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Strength of cold formed steel Z-purlins supporting standing seam metal roofing systems under wind uplift

S. Ravikanth Reddy[1], Arul S Jayachandran[2]

Abstract
Roofing systems along with the cold formed steel purlins are more popular in the secondary frame systems due to high strength to weight ratio and durability. Standing seam roofing sheets after installation provides lateral and torsional support to purlins. This support can alter the structural behavior of purlins and enhance the performance during wind uplift. This paper presents an experimental investigation on Z-purlins supporting standing seam metal roofing (SSMR) systems during wind uplift. The aim is to assess reduction factor for design in determining the nominal flexural strength of the purlin. Test results reveal the effect of the restraint provided by the SSMR systems to the Z-purlins in wind uplift. The test results obtained from the test are compared with Eurocode EN 1993-1-3 2006.

1. Introduction
Cold formed steel purlins as a secondary framing system are the most common in roofing systems due to high strength-to-weight ratio. Along with standing seam roof systems, they provide additional advantages of weather tightness, leak proof performance and durability and these make metal roofing systems more economical and a better option. In the standing seam metal roofing systems (SSMR), the panels are connected to the purlins by hidden clips which are not exposed. The cold formed steel purlins are relatively thin and slender having low lateral and torsional stiffness. During wind uplift, the free flange of the purlin is subjected to compression and receives lateral and torsional support from the sheeting. Thus, the capacity of the purlins supporting standing seam systems may vary from full braced condition to no braced condition. Due to this complexity, the codes of practice do not quantify the restraint effect of SSMR systems to purlins and rather prescribe experimental procedure to predict the failure loads.

To evaluate the interaction effect of the roofing systems, (Soroushian 1982) developed an analytical model by a combination of vertical bending and torsion. The model replaces the sheeting with linear and rotational springs representing the shear and bending stiffness of the sheeting, respectively.(Rousch and Hancock 1997) validated the above analytical models and found a good correlation with the experiments. (Ye, Kettle, and Li 2004) developed an analytical model for predicting the pre-buckling stress distribution and then buckling loads are predicted with a finite strip program with the inclusion of the nodal spring restraints in the model. The authors quantified the influence of the translational and rotational springs on

[1] Research scholar, Indian Institute of Technology Madras, India, <ravikanthreddy039@gmail.com>
[2] Professor, Indian Institute of Technology Madras, India , < aruls@iitm.ac.in >

various modes of buckling. (Li, Ren, and Yang 2012) developed the analytical model on Z-purlin by energy methods with cubic spline functions and investigated the effect of the anti-sag bars, boundary conditions, and moment gradient effect on the buckling behavior. The authors also developed an analytical model for partially restrained Z-purlins and compared it with the Eurocode. The models are accurate with the prediction of Eurocode (EN 1993-1-3 2006) for medium and long lengths. The analytical models discussed above are developed to simplify sheeting and connection as linear and rotational springs in the design of purlins. However, the hidden clips method of installation in the SSMR systems cannot be used for design of purlins using the model described above.

Many researchers have carried out experimental works to quantify the effect of SSMR systems. They (Song, Zhang, and Zhang 2017) showed the performance of two types of SSMR systems provided with 360^{o} and 180^{o} interlocking through experiments. The former interlocking provides larger restraint and higher load bearing capacity compared to the later system. (Zhang, Song, and Zhang 2017) carried out the numerical analysis of SSMR systems and suggested a formula for predicting reduction factor for a particular SSMR system, accounting the thickness and yield stress of the purlins. (Luan and Li 2019) carried out series of experiments on zed purlins supporting SSMR systems and showed that anti-sag bars along with SSMR systems can together increase the load bearing capacity.

This paper presents an experimental study on the load bearing capacity of the Z-purlins supporting SSMR systems. The experimental results were compared with the Eurocode (EN 1993-1-3 2006) and the effect of the restraint provided by the SSMR systems have been quantified.

