Engineering Structures 177 (2018) 459–472

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Pull-through capacities of cold-formed steel roof battens considering loading rate sensitivity

Kathekeyan Myuran, Mahen Mahendran*, Mayooran Sivapathasundaram

Queensland University of Technology (QUT), Brisbane, Australia

A R T I C L E I N F O

Keywords:
Cold-formed steel roof battens
Pull-through failures
Static and cyclic tests
Low-high-low cyclic tests
Loading rate

A B S T R A C T

Static and fatigue pull-through failures of thin steel roof battens in the vicinity of batten to rafter screw connections are part of the major premature connection failures which lead to severe roof failures during high wind events. As wind speed and thereby wind uplift loading rate on a building roof varies over a wide range, the loading rate which should be used to conduct prototype roof tests is a moot point. Current wind loading standards and guidelines recommend a wider range of loading rates/frequencies in simulating static and cyclic wind loads. This could adversely affect the test results of loading/strain rate sensitive materials. Since cold-formed steels appear to be sensitive to loading rate, it is necessary to investigate the effect of loading rate on both static and fatigue pull-through capacities of cold-formed steel roof battens. Therefore, a series of static and cyclic pull-through tests was conducted at various loading rates on roof battens made of two grades (G300 and G550) and two thicknesses (0.75/0.80 and 0.95/1.00 mm). Test results showed that both static and fatigue pull-through capacities increase with increasing loading rate. To understand the loading rate sensitivity of roof battens, the effect of loading rate on the ultimate tensile strength of cold-formed steels was also investigated through a series of tensile coupon tests. Based on both pull-through and tensile coupon test results, suitable modifications and recommendations have been made to the current pull-through capacity equations and the current Low-High-Low (LHL) cyclic test loading frequency. A suitable material model is also proposed to determine the dynamic mechanical properties of cold-formed steels.

1. Introduction

Thin cold-formed steels are high strength construction materials of special interest to the building industry. As they are used to produce roof sheeting and battens exposed to fluctuating high wind loads, their sensitivity to loading rate must be well understood for the design of safe and economical roof structures. For roof components exposed to high wind uplift loads, their screw fastener connection failures such as pull-through and pull-out failures are the most common and critical failures. Therefore, the effect of loading rate on such connection failures is a critical issue that needs to be investigated. This study focuses on the effect of loading rate on the pull-through failure of roof batten to rafter or truss connections. Fig. 1(a) and (b) show the static and fatigue pull-through failure modes of batten to rafter or truss connections, respectively.

Roof components are subjected to a certain wind loading frequency, considered to be in the range of 1–3 Hz. Cyclonic wind loading that produces premature, low cycle fatigue failures of roof components (specially connections) is also believed to have a frequency up to 3 Hz [1]. The cyclonic wind pressure variations recorded during real cyclones, as reported in [2,3], also confirm such high wind loading frequencies. Considering this wind loading frequency range (1–3 Hz), many cyclic test guidelines [4,5] recommend prototype cyclic wind loading tests at a frequency less than 3 Hz, based on the assumption that the effect of loading rate on the wind uplift capacity of roof components is negligible. Although the cyclic test maximum loading rate can go up to 3 Hz, some research studies [6] have used a very slow loading rate of 2.54 mm/min to simulate cyclic wind loads.

Although the loads acting on building roofs during cyclones are cyclic loads at a high frequency, some standards, test guidelines and research studies [7–10] recommend conducting tests under quasi-static loading to simulate severe wind storm actions. The static test based designs cannot be used to design buildings prone to cyclones or hurricanes. Similar to the cyclic test standards, these static test standards and guidelines [7–10] also recommend a large range of loading rates from 1 to 51 mm/min. Many researchers [11–14] conducted wind uplift tests using different loading rates, assuming that the failure capacities do not vary with loading rate. For example, the current design equations for

---

* Corresponding author.
E-mail address: m.mahendran@qut.edu.au (M. Mahendran).

https://doi.org/10.1016/j.engstruct.2018.09.008
Received 24 October 2017; Received in revised form 31 August 2018; Accepted 8 September 2018

