Engineering Structures 105 (2015) 231–248

Contents lists available at ScienceDirect

Engineering Structures

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

Full-scale testing to evaluate the performance of standing seam metal roofs under simulated wind loading

Filmon Habte[a], Maryam Asghari Mooneghi[b], Arindam Gan Chowdhury[a,*], Peter Irwin[a]

[a] Department of Civil and Environmental Engineering, Florida International University, Miami, FL, USA
[b] Advanced Technology and Research, Arup, San Francisco, CA, USA

ARTICLE INFO

Article history:
Received 27 May 2015
Revised 5 October 2015
Accepted 6 October 2015

Keywords:
Full-scale testing
Standing seam metal roof
Roof aerodynamics
Roof panel deflection
Roof failure
Uniform uplift testing
Wall of Wind

ABSTRACT

The current methods for evaluating the adequacy of metal roofs in withstanding wind-induced loads involve undertaking uniform uplift pressure tests. These methods may not be truly representative of real conditions, and might set higher minimum design requirements than necessary in some cases, and in others they could underestimate effects of very localized peak pressures. This research work presents results of a full-scale experimental study conducted under more realistic wind loading with the panels installed as they would be in the American Society for Testing and Materials (ASTM) E1592 test chamber. The research objectives were to (i) measure the uplift roof pressure experience by mono-sloped standing seam metal roofs and compare them with the provisions of the American Society of Civil Engineers (ASCE) 7–10 standard, (ii) evaluate the performance of standing seam roofs under high winds, and (iii) compare the deflections and failure modes observed under more realistic wind loading to uniform loading tests. The research has provided test based data on aerodynamic loading of two types of standing seam metal roofs (i.e. vertical-leg and trapezoidal), as well as their performances under high wind speeds. Significantly higher pressure was recorded on the trapezoidal roof. This showed that roof panel profile and perimeter eave attachments can significantly affect uplift pressures. The ASCE 7–10 standard was observed to underestimate corner wind suctions on trapezoidal roof. Lower deflections were recorded by the vertical-leg roof owing to its higher stiffness and lower suctions experienced. The ASTM E1592 test protocol was observed to produce higher deflections and more conservative failure wind speeds than those experienced in the current tests. However, entirely different failure modes were observed between the uniform and dynamic tests. This was attributed to wind-induced vibrations that were observed in the current tests that are not present in the ASTM E1592 test, which is entirely static. The current research results may suggest future directions to enhance the existing testing standards.

1. Introduction

Roofs have been identified as one of the most wind storm vulnerable components of a building envelope. High dynamic wind suctions created at the surface of a roof due to wind flow separation (or conical vortices) coupled with positive internal pressures are the main cause of damage to the roof systems. Water leaking through a failed roofing system during rain accompanied wind storms can result in major damage to interior contents, disrupt the functionality of critical and essential facilities, and even cause ceiling weakening and collapse which can result in injury to the occupants [1–3]. Currently, the performance of metal roofs under wind load is evaluated by undertaking physical tests to assess their capability to withstand a “design load” as provided by wind loading codes and standards. The ability of such tests to assess the true performance of the roof system depends on how well the tests represent the true wind loading actually experienced in wind storm conditions.

In North America, the methods of physical testing protocols which are most commonly recommended by testing standards to evaluate the adequacy of metal roof panels in withstanding wind loads are the Underwriter Laboratories (UL) 580 [4] and American Society for Testing and Materials (ASTM) E1592 testing protocols [5]. The UL 580 involves putting the test specimen in a pressure chamber capable of applying steady positive pressure on the underside of the test assembly and a uniform oscillating negative

---

[*] Corresponding author at: Dept. of Civil & Environmental Engineering, Florida International University, 10555 W. Flagler Street, Engineering Center, EC 3604, Miami, FL 33174, USA. Tel.: +1 305 348 0518.

E-mail addresses: fhabt003@fiu.edu (F. Habte), maryam.asghari@arup.com (M. Asghari Mooneghi), chowdhur@fiu.edu (A. Gan Chowdhury), peairwi@fiu.edu (P. Irwin).

http://dx.doi.org/10.1016/j.engstruct.2015.10.006

pressure on its top surface. Regular checks for permanent deformations are conducted, and the roof metal is assigned a class rating depending upon the magnitude of positive and negative pressures that cause permanent deformation. In the ASTM E1592, a static positive air pressure is applied on the underside of a test specimen at regular pressure increments until failure of principal or critical element is observed. The deflections and deformations of panels and anchors are recorded, from which load versus deformation curves are obtained. Those plots are then used to evaluate the strength and serviceability of the metal panels. Both testing protocols use defined positive/negative pressures that include neither the temporal nor the spatial pressure variations which are inherent in "real" wind loading, and might on one hand set higher minimum design requirements for the entire system than necessary or on the other hand might underestimate effects of localized peak pressures on critical locations. Moreover, the modes of roof specimen failures observed in uniform loading tests might not be representative of observed field failures [6,7].

