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Standing seam metal roofs under extreme winds

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The following presents a summary of *Failure mechanisms and load paths in a standing seam metal roof under extreme wind loads; Engineering Structures 296 (2023)*.

Standing seam metal roof (SSMR) systems are widely used due to light weight, high strength, and convenient construction. The typical components and structure of a SSMR system are shown in Figure 1. Instead of using penetrative screws, two panels are mechanically fastened together at the seam, which provides superior watertight qualities. Different from traditional roof systems with large masses, roof panels of SSMR systems experience large geometric deformations, even under low wind pressures, changing the structural behaviour of the roof system significantly. Previous research has shown that the formation of conical vortices by oblique or cornering winds create strong uplift forces on the roof surface (see Image 1). Under increasing uplift load, the seams can be forced apart, resulting in clip pullout failure.

Several standardized pressure tests have been used to evaluate the performance of SSMR systems subjected to wind load. Most of these works focus on the ultimate bearing capacity of the roof systems (e.g. FM 4474, ASTM E1592, UL 580, UL 1897, CSA A123.21). Differences of panel size and boundary conditions change the structural behaviour and failure modes between test and actual field conditions.

Figure 1. Schematic drawings of (a) the panels, seams, and purlins, (b) cross section of the seam and clip, and (c) an isometric view of a clip.

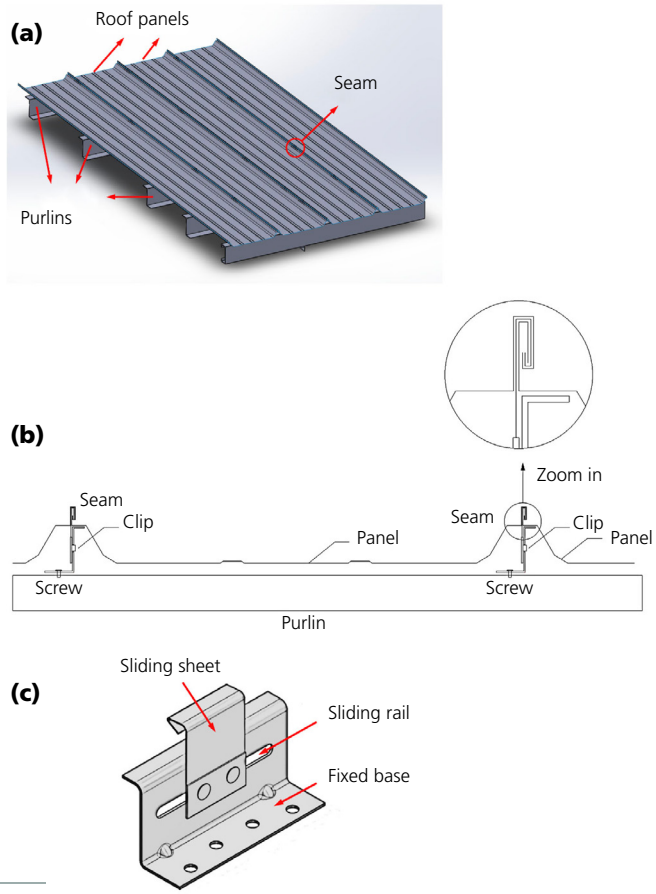
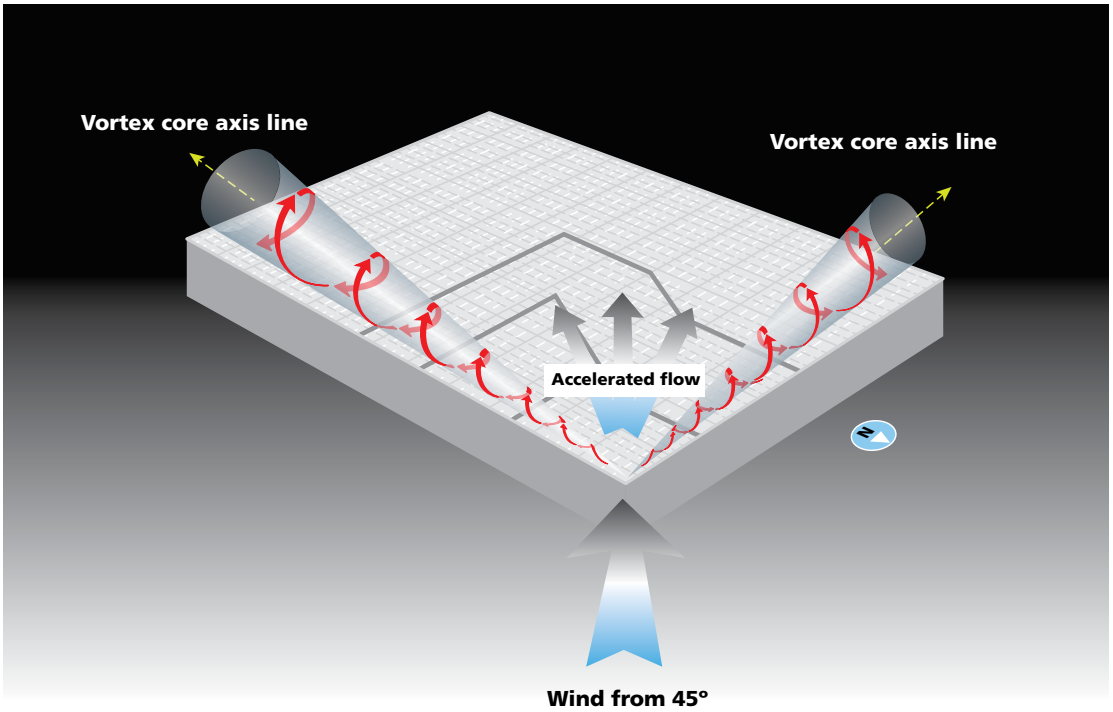