2. Test setup

A test setup was prepared with an MR-24 profile (named by an industry manufacturing steel sheet profiles) shown in Fig. 1, clips shown in Fig. 2, and Z- purlins. The panels are seamed to form 360° interlocking with clips and fastened to the purlin. The panel was 500 mm in width and BMT of 0.6 mm was used in the experiments. The clips base is 115 mm in length and thickness is 1.5 mm. The slide tab is 1.0 mm thick and is attached to the clip base to slide on a solid rib which allows relative movement. The clips were fastened to the purlin flange with a single self-drilling screws. The yield stresses of the panels and purlins are considered as per the test reports submitted by the manufacturer. The dimensions of the purlins are provided in Table 1. Each test specimen comprises three lines of purlins with a span of 5.66 m. The end supports of purlins are connected with standard cleats and the flanges are facing in the same direction.

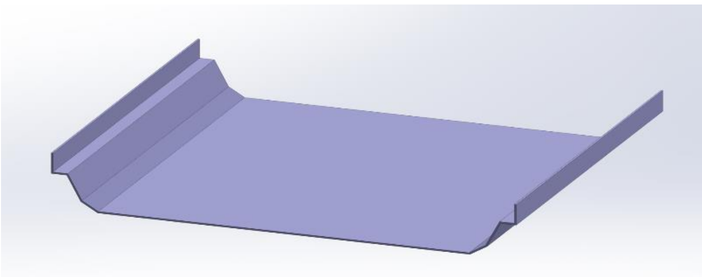

Figure 1: MR-24 panel profile

Figure 2: MR-24 clip

Table 1: Specimen dimensions

Test identification	Purlin shape	Purlin dimensions (mm)				Roof type
		Depth	Flange width	Lip depth	Thickness	
T1	Z	200	68.4	23.8	2.38	MR24
T2	Z	203	69.8	22.6	2.40	MR24

3. Test rig

For simulating wind uplift, a rectangular test chamber shown in Fig. 3 is fabricated with steel channel sections of 0.4 m depth, 5.66 m length, and 3.0 m width. The bottom of the chamber is fabricated with a steel plate of 8 mm thick and ensured to be stable at desired differential pressures. The purlins and the roof sheeting were placed upside down in the test chamber and fixed to rafters with cleats on either side of the purlins. The vacuum chamber is covered with 0.15 mm polyethylene sheeting with enough folds to follow the defection profile of the sheeting. Fig. 3 shows 3D model of the test rig along with purlins and panels. For applying wind loads, a 2000 liters per minute vacuum pump is used and a vacuum pressure sensor is installed to record the pressure differential at lower magnitudes. Vertical and horizontal displacement transducers are attached to the free flange of the purlin at mid span.

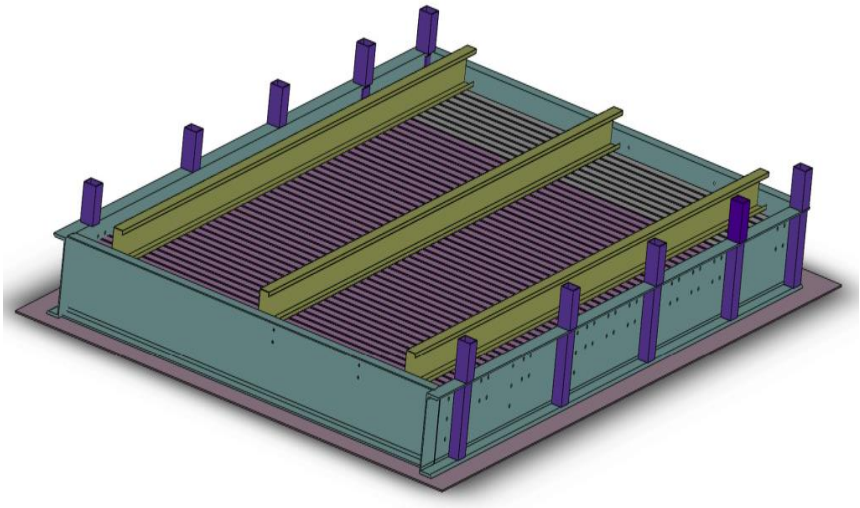

Figure 3: Test rig along with purlins and panels

4. Experimental results

For the test without a sag rod, the purlin experiences local buckling at the web flange junction (Fig.4) with the LTB failure after considerable lateral and vertical displacement. The load-displacement curves are shown in Fig. 5 & Fig. 6. The load-displacement curves obtained from experiments were compared with linear beam theory shown by a dotted line. It is observed that the purlins show significant non-linearity at the initial stages of loading due to the lateral deformation and bending about the inclined principal axis (for point symmetric sections).