Experiments conducted using the BRERWULF setup were one of the earliest efforts to evaluate the performance of standing seam metal roofs subjected to non-static simulated uplift pressures [8]. Although the BRERWULF setup can apply pre-defined time varying pressure loads on a specimen, it uses uniform pressure hence doesn't duplicate the spatial variation of actual wind loading [8]. The authors in [8] used influence surface experiments to understand the spatial variation in load transfer mechanism of standing seam metal roofs. They also showed that the choice of specimen end restraints can significantly affect the clip loads. Under the objective of relating high local loads to their corresponding design uniform static loads, Sinno et al. [9] used electromagnetic drivers to simulate the non-uniform dynamic uplift forces due to wind on standing seam metal roofs at Mississippi State University (MSU). Even though the tests at MSU used real roof structures, and applied dynamic uplift forces on the roof, the resolution of the forces was limited and the magnetic actuators could apply loads of single polarity [7]. Farquhar et al. [10] conducted small scale uniform uplift and dynamic wind tunnel pressure tests on elastic standing seam roof model at University of Western Ontario (UWO), and formulated an effective pressure coefficient that can relate uniform uplift failure pressures with the actual dynamic wind pressures that cause clip-failure. Those authors also demonstrated that the relationship of effective uniform pressure to wind speed can be predicted analytically, with good accuracy, by integrating clip reaction influence functions with non-uniform external pressures measured on a rigid model in the wind tunnel. Even though the tests at UWO used "realistic" wind loads, scaled models of standing seam metal panels were used, which posed difficulty in modeling the detailed behavior of all roof components in small-scale. In full-scale testing, besides being able to represent the true details of roof systems, Reynolds number mismatches, which are inherent in small scale wind tunnel experiments, can be avoided. In small-scale experiments, the viscous forces within high-frequency turbulent eddies become larger than their full-scale counterparts and cause viscous dissipation of those eddies' energy [11]. In a sense, while the MSU tests used real roofs under approximated wind load, the UWO tests used realistic wind load but approximated roof structures. The results from both approaches suggest that the ASTM E1592 test contains conservatism of as much as about 50% for the particular roof systems studied [7].

The objective of this paper is to understand the behavior of standing seam metal roofs under as close to realistic wind loading as possible and using full scale specimens rather than models. Experimental investigations which included aerodynamic pressure measurement and deflection measurement were carried out on mono-sloped full-scale standing seam metal roofs using Florida International University's (FIU) Wall of Wind (WOW) facility. To evaluate the adequacy of the "design loads" adopted in the testing of the roof panels, the pressure results were compared with the provisions of the ASCE 7–10 standard [12]. Although it is generally agreed that using realistic wind loading and real mockups produces the best results, the costs associated with running tests on a large scale test specimen for all angles and speeds in a large wind tunnel represents an impediment to undertaking such tests on a routine basis for product approval purposes. Therefore, one of the objectives of this research is to compare the performance of identical metal roof systems under dynamic and uniform wind loading. The strength and serviceability performance of identical metal roofs under uniform and realistic wind loads are evaluated and compared. This is expected to be helpful in evaluating the validity of conventional uniform pressure testing protocols.

2. Experimental setup and testing protocols

Two types of standing seam metal roof systems; a vertical-leg standing seam metal roof and a trapezoidal standing seam metal were selected for testing. A two-phase full-scale experimental investigation was conducted on each roof system. The vertical-leg standing seam metal roof and the trapezoidal standing seam metal roof are henceforth referred to as vertical-leg roof and trapezoidal roof respectively for brevity. In the first phase, aerodynamic pressure measurements were conducted at different wind directions. In the second phase, deflection measurements were undertaken at different wind directions and different wind speeds. Failure observations were also performed.

2.1. FIU 12-fan Wall of Wind (WOW)

The 12-fan Wall of Wind (WOW) open jet facility at Florida International University (FIU) was used to generate the wind field in this experimental investigation. The 12 electric fans are arranged in a two-row by six-column pattern to produce a wind field 6.10 m (20 ft.) wide and 4.27 m (14 ft.) high, allowing aerodynamic testing of large-scale models or full-scale portions of buildings. A contraction section is used downwind of the array of 12 fans to create acceleration of the flow and the attainment of a uniform flow field with high wind speeds (up-to 70 m/s (157 mph)). A 9.75 m (32 ft.) long flow simulation section downwind of the contraction incorporates triangular spires and floor roughness and provides the required fetch length and flow confinement to develop the desired mean velocity profile and turbulence characteristics. Fig. 1 shows the WOW simulated open country condition's mean wind speed (with target velocity profile exponent $\alpha = 1/6.5$) and turbulence intensity which were used in the experiments. It should be noted that the tests were performed in partial turbulence simulation, hence the turbulence intensity at roof height was lower than that of atmospheric boundary layer (ABL) which contains full spectrum of turbulence. However, using the method proposed by Irwin [13,14] and Asghari Mooneghi [15,16] the adequacy of the current turbulence intensity can be shown. The comparison of the WOW partial spectrum and Kaimal spectrum (Fig. 2) shows that while the low-frequency turbulence is missing, satisfactory agreement is achieved in the high frequency end which has been noted by a number of researchers [17–21] as necessary for the correct simulation of flow separation and reattachment.

2.2. Test building model and roof systems

The standing seam metal roofs were attached to a base structure which was designed to support interchangeable mono-sloped roofs