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A strain criterion for pull-through failures in crest-fixed steel claddings

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ABSTRACT

Crest-fixed steel claddings made of thin, high strength steel often suffer from local pull-through failures at their screw connections during high wind events such as storms and hurricanes. Adequate design provisions are not available for these cladding systems except for the expensive testing provisions. Since the local pull-through failures in the less ductile steel claddings are initiated by transverse splitting at the fastener holes, numerical studies have not been able to determine the pull-through failure loads. Numerical studies could be used if a reliable splitting criterion is available. Therefore, a series of two-span cladding and small scale tests was conducted on a range of crest-fixed steel cladding systems under simulated wind uplift loads. The strains in the sheeting around the critical central support screw fastener holes were measured until the pull-through failure occurred. This paper presents the details of the experimental investigation and the results including a strain criterion for the local pull-through failures in crest-fixed steel claddings.

1. Introduction

In Australia and its neighbouring countries, trapezoidal and corrugated steel roof claddings made of thin (0.42 mm base metal thickness), high strength steel G550 (minimum yield stress 550 MPa) are commonly used in the building industry. They are always crest-fixed when used as roof cladding as shown in Fig. 1. The connection between roof sheeting and battens/purlins is often the weakest link in the structural system when subjected to wind uplift loading. The loss of roofing results in severe damage to the entire building and its contents. This situation is continuing because of the lower priority given to the design of roof and wall cladding systems.

Field and laboratory investigations and past researches [1–3] have shown that loss of steel roofs has often occurred due to local failures of their screwed connections. The presence of large stress concentrations around the fastener holes under wind uplift loading is attributed to the local pull-through or pull-over failures at screwed connections in which the roof sheeting is pulled through or pulled over the fastener heads (see Fig. 2(a)). These failures are initiated by a transverse split at the screw fastener hole [4–6]. For some steel roofing, a local dimpling failure occurs without any transverse splitting/fracture (see Fig. 2(b)). In this case the disengagement of sheeting does not occur and it is a preferred failure mode. Past research has shown that the stress/strain patterns around the fastener hole are very complicated. However, it is considered that there must be a unique strain criterion for the transverse split caused pull-through failures. This paper is therefore aimed at determining this criterion, which can be used in the numerical modelling of crest-fixed steel claddings.

Currently, the Australian cold-formed steel structures standard AS/NZS 4600 [7] gives the following formula for the capacity of screwed connections in tension (F_{ov}).

$$F_{ov} = 1.5 t d_w f_u \quad (1)$$

where

t = thickness of steel cladding material

d_w = larger value of the screw head or the washer diameter $\leq$ 12.5 mm

f_u = ultimate tensile strength of steel.

However, its accuracy for the pull-through strength of crest-fixed claddings is questionable, and thus cladding manufacturers rely on an expensive testing process. Recently, Mahendran and Tang [6] have developed a design formula for the pull-through strength of crest-fixed steel claddings.

$$F_{ov} = c d_w^{\alpha} t^{\beta} f_u^{\chi} \quad (2)$$

where $c = 0.22, 0.23$, $\alpha = 0.4, 0.2$, $\beta = 2.2, 1.7$, $\chi = 0.4, 0.4$ for the standard trapezoidal claddings Type A (with wide pans) and Type B (with closely spaced ribs) shown in Fig. 1(a), respectively, while others have been defined in Eq. (1).

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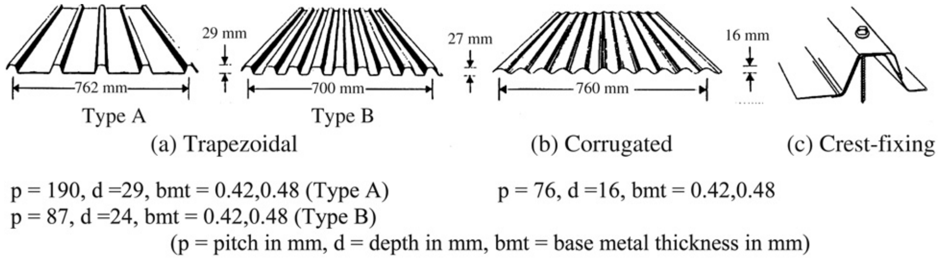
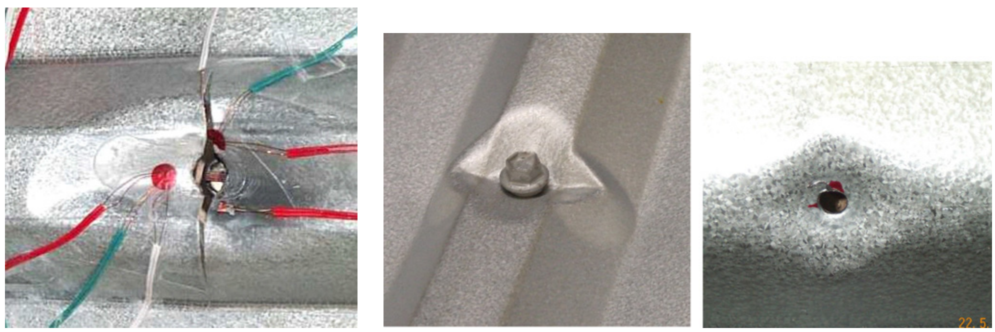