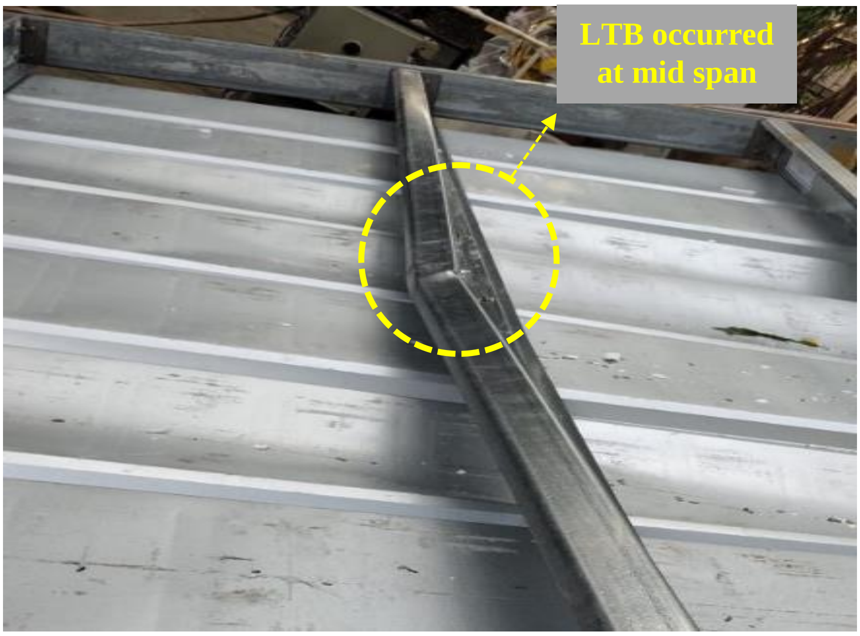

Figure 4: Failure mode of purlin

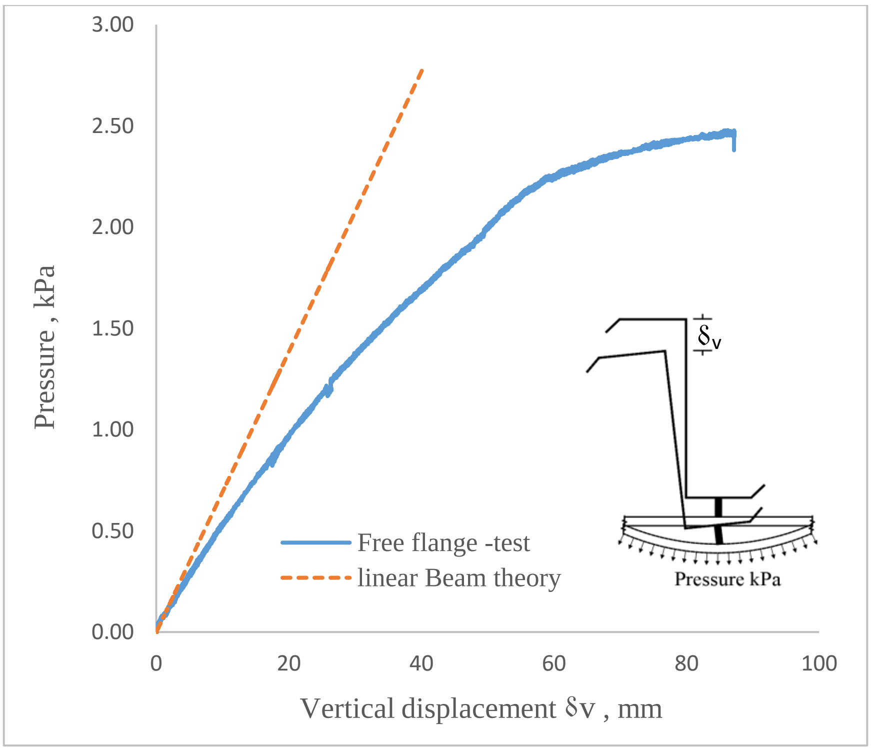

Figure 5: Pressure –vertical displacement curves of zed purlins

Test identification	P_f (kN/m^2)	P_d (kN/m^2)	S (m)	W_f (kN/m)	M_f (kN-m)	M_y (kN-m)	R_t (M_f/ M_y)
T1	2.279	0.113	1.2	2.59	10.40	18.84	0.55
T2	2.47	0.113	1.2	2.82	11.32	18.84	0.60

Table 2 Test results

Note: P_f is the pressure at failure, P_d - self weight of specimen, S is the tributary width, M_y is the yield moment.

The test results are summarized in Table 2. The failure pressure of purlins (Pf), the flexural strength of the purlins from experiments, and the theoretical yield moment of the purlin were calculated. The reduction factor (Rt) is calculated as per AISI S908 (AISI 2013). From the test results, it is shown