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INVESTIGATION OF SCREW FASTENED PROFILE STEEL SHEET SUBJECTED TO SIMULATED UPLIFT LOAD

S. M. Zahurul Islam[1], Habibur Rahman[2] and Mohd. Waliul Alam[3].

[1] *Professor, Department of Civil Engineering, Rajshahi University of Engineering and Technology, Bangladesh, e-mail: zahurul90@gmail.com*
[2] *Student, Department of Civil Engineering, Rajshahi University of Engineering and Technology, Bangladesh e-mail: dedar007@gmail.com*
[3] *Student, Department of Civil Engineering, Rajshahi University of Engineering and Technology, Bangladesh e-mail: waliulalamnayan12@gmail.com*

ABSTRACT

Profiled steel sheets play an important role in light gauge metal building construction, particularly as roof claddings in houses, low-rise commercial and industrial buildings. Thin profiled steel sheets are commonly connected to the underlying purlins of steel trusses and frames by drilling or tapping of screws. Screw fastened light gauge steel profiled roofing sheets are mostly subjected to wind suction or wind uplift forces. Strong and fluctuating wind uplift force may fail locally in the vicinity of screw. The objective of this study is to investigate the structural strength and behaviour of profiled steel sheet roofing elements under simulated wind uplift forces. A series of tests was performed on profiled steel sheet roofing subjected to wind uplift simulated pressure. Different diameter of screw and different span length of sheeting were considered in this research. The failure loads, failure modes and the load- deformation behaviour of screwed fastened profile steel sheet under simulated wind load were presented. It was observed that during the increase of loading, the upward deflection of the unscrewed crest became larger than that of the screwed crest. It was found that the local diamond-shaped deformations progressively developed around the screw fasteners at the support due to uplift load. The use of cyclone washers with screw fasteners reduced local plastic deformations and, in general, increased initial failure loads of the roofing sheets. It was found that, the structural behaviour of the roofing sheets under uplift loads was greatly dependent on the diameter of the screw and span length of profiled steel sheet.

Keywords: *Test, roofing, profiled sheet, screw fastener, uplift load, local failure*

1. INTRODUCTION

Profile steel shell structures are used in roofing elements popularly due to aesthetic and economical use of materials. Profiled steel sheets are increasingly used in structural application in recent years as shown in Fig. 1. The light gauge steel profiled roofing sheets are usually screwed and bolted fastened to cold-formed steel purlins or high-quality timber battens. Screwed and bolted are conventional connection type which are widely used in light gauge and thin steel structures as shown in Fig. 2. When used in high wind areas, structural performance of such roof systems under wind loads became a main concern for the structural design engineers. Wind loads acting on the roofs and walls of a low building are determined by the interaction of wind flow with the surface of the building. A large quantity of wind tunnel tests and field measurements has shown that roof claddings are predominantly subjected to wind suction, i.e., wind uplift (Holmes et al. 1990). Cyclone-induced sustained fluctuating wind uplift may cause fatigue damage to roofing sheets whilst short-term strong wind uplift could damage roofing sheet collapses (Beck and Stevens, 1979). Parsons (1976) conducted an extensive test of steel roofing sheets under static and cyclic loads for commercial purposes. Only the maximum allowable load which the sheeting can sustain without permanent deformations was involved in the static load test. Beck and Stevens were probably the first to perform fatigue tests of the arc-tangent type roofing sheet. Before the fatigue tests, some static tests simulating wind uplift were carried out on the roofing sheets with different crest fastening arrangements. They found that a local diamond-shape deformation progressively developed on the crest of the corrugation under the head of the central screw fastener, which was followed by an elastic buckle at a nominal fastener tensile reaction force of 700 newtons per fastener. Mahendran (1990) investigated the effects of cyclone washers, roofing spans and fastener spacing on the structural behaviour of the arc-tangent type roofing sheets. He found that for a roofing assembly with an alternate crest fastening system, the local plastic buckling 'load', in terms of reaction force per fastener at the central support, was independent of the roofing spans and could be significantly increased by using cyclone washers. Xu and Reardon (1992,1993) conducted research on screw fastened profiled roofing sheets subject to simulated wind uplift. Howerver, very little information on the structural behaviour of roofing sheets under wind suction is available in the public domain. Therefore, a research is needed to investigate the structural strength and behaviour of profiled steel sheet roofing elements under simulated wind uplift forces. It is a novel approach for light gauge profile steel sheet for housing construction.