Image 1. Flat roof wind environment:
Cornering winds create conical vortices



Example of conical vortices from cornering winds. Reproduced from https://cppwind.com/get-to-know-a-flow-feature-vortices/. Not in original article.

The objective of this study was to examine the load paths and load sharing in SSMR near the limit state (i.e. the state when the roof is stressed beyond design). With this objective, a series of full-scale experiments were conducted at the Insurance Research Lab for Better Homes (IRLBH) at the University of Western Ontario, London, Canada (see Figure 2). The load deformation behaviour and failure sequence of SSMR systems with realistic panel size, boundary conditions, and wind loading were examined.

The tested SSMR system had a plan dimension of 9.1 m (30 ft) by 11.3 m (37 ft) and a roof slope of 1/4 on 12, which has real perimeter boundary conditions and specimen size. The metal panel had a width of 0.61 m (2 ft), while the panel in the middle of the roof had a width of 0.3 m (1 ft). Figure 3 provides a schematic of the purlin layout and clip locations, as well as the arrangement of pressure chambers.

Figure 2. Photographs of (a) the overall roof of the metal building with panels partially installed, and (b) the installed SSMR.

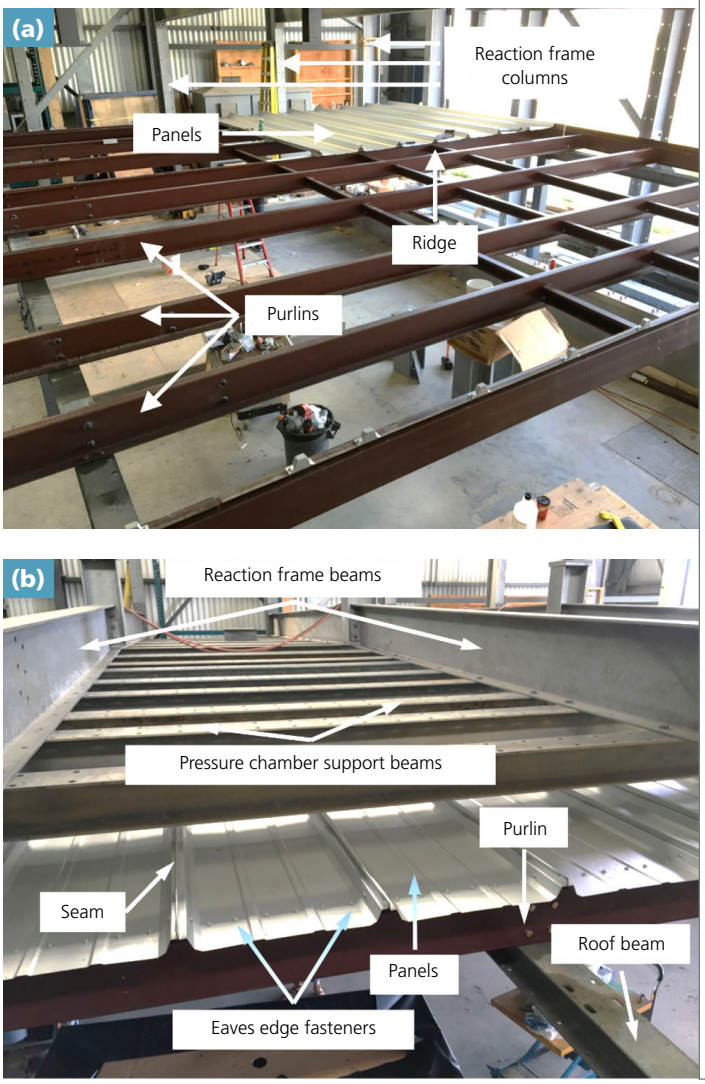
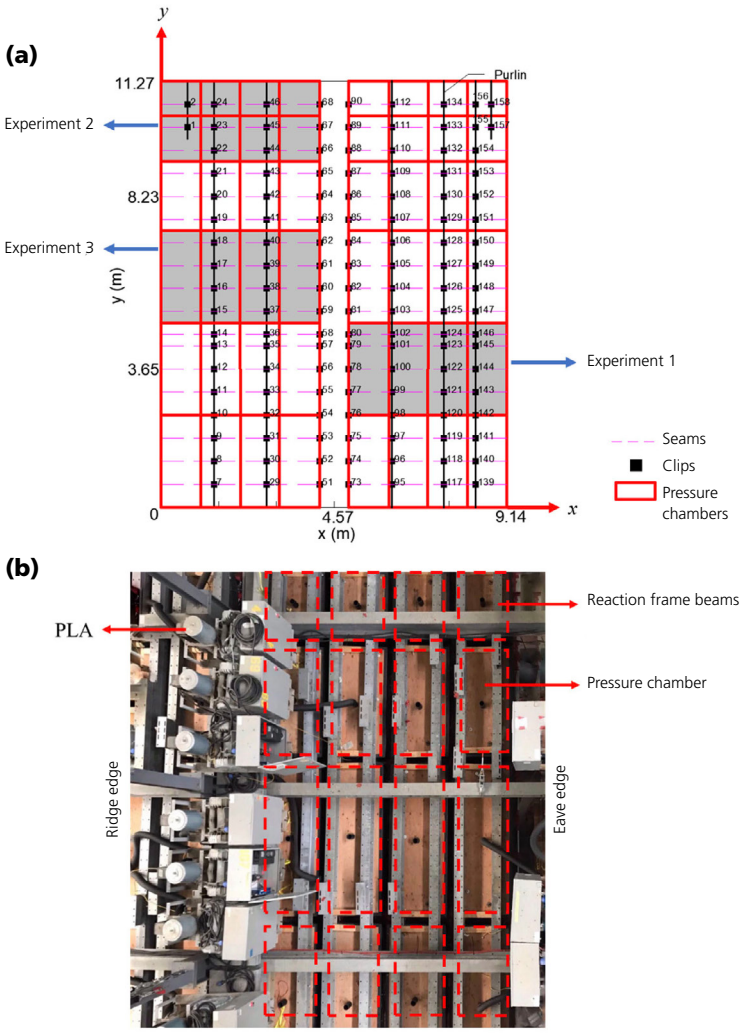


Figure 3. (a) Plan view schematic of the locations for purlins (black lines), clips (black squares), and the arrangement of pressure chambers (red lines) on the tested roof. Note that the numbers are labels for the clips following that of Morrison and Reinhold (2015). (b) Photograph of the roof from above showing PLAs, the reaction frame, and the pressure chambers.



Three experiments were carried out with uniform pressures applied on the roof specimens.

The failure behaviour of the SSMR system subjected to wind pressure under different load conditions was observed, revealing the progressive failure process and characteristics of different failure modes (failure of roof panels, clips, or screws). Before delving into further discussions, it is important to introduce the two failure modes of roof panels: *local buckling* and *global buckling*. *Local buckling* refers to the occurrence of buckling in localized regions of the roof panel without significantly altering the overall form and behaviour of the structure. In contrast, global buckling entails buckling that affects the entire roof panel, leading to significant changes in shape and structural behaviour.