Fig. 1. Standard profiled steel cladding systems used in Australia.



(a) Local pull-through failures with transverse splitting.

(b) Local dimpling failure in Type B trapezoidal and corrugated roof sheeting.

Fig. 2. Local failures at screwed connections.

However, their research was mainly based on small-scale tests, and has not resolved the critical issue of splitting at the screw holes.

Since the local pull-through failures in the less ductile G550 steel claddings are initiated by transverse splitting at the fastener hole, Tang [8] found that the finite element analyses could not predict the failure loads as elastic–perfect plastic material behaviour with infinite ductility is assumed without any allowance for splitting. Numerical studies could be used only if a reliable splitting criterion is available. Therefore, a series of full-scale two-span cladding tests was conducted on a range of crest-fixed steel cladding systems under simulated wind uplift loads. The strains in the sheeting around the critical screw fastener hole were measured until the pull-through failure occurred. The results were then used to develop a strain criterion. The failure loads were also used to verify the design formula (Eq. (2)) developed recently from small-scale tests. This paper presents the details of this experimental investigation and the results.

2. Experimental method

Analyses of a multi-span roofing assembly show that the critical second support from the eaves or ridge of the roof is adequately represented by the central support of a two-span roofing assembly. Therefore, in this study a two-span roofing assembly with simply supported ends was tested under a wind uplift pressure loading (see Fig. 3(a)). In order to accurately simulate a uniform wind uplift pressure, an air box measuring 1800 mm wide by 4200 mm long by 300 mm deep was used (Fig. 3(b)). The test roofing assembly was set-up up side down in the air-box, which was then sealed with 4.5 μm polythene sheets. The uniform wind uplift pressure was simulated by extracting the air from the air box using a vacuum pump. Most of the test roofing assemblies were 800 mm wide (one sheet wide) $\times$ 1000–2300 mm long as their span was varied from 425 to 1100 mm (Fig. 3(c)). The gaps on both sides of the roofing assembly were filled with polystyrene foam.

The trapezoidal Type A (Fig. 1) roofing sheets were fastened at every crest whereas trapezoidal Type B and corrugated roofing sheets were fastened at alternate crests as recommended by the manufacturers. In order to investigate the splitting mechanism in a variety of roofing profiles and to determine the effect of profile geometry on splitting criterion, many non-standard Type A roofing sheets were made in the university workshop and were used in the tests with a shorter span of 425 mm and also in some small scale tests (see Tables 1 and 2). The No.14-10$\times$50 mm Type 17 self-drilling screws with neoprene washers were used to secure the test sheet to the timber supports. The No.14 screws have head and shaft diameters of 14.5 mm and 5.1 mm, respectively, and the 2 mm thick neoprene washers have outside and inside diameters of 11 mm and 5 mm, respectively. All the screws were centred at the crests, set perpendicular to the plane of the sheet and tightened until the neoprene washers were just prevented from rotating to avoid over-tightened or loose screws.

The load per fastener at the central support is an important parameter controlling the pull-through failures [1]. Therefore, two 5 kN load cells were used to measure the loads in two of the central support fasteners. For this purpose the crests of roofing and the central support purlins were predrilled for the insertion of specially made screws. These special screws had the same No.14-10 screw heads, but had a longer shaft (300 mm). The 5 kN load cells were inserted within the longer shaft and tightened with end plates (see Fig. 4). In addition to the measurement of individual fastener loads at the central support, the reaction forces at the ends of central and end support purlins were also measured using four 30 kN load cells (see Fig. 3(a)). The latter measurements enabled the determination of the average load per fastener at the central support. The pressure in the air box was monitored by a pressure gauge that had been calibrated with a manometer. It was then used to calculate the nominal load per fastener at the central support using a simple formula. Deflections of the steel claddings were measured using five displacement transducers at important locations such as the central support and midspan crests and pans (see Fig. 3).

Eight 2 mm strain gauges were used in each test to determine the strains in the roofing in the vicinity of central support fasteners. Since the principal strain directions were unknown, three arm