In this paper, the structural strength and behaviour of profiled steel sheet roofing elements are investigated under simulated wind uplift forces. A series of tests was performed on profiled steel sheet roofing subjected to wind uplift simulated pressure. Different diameter of screw and different span length of sheeting are considered in this research. The failure loads, failure modes and the load- deformation behaviour of screwed fastened profile steel sheet under simulated wind load were investigated. The interaction between the overall and local structural behaviour of the roofing sheets was examined, to some extent, in terms of measured sheeting deflections, uplift loads and fastener reaction forces at the central support. The effects of cyclone washers and roofing spans on the structural behaviour of all three types of roofing assemblies were studied in terms of sheeting deflections and initial or ultimate failure loads. The structural behaviour of the roofing sheets under uplift loads was greatly dependent on the diameter of the screw and span length of profiled steel sheet is investigated.

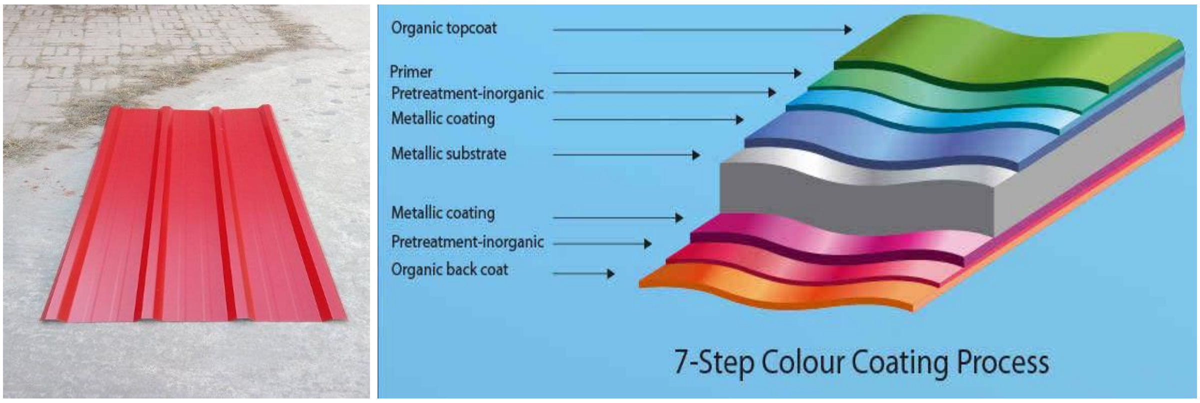
Figure 1: Field application of profiled steel sheet for roofing system

Figure 2: Field application of profiled steel sheet using screwed and bolted connections

2. METHODOLOGY

2.1 Material Properties

Profile steel sheets are being used on an increasing scale for roofing. Profile steel sheet element is suitable for roofing because of its efficiency as load carrying member with a high degree of reserved strength and structural integrity, high strength to weight ratio, very small thickness ratio to other dimensions, very high stiffness and containment of space. The main advantages of using profile steel sheet as a roofing material are speedy installation, no shuttering required, less installation errors, lower dead load on the walls, light weight and easy handling, high strength to weight ratio, corrosion-resistant, economical considering mean service life. Profile steel sheets are available in an extensive range of models that are used as an excellent material for wide variety of architectural styles. Profiled steel sheet is extremely durable against corrosion because of the usage of seven layers of coating as shown in Fig. 3(b). Profile steel sheet and composition layer of profiled steel sheet are shown in Fig. 3. Moreover, profiled steel sheet can be used in relief center after disaster for short-term construction. The material properties of the profiled steel sheet were determined by tensile coupon tests. The tensile coupons were prepared and tested according to the American Society for Testing and Materials Standard, ASTM (1997) and the Australian Standard AS 1391 (1991) for the tensile testing of metals using 12.5 mm wide coupons as shown in Fig. 4. (Zahurul-Islam et al 2006). The coupons were tested in a Universal Testing Machine and the load was applied gradually. Deformation was measured by using deformation gauge. The test set-up and tested specimen after tensile test is shown in Fig. 5(a) and 5(b) respectively. Measured material properties obtained from tensile coupon tests are given in Table 1 and Fig 6.



