Reliability based design of Standing Seam Metal Roofing System

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Abstract

Safety of metal roof is vital to the survival of steel buildings in cyclone. Loss of weather protection will lead to water damage to building interiors. In order to protect the roof cladding, it is essential to enhance the hold-down capacity of the panel connectors, especially at the edge zones. In a through fastened roof system, this is achieved by reducing the screw spacing at the critical zones. But it is not possible to reduce the connector spacing in Standing Seam Metal Roofing (SSMR) system, as it is limited by the panel width. Experimental studies have been made to systematically study the performance of a standing seam metal roof system in the event of wind uplift. The safety of current construction practice has been examined by a reliability analysis of the experimental results. A reliability analysis is carried out using the non-uniformity of wind pressure on roof surface. Critical zones are identified based on reliability index values. Redesign is suggested by varying the halter length and reducing purlin spacing, based on the concept of an adjustable halter length in critical zones.

Keywords: Metal roof; SSMR system; Reliability analysis; Adjustable halter length; Fuse for steel building

1. Introduction

Significant damage to metal roof systems is observed after every cyclonic storm. Due to the changes in the global climatic conditions, the frequency of cyclonic attack has become more, the evidence of which are observed worldwide for the last few years. The action of wind on a pre-engineered building, as well as the behavior of a roofing system under wind uplift are affected by a number of factors. Current construction practices do not take into account the spatial variation of pressure on roof surface for design of panel-purlin connection in metal roofing system. Many varieties of roofing panels and clips/halters are in use and hence a unified design procedure is not viable. A rational design procedure rooted on experimental evidences is essential.

Experimental investigations were carried out for the estimation of the capacity of Standing Seam Metal Roofing (SSMR) systems under wind uplift. Tests were done as per the standard uniform static air pressure difference method, as given in ASTM:E1592-05 (Reapproved 2012)[1]. Analysis of the results, proposal of new design method and a few guidelines for construction of SSMR system based on the analysis are discussed here.

1.1. Rigid purlin-panel system

Usually purlins are sufficiently stabilized using anchorage devices such as sag rods, bridging and anti-roll clips. They do not roll along with panel during loading. The concept of sag rods was introduced for roofs with slope more than 1:5. However for pre-engineered building systems, even at 1:10 slopes, sag rods are still provided. This further stabilizes the purlins. Such a system can be considered as ‘rigid purlin-panel system’. Earlier literature on SSMR systems have been focusing mainly on strength and stability of purlin. Three limit states of strength for design of panel-halter-purlin connection in SSMR system have been introduced by the authors. They are (i) halter-panel disengagement (mode 1), (ii) pull-out of halter (mode 2) and (iii) yielding of halter base (mode 3) [2][3].
2. **SSMR system with uniform safety over the surface**

The objective of the integral design of the SSMR system is to ensure its ‘satisfactory performance’ during action of wind. The meaning of ‘satisfactory performance’ may be described by the following set of performance objectives:

a) The roof should resist low, medium and high wind pressures
   i. without any damage to the roof panel or building frame (rigid purlin).
   ii. with panel-purlin interaction, deforming building frame (flexible purlin).

b) The roof should resist cyclonic wind pressure by releasing the energy by opening out of a part of the roof (fuse).

Evolving a design method integrating the above objective is highly complicated due to the high degree of uncertainty inherent in it. There are large uncertainties in predicting the intensity and characteristics of future winds. Hence it is necessary that the design procedure should reflect this uncertainty. The response of the roof structure is also highly unpredictable due to large variability of system capacity. With the aid of reliability analysis, it is possible to achieve an SSMR system, which can withstand the wind uplifting forces with a uniform safety across the entire roof surface. The steps in the design are as follows:

I. **Wind load analysis**: Determination of halter pulling force at various zones of the roof for different cases of wind load and building permeability.

II. **Reliability analysis**: Calculation of reliability index in each case with the mean resistance as obtained from tests and mean halter pull (average gripping resistance) as obtained from step I.

III. Marking the zones where reliability indices fall short of the target value (target reliability index).

IV. Calculation of the halter length or purlin spacing required for achieving the target reliability index.

3. **Wind Load Analysis**

Wind load acting normal to the roof panel at different locations on the roof is determined by taking into account the pressure difference between opposite faces of the roof panel, as given by Section 7.3.1 of IS:875 (Part3)[4]. As a demonstration of the proposed method, four wind pressure cases, (three as given in SP:38 (S&T)[5] along with cyclonic wind pressure) are considered, viz., Low: 1 kPa, Medium: 1.5 kPa, High: 2 kPa and Cyclonic: 2.5 kPa. Three cases of building permeability are considered, viz., enclosed, medium opening and large opening. Various load combinations are considered with DL/ LL = 0.267, CoL/ DL = 1. The load condition (0.9 DL - wind uplift) is the most critical combination considered. Appropriate external pressure coefficients to be used at zones of high local suction, for a roof angle of 5°, for different wind directions and building heights, taken from Table 6 of the code. Choosing appropriate values of external pressure coefficients for panel and edge zones on windward and leeward side, net pressure on the panel is calculated as

\[
q = 0.9 \left( D_m - (C_{pe} - C_{pi})W_m \right)
\]

