, t^{1.4} d^{0.6} f_{u-300} \qquad (4)$$

However, this study recommends the use of *Eqs. (1)* and *(2)* to conservatively design the battens for static pull-through failure and the LHL cyclic tests at 1 Hz with the middle sequence loading rate of 1 mm/min to design the battens for cyclic wind load applications. *Eqs. (3)* and *(4)* can only be used for special purposes to predict the actual capacities of roof battens. However, it should be noted that *Eqs. (3)* and *(4)* are only proposed for F_{ov} at a wind loading rate closer to 300 mm/min.

5 CONCLUSION

This paper discusses the influence of strain/loading rate on both the static and cyclic pull-through capacities of CFS roof battens based on a series of quasi-static, dynamic and constant and multi-level cyclic pull-through tests. The strain rate sensitivity on the ultimate tensile strength of CFS has also been investigated by means of quasi-static and dynamic tensile coupon tests conducted at a loading rate in the range of 1 - 300 mm/min. Based on the test results, the reasons for the increment in the pull-through capacity of roof battens with increasing loading rate is discussed. Finally, the static pull-through design equations [7, 8] were modified to include the effect of loading rate, and a recommendation is made in relation to the loading rate and frequency to be used with LHL cyclic tests.

6 ACKNOWLEDGMENT

The authors are grateful to Australian Research Council and Queensland University of Technology (QUT) for the financial support and necessary facilities provided, Banyo Pilot Plant Precinct and QUT - O-block technical staff for the laboratory technical support and finally to Daniel Mill and Sudarshan Bhandari for the support given in conducting some of the laboratory tests.

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