(a) Profile steel sheet (b) Composition layer of profile steel sheet

Figure 3: Profile steel sheet and its composition

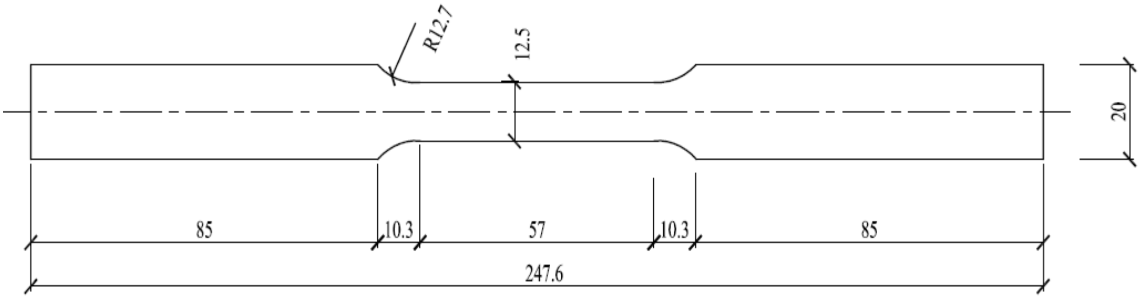


Figure 4: Dimension (mm) of coupn test specimen

(a) Coupon test (b) Failure mode

Figure 5: Tensile coupon test and failure mode of profiled steel sheet

Table 1: Measured material properties obtained from tensile coupon tests

Specimen No.	Width b_c (mm)	Thickness t_c (mm)	Yield Stress σ_y (N/mm^2)	Ultimate Stress σ_u (N/mm^2)
1.	12.5	0.46	245.50	260.07
2.	12.6	0.46	237.54	262.51
3.	12.5	0.46	239.7	260.73

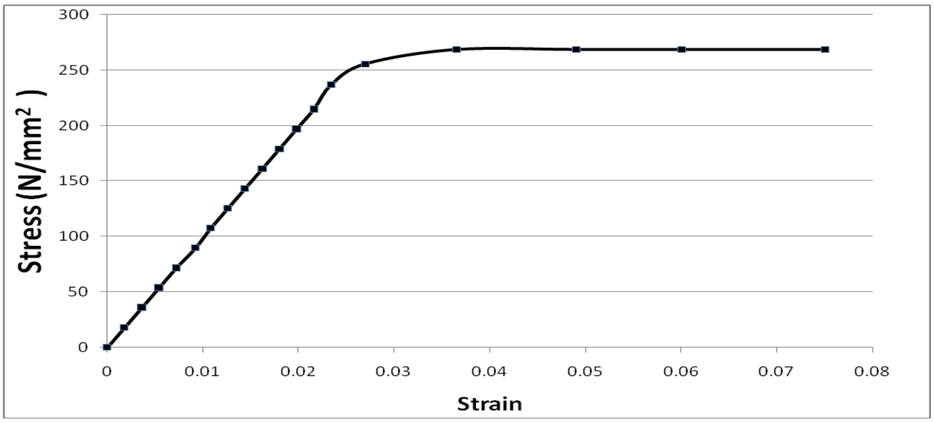


Figure 6: Stress- strain curve of coupon test results of profiled steel sheet

2.2 Screwed Connection Tests

A series of screwed connection tests were conducted in this study. The screwed connection tests were conducted by a servo-controlled hydraulic Universal Testing Machine which is mainly used for the coupon tests. Drilling and conneting of tensile test specimen are shown in Fig 7. The connection specimens were set into the grip of the machine as shown in Fig. 8. A pair of grip apparatus was specially fabricated in order to provide pin assembly at both ends of the test specimen. Two special gaskets were inserted in the grips, so that the shear surface of the single and doubly lapped specimen was purely vertical in-line to the loading direction. Clips linked with iron wire were used to prevent the extent of out-of-plane curling at the end of the profile steel sheet. After that, tensile load was applied gradually and the tensile stresses obtained from the machine were recorded at the room temperature.

Figure 7: Drilling and conneting of tensile test specimen

Figure 8: Test setup of tensile test specimen

A series of test was conducted on screws connection of 3 different diameter of 5.90 mm, 4.70 mm and 4.30 mm for single shear and double shear conditions to find out suitable connection specimen and optimum screw dia. Failure mode of screw and bolt connection are show in Fig. 9. The optimum diameters of 4.7 and 4.3 mm for screw connections were found for single shear and double shear respectively. Based on test results, two screwed parallel connections provided better performance than vertical arrangement.

Figure 9: Tested failure mode of screw and bolt connection

3. WIND LOAD CALCULATION

Wind loads are of important, particularly in the design of large structures tall buildings, radio towers, and long span bridges and for structure such as mill building and hangers having large open interiors and walls in which large opening may occur. Profile steel sheets are being used efficiently for roofing element which is frequently experienced wind load (Lysaght, 1990). Roofing element should satisfy wind load which is prescribed in Code. Roofing element should fulfill the code of practice or wind load for different areas as described in BNBC. The minimum design wind load on buildings and components there of shall be determined based on the velocity of the wind, the shape and size of the building and the terrain exposure condition of the site. For building specification, AISI state that the frame of a building must be designed to carry a pressure not less than 20 psf, on the vertical projection of the exposed surface of the finished structure. Wind load can be calculated based on Datchman wind effect, ASCE recommendation and BNBC code.