Mean pulling force in halter, \( Q_m = q.a.b / L \)

where,

- DL: Dead Load
- CoL: Co-lateral load
- C_{pe}: External Pressure coefficient
- W_{m}: Mean wind load
- a: Halter spacing
- LL: Live load
- D_{m}: Mean DL
- C_{pi}: Internal Pressure coefficient
- L: Halter length
- b: Purlin spacing

4. **Reliability Analysis**

The safety of the roof system with respect to various limit states of strength is assessed by a reliability analysis. This also quantifies the applicability of the experimental results to practical designs. Reliability indices (\( \beta \))
are calculated for different regions of the roof surface, for various permeability conditions of the building. A target reliability index (β₀) of 2.5 is adopted as suggested by SEI/ASCE 8-02 (2002)[6]. Indian standard codes assume normal distribution for wind load. The halter resistance values calculated from test data are observed to follow a normal distribution with a mean value of 28.72 N/mm and standard deviation of 3.14. A value of β≤β₀ indicates that the connection is prone to failure and needs redesign.

The reliability index (β) is larger than the target value of 2.50 for the following cases / conditions, which means that the current halter length of 60 mm is sufficient.

1. ‘Enclosed’ building
   - all across the roof at low and medium wind pressures.
   - on leeward panel zones for all wind pressure cases including cyclone.
   - both at windward and leeward panel at high wind.

2. Building with ‘medium’ openings
   - all across the roof at low wind pressures.
   - all across the roof for negative internal pressure.
   - on panel zones at medium wind pressures.
   - on leeward panel zones for all wind pressure cases including cyclone.

3. Building with ‘large’ openings
   - all across the roof at low wind pressures.
   - all across the roof for negative internal pressure.
   - on panel zones at medium wind pressures.
   - on leeward panel zones for all wind pressure cases except cyclone.

In all the cases, redesign is required at edge zones and windward panel zone for cyclonic wind pressure. The same trend of variation of β is observed for both the wind incidence angles of 0° and 90°. Edge zones of the roof of ‘enclosed buildings’, designed with a halter length of 60 mm, become unsafe at a wind pressure of 1.8 kPa, which corresponds to a wind velocity of 54 m/s. Similarly, 50 m/s and 47 m/s respectively are the limiting wind velocities for buildings with ‘medium’ and ‘large’ openings. Higher negative internal pressure in building with ‘medium’ openings and building with ‘large’ openings reduces the uplift on roof considerably. Hence, there is uniform safety on the entire roof of these buildings, which employs the tested system, even at cyclonic wind pressure (2.5 kPa). This corresponds to a wind velocity of 64 m/s. Similar evaluation for eaves height of 10 m shows that the increased turbulence due to storm surge makes the roof much less resistant. Even for medium wind, the edge zones and parts of panel zone on windward side needs redesign.

5. Redesign based on reliability Analysis

The reliability analysis shows that the safety of the panel-purlin interface interaction is limited in some of the areas especially in the edge zones. This results from the fact that the same purlin spacing and halter length are used throughout the plan area of the roofing in conventional construction practice. Redesign is proposed for all cases with β≤β₀.

5.1. Reducing purlin spacing

The safety of the roofing system can be increased by reducing the purlin spacing as low as 900 mm, thereby bringing down the gripping pressure on halters. However, reduced purlin spacing amounts to increasing the weight of the building structure and thereby, the overall cost of construction. Hence, reducing the purlin spacing is not the right solution to bring in uniform safety for the SSMR system.

5.2. Concept of ‘adjustable halter length in critical zones’

It has been observed in the experimental investigations of prototype SSMR that the gripping pressure on the halters is the governing force in the safety of panel-purlin interface interaction. Hence, it is possible to enhance the safety of the interface behavior by simply increasing the length of the halters. Concept of ‘adjustable halter length in critical zones’ is proposed based on the reliability analysis. Minimum halter length required to achieve the target
reliability is suggested. Accordingly, the minimum halter length required at panel and edge zones for cyclonic wind pressure for various purlin spacing are listed in Table 1. On an average, the edge zone halters are 33% longer in comparison to that in the panel zone. A reduction of 100 mm in purlin spacing cuts down the halter length demand by an average of 8%.