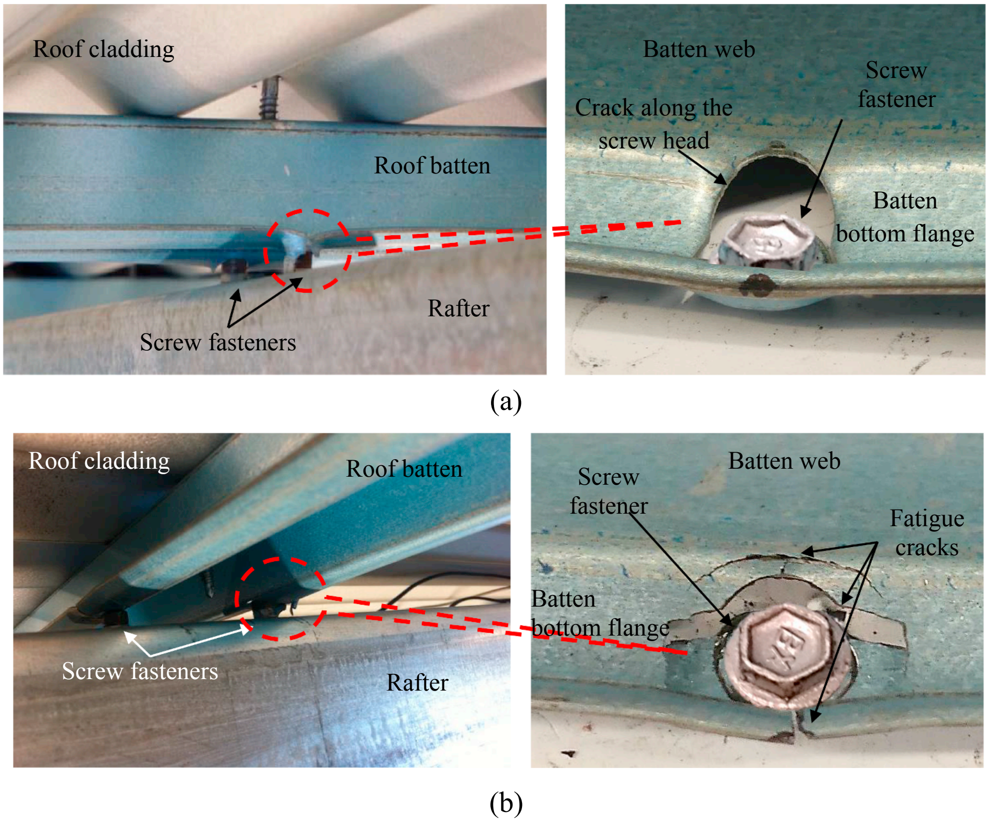

Fig. 1. Pull-through failure modes: (a) Static; (b) fatigue.

the static pull-through capacity of roof batten to rafter connections, recommended in [15,16], were developed based on static pull-through tests conducted at a quasi-static loading rate of 1 mm/min based on the American Iron and Steel Institute (AISI) test guidelines [7]. However, similar static wind uplift capacities of different roof connections and members investigated by Reinhold and Rosowsky [12], McBride et al. [11], Morrison and Kopp [14] and Baskaran et al. [13] used 2.54, 2.92, 2.54–6.35 and 51 mm/min loading rates, respectively. This implies that currently available test guidelines and past wind uplift studies are based on the assumption that the influence of loading rate on the wind uplift capacities of roof components is insignificant. Conversely, if the roof components are very sensitive to loading rate, the tests conducted at slower loading rates would lead to much conservative designs and thereby affect the cost effectiveness of buildings. Similarly, the tests conducted at faster loading rates would lead to unconservative designs, and thereby significantly affect the safety of buildings. Therefore, it is important to investigate the effect of loading rate on the pull-through capacities of cold-formed steel roof battens. This paper presents the details of an experimental study based on pull-through tests and tensile coupon tests and discusses the effect of loading rate on the pull-through capacities of cold-formed steel roof battens subjected to high wind uplift loads.

2. Current pull-through capacity design rules

2.1. Static pull-through design

Current design of roof battens in non-cyclonic areas is based on capacity tables prepared by their manufacturers. The specified batten spacings and spans in the capacity tables are obtained based on the minimum batten capacities based on the member (bending) and connection (pull-through and pull-out) capacities. These capacities are obtained either based on experiments or available design capacity equations. Among them, the pull-through capacities (F_{ov}) are obtained based on the following equations developed in [15,16].

For G550 battens:

$$\Phi F_{ov} = \Phi 8.68\, t^2 f_u \quad (11 \leqslant d \leqslant 14.5\text{ mm} \;\&\; 0.42 \leqslant t \leqslant 1.15\text{ mm}) \tag{1}$$

and, for G300 battens:

$$\Phi F_{ov} = \Phi\, 3.07\, t^{1.4} d^{0.6} f_u \quad (11 \leqslant d \leqslant 14.5\text{ mm} \;\&\; 0.80 \leqslant t \leqslant 1.00\text{ mm}) \tag{2}$$

where F_{ov} - batten pull-through capacity, t - batten thickness, d - screw head diameter, f_u – ultimate tensile strength of steel and Φ - capacity reduction factor equal to 0.6.

2.2. Fatigue pull-through design

The current fatigue pull-through design of steel roof battens for buildings in cyclonic regions is based on the Low-High-Low (LHL) cyclic test as specified in the National Construction Code [4]. Prototype roof assemblies including batten to rafter connections have to survive seven sequences of cyclic loads shown in Table 1 without disengagement of any roofing component. Cyclic loads must be applied at a frequency less

Table 1
LHL cyclic test pressure sequences [4].

Sequence	Number of cycles	Cyclic loads
A	4500	0–45% P_t
B	600	0–60% P_t
C	80	0–80% P_t
D	1 (10 s hold)	0–100% P_t
E	80	0–80% P_t
F	600	0–60% P_t
G	4500	0–45% P_t

P_t - Ultimate limit state wind pressure.