that Rt for test T1 is lower compared to test T2. This is due to the initial sweep of purlins in LTB mode and may be due to the non-contact of follower load through the polythene cover during the test.

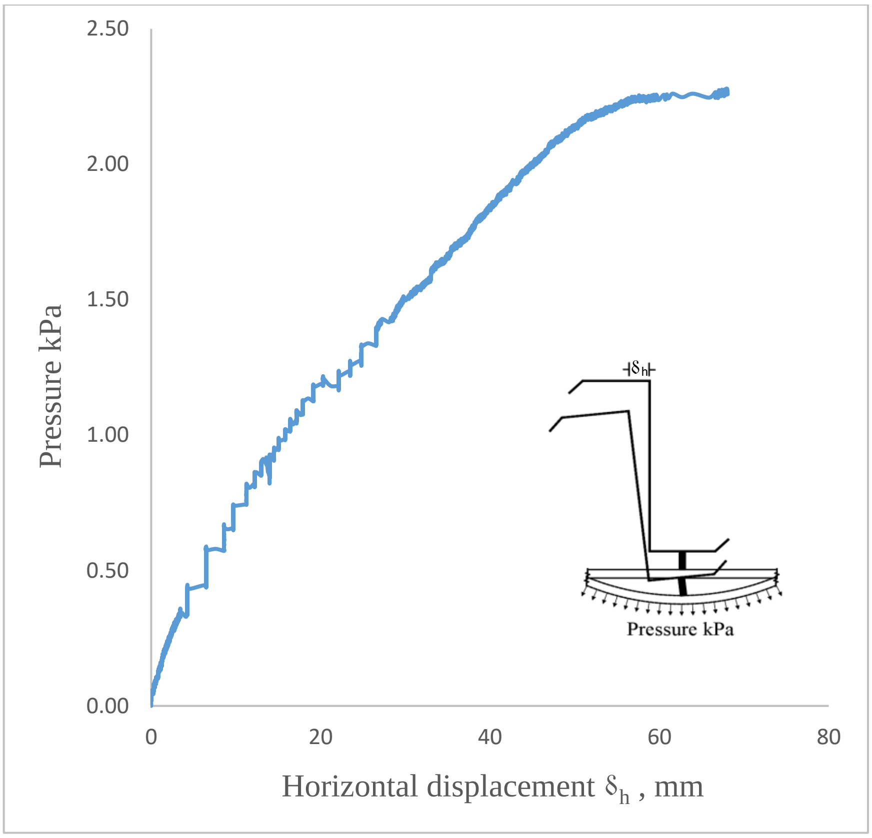

Figure 6: Pressure–horizontal displacement curves of zed purlins

5. Design codes of practice

As per Eurocode (EN 1993-1-3 2006) for beams restrained by sheeting, full lateral restraint, and partial rotational restraint is assumed in the purlin design. For SSMR systems, no special guidelines are provided, still, the predicted purlin strength is higher than the nominal flexural strength. The necessity for allowing the restraint effect provided by SSMR systems is beneficial in the purlin designs which accurately predict purlin capacity and mode of buckling.