Table 1. Proposed design by varying halter length and purlin spacing

| Permeability of building | Zone    | Minimum Halter length, mm for purlin spacing (mm) of |
|--------------------------|---------|------------------------------------------------------|
|                          |         | 1200 | 1100 | 1000 | 900 |
| Enclosed                 | Panel   | 60   | 60   | 60   | 60  |
|                          | edge    | 90   | 80   | 75   | 70  |
| Medium opening           | Panel   | 80   | 70   | 65   | 60  |
|                          | edge    | 105  | 100  | 90   | 80  |
| Large opening            | Panel   | 90   | 80   | 75   | 70  |
|                          | edge    | 120  | 110  | 100  | 90  |

5.3. Increasing flange width of purlin

The aluminum halters are produced by extrusion, and therefore it is possible to make halters of different length to our requirement. However, it is not possible to accommodate the increased length of halter on the purlin, if it exceeds the flange width of the purlin. This indicates the need to increase the flange width of purlin. Usually, the maximum flange width of the C and Z section purlin is 80 to 90 mm. It is seen from the industry practice that, it is possible to provide the flanges as wider as 100 to 110 mm. Thus, by a simple alteration of the halter length, it is possible to increase the gripping pressure on the halters in the edge zones, preserving the same purlin spacing all over the roof area. Fig.1 shows the typical cross sections of Z-section purlin, which are proposed to be used in zones wherever the safety index is violated. A typical purlin-halter assembly using the above configurations is shown in Fig.2.
The lateral buckling strength of the purlin is dependent on the moment of inertia of the purlin about the minor axis of its cross section. In the configurations b and c shown in Fig.1, it is seen that the minor axis moment of inertia is increased. A simple calculation shows that the lateral buckling resistances of these configurations are in the proportion 1: 3: 3.6. Hence, increasing the flange width brings in two advantages: gripping strength of halter is increased, and the lateral buckling capacity of purlin also increased.

5.4. Additional clamping for halters

Thus, by increasing the halter length in the zones where the target reliability is violated, it is possible to achieve uniform safety against mode 1 failure under wind uplift across the entire roof structure. However, increased halter length increases the halter pulling force, which may initiate the failure by mode 2 (halter pull-out) and mode 3 (halter base yielding). The additional pulling force need to be resisted by the screws. Accordingly, in safe zones (where normal halter length is provided) halters can be clamped by four screws, whereas in zones where halter length is increased, six screws should be provided. This arrangement is shown in Fig. 3. The additional pair of screws helps to avoid mode 3 failure also.

The proposal of varying halter length can be easily implemented in construction practice, since, by a small change in the roll set operations, purlins of different flange width can be produced as required. If the increased halter length is not feasible, reduced purlin spacing is proposed as an alternative for achieving a uniform safety over the SSMR surface, which is a costly solution.

6. Concept of part of roof as ‘fuse’ for steel building

It has been observed that in many failures of the metal roof during cyclones, the edges zones contributed to the initiation of failure. Failure of the edge zones quickly releases the internal pressure in the building and the roof is relieved of high uplift pressure. In such a scenario, the roof panel is blown off leaving the supporting structure intact due to less pressure that is transferred onto the supporting skeleton system. This will prevent the propagation of collapse along the wind load flow path and concentrate damage on disposable and easy-to-repair structural elements. On the other hand, if the entire roof panel remains fixed, the supporting structure has to bear all the load extremities. In this case, the supporting structure gets deformed, and any rehabilitation procedure becomes very costly. This phenomenon was observed in two adjacent buildings during the Hud Hud cyclone. In one building, where the roof panels were blown off saved the entire supporting structure. The other building with roof structure clamped down with more screws was completely uprooted and resulted in a costly rehabilitation.

In this study, a reverse analogy is introduced to what has been described in the previous section. This is the concept of providing a lesser halter length in properly identified zones, so that it can initiate mode 1 failure in the event of an extreme wind pressure. With the results from reliability analysis, it is possible to design panel at selected area of roof by providing halter length just adequate to withstand normal pressures, but expected to open out in cyclones. This portion can be considered as a ‘fuse’ for releasing the internal pressure of the entire building. Utmost caution is
required in the application of this concept. Blowing off panel can be hazardous, hence a fixture which allows opening up of panel, without detaching it from halter, must be designed. Implementation of this proposal is straightforward, as we can accommodate the lesser halter length, retaining the original flange width of purlins.

7. Conclusion

The safety of the tested SSMR system as applied on a pitched roof has been evaluated by a reliability analysis. The variation of the resistance has been taken as probabilistic. The probabilistic variation of the load has been taken from the codes of practice. Using these data, the uncertainties and variability involved in the design are quantified as reliability indices at various zones of the roof surface. Limiting wind velocities for buildings with various permeability conditions are suggested.

Redesign of connection is proposed at all critical zones where the target reliability has not been achieved. Minimum required halter lengths have been worked out at these zones for achieving the target reliability. On an average, the edge zone halters end up with lengths which are 33% more in comparison to that in the panel zone. The additional halter length can be accommodated by using purlins with wider flange. The lateral buckling capacity of purlin is also increased by increasing the flange width. A concept of ‘fuse’ for steel building has been introduced, which allows an internal pressure drop by a controlled failure of roof sheeting.

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