Overview of test parameters and results

	Test 1	Test 2	Test 3
Applied pressure and loading rate	Increased linearly until failure Loading rate: 0.5 kPa/min	Increased successively until failure Loading rate: 0.25 kPa increments with a loading rate of 0.5 kPa/min between steps Rate maintained for 30 s at each step until failure	Dynamic (fluctuating) pressure until failure Time histories include several segments (#1 through #5) Rates maintained for 60 s for each segment
Failure sequence			
Stage 1	**Panel billowing*** • Max. deflection along centreline • No visible damage observed at seams	**Panel billowing** • Max. deflection along centreline • No visible damage observed at seams	**Panel billowing** • Max. deflection along centreline • No visible damage observed at seams
Stage 2	**Partial detachment at seam** • Slight separation between panel and clips • No significant damage observed at seams	**Partial detachment at seam** • Slight separation between panel and clips • No significant damage observed at seams	**Partial detachment at seam** • Slight separation between panel and clips • No significant damage observed at seams
Stage 3	**Local buckling** • Near the seam region • Withdrawal of screw fasteners between panels and underlying structure • No significant damage or fracture detected at seams	**Local buckling** • Near the seam region • Withdrawal of screw fasteners between panels and underlying structure • No significant damage or fracture detected at seams	**Local buckling** • Near the seam region • Withdrawal of screw fasteners between panels and underlying structure • No significant damage or fracture detected at seams
Stage 4	**Global buckling** • Initiated in the middle of the panel • Panels underwent severe deformation • Severe loss of structural integrity, especially at seam	**Global buckling** • Initiated closer to the ridge • Panels underwent severe deformation • Severe loss of structural integrity, especially at seam	**Global buckling** • Initiated in the middle of the panel • Panels underwent severe deformation • Severe loss of structural integrity, especially at seam
Stage 5	**Seam opening** • Permanent deformation of roof panel • Gradual exposing of sliding sheet	**Seam opening** • Permanent deformation of roof panel • Gradual exposing of sliding sheet	**Seam opening** • Permanent deformation of roof panel • Gradual exposing of sliding sheet • **No clip slippage occurred in Test 3** • **Fastener failure was observed** • **In Test 2, the fastener head was intact, while in Test 3, it was fractured** • **Possibly due to dynamic wind pressure used in Test 3** • **More research required**
Stage 6	**Clip slippage** • Sliding sheet disconnected from the seam and roof panels uplifted completely • Clip remained securely fastened to the purlin • No visible damage to the fixed base • Significant damage to eave edge	**Clip slippage** • Sliding sheet disconnected from the seam and roof panels uplifted completely • Clip remained securely fastened to the purlin • No visible damage to the fixed base • Significant damage to eave edge • **Fastener failure at the edges occurred** • **Failure at both the ridge and eave edges, not at a clip** • **Resulted in detachment between the roof panel and purlin**	N/A

* Panel popped up.

In the *global buckling* mode, the stiffness of the roof panel is severely compromised, potentially resulting in structural failure.

To summarize, for all three experiments it was observed that the responses included states 1 to 5 but exhibited different final failure modes. In experiments 1 and 3, global buckling initiated in the middle of the roof panel. However, global buckling initiated closer to the ridge in experiment 2. Only fastener failure occurred in experiment 3. Both clip slippage and fastener withdrawal occurred in experiments 1 and 2, although some capacity remained at eave edge in experiment 1.

These variations in failure modes highlight the influence of boundary conditions and clip arrangement on the initial locations of global buckling.

ASTM E1592 does not provide a specific definition of the ultimate limit state, but does state that failure is "fracture or disengagement of any of the components where the system is no longer capable of sustaining load, or the system no longer functions as a weathertight membrane." Based on the observations from these experiments, multiple failure modes can be associated with SSMR systems, including panel buckling, panel seam separation, and fastener failure. However, it should be noted that the occurrence of these failure modes does not necessarily imply that the roof system is unable to withstand higher loads. For instance, panel buckling may be regarded as a failure, but the roof system may still continue to perform under higher wind loads. However, in traditional wind engineering design, it is typically required that all structural members remain within the linear range when subjected to specified load combinations. Thus, buckling would be considered to be the ultimate limit state.

In contrast, for performance-based wind design, the focus shifts to ensuring that the roof systems can continue to function and withstand higher loads, as the roof panels can be replaced if necessary. Therefore, from the perspective of performance-based design, the ultimate limit state can be defined as the detachment of the roof from the clips or purlins (corresponding to panel seam separation and/or fastener failure). The difference in capacity between these two concepts is significant.

Failure mechanisms and load paths in a standing seam metal roof under extreme wind loads can be purchased online and downloaded at https://www.sciencedirect.com/science/article/abs/pii/S014102962301369X

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