The code provides an analytical approach to calculate the purlin capacity restrained by the sheeting. For calculating the stresses, the free flange and the restrained flanges are treated separately as follows:

For restrained flange

$$\sigma_{max} = M_{\mathrm{y,Ed}}/Z_{\mathrm{e}} \leqslant f_{\mathrm{y}} \tag{1}$$

For free flange

$$\sigma_{max} = M_{\mathrm{y,Ed}}/Z_{\mathrm{e}} + M_{\mathrm{fz,Ed}}/Z_{\mathrm{fz}} \leqslant f_{\mathrm{y}} \tag{2}$$

If the free flange is in compression, the max stress should satisfy

$$\sigma_{max} = \left(M_{\mathrm{y,Ed}}/Z_{\mathrm{e}}\right)/\chi_{\mathrm{LT}} + M_{\mathrm{fz,Ed}}/Z_{\mathrm{fz}} \leqslant f_{\mathrm{y}} \tag{3}$$

where $M_{\mathrm{y,Ed}}$ is the in-plane moment calculated from the vertical load, Ze is the effective section modulus about y-y axis, $M_{\mathrm{fz,Ed}}$ is the bending moment in the free flange due to the equivalent lateral load, Z_{fz} is the gross elastic section modulus of the free flange plus the contributing part of the web for bending about the z-z axis, part of the web may be taken equal to 1/5 of the web height from the point of web-flange intersection in case of C and Z-purlins and 1/6 of the web height in case of Σ (sigma)-sections.

As per Eurocode (EN 1993-1-3 2006), the rotational restraint provided by sheeting can be replaced with a rotational spring obtained either from analytical formula or from testing. The calculated rotational spring stiffness is converted to equivalent linear foundation spring acting at the free flange. The effect of the spring directly relates buckling length and bending moment of the free flange. The wind uplift loads were calculated after satisfying Eq. 3.

Table 3 Comparison of test results with Eurocode (EN 1993-1-3 2006),

Test identification	M_f (kN-m)	M_{EC} (kN-m)	R_t (M_f/ M_y)	$R_{(EC)}$ (M_{EC}/ M_y)
T1	10.40	2.53	0.55	0.13
T2	11.32	2.53	0.60	0.13

From Table 3, it is observed that the purlin flexural capacities according to Eurocode are highly conservative as the code provisions do not account for the effect of the restraint provided by the SSMR systems. The reduction factor values (Rt) signify the extent of the constrained stress distribution corresponding to the first yield used in determining the flexural strength of the purlins during wind uplift. The average values of Rt from the experiments were 0.57, which implies that 57% of the pure bending stress distribution corresponding to the first yield may be used for calculating the wind uplift loads supporting MR24 profiles. In comparison with Eurocode (EN 1993-1-3 2006), the values are 0.13, which is found to be too conservative. The flexural capacities of the purlins predicted according to the Eurocode were conservative to the nominal capacities of the purlins when the restraining effect of SSMR systems is not considered.

6. Conclusions

This paper presents the experimental investigations on load bearing capacity of the Z-purlins supported by SSMR systems during wind uplift. A test rig with steel plates and channels is fabricated for simulating wind uplift. Two experiments were conducted with zed purlins supported by MR24 SSMR panels. The local buckling and restrained LTB failure modes are observed in the experiments. The purlin capacities according to Eurocode (EN 1993-1-3 2006) have been found to be conservative as compared to the experimental results. From the present experimental work, it is concluded that SSMR systems provide significant restraints to purlins during wind uplift. The authors are interested in developing the experimental data and FEM models of various types of SSMR systems to validate the restraint provided by the SSMR systems.

Acknowledgments

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