Dutchmen wind effect:

Load, $P = KV^2 = 29.65$ lb/ft^2 (1)

Where, K=0.003, V= 99.42 mph

$$P_{n.} = P \times \frac{2Sin\theta}{1+Sin^2\theta} = 29.65 \times \frac{2Sin26.56°}{1+Sin^2 26.56°} = 22.1 \text{ lb/ft}^2 \quad (2)$$

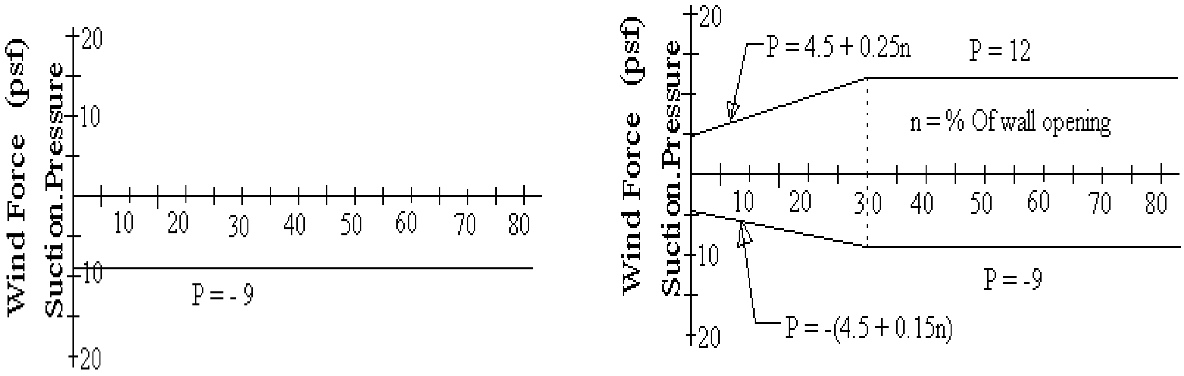
BNBC code wind effect:

For average condition = $0.002558\, v^2$ = 23.73 psf (3)

Here, V = wind velocity in mile/h, P = wind pressure in psf,

For Rajshahi city, v = 155 km/h,= 96.31 mile/h,

Wind load as recomendated in ASCE, final report is shown in figure 10. According to ASCE final report, the maximum wind force and suction pressure is 16.128 and 21 psf wind word and lee word directions respectively.



(a) External force on leeward side. **(b)**External force on both side)

Figure 10: Wind load calculation according to ASCE final report (ASCE,2005)

4. TEST ARRANGEMENT

Recently, there are three methods used to test roofing sheets namely the air bag method, the mid span load method, and the chamber method. It is believed that the mid span load method is the least expensive and easy to perform in a common structural laboratory. In the mid span load method, the limited band pressure at the mid span across the full width of the sheeting is used to replace the uniformly distributed pressure over the entire sheeting surface. Correspondingly, an equivalent sheeting span should be used in the test to replace the sheeting span in the prototype such that the fastener reaction force and bending moment of the test sheet at the central support are the same as those of the sheet prototype (as a two-span continuous beam). A force relationship between the mid span load on a test sheet and the average wind pressure on the sheet prototype is also established from the above modeling requirements. In this investigation, the mid span load method was chosen partly due to the practical considerations associated with the use of a commercial hydraulic jack. The basic sheeting span in the test was 1’6”, 2’0”, 2’6”. A total of 24 roofing sheets were tested with and without cyclone washers. The experimental set-up is shown schematically in Fig. 11, with a hydraulic testing machine of 100kN capacity being the major apparatus. Flexible rubber loading pads were used to apply a narrow band of pressure to the bottom surface of the test sheet to simulate wind uplift.

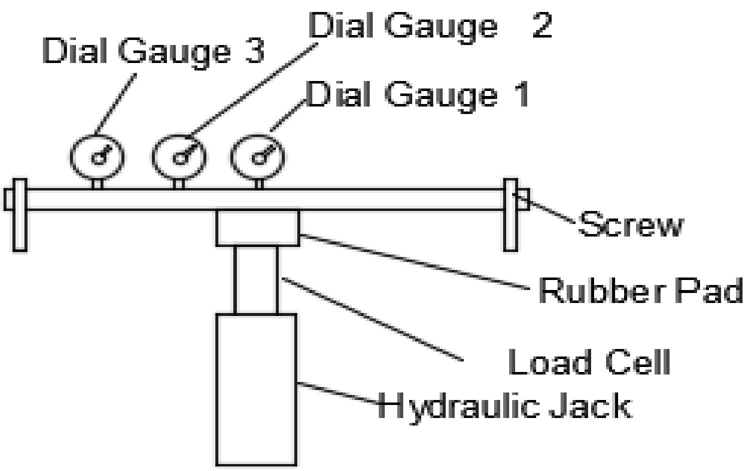


Figure 11: Schematic view of experimental set-up

Test arrangement of wind uplift load is shown in Fig 12. The upper face of the loading pads was formed to coincide with the shape of the sheeting profiles. The total fastener reaction force at the central support was measured by a load cell. The average reaction force on each fastener was obtained by dividing the total reaction force by the number of fasteners at the central support. A load cell of a capacity of 30 kN was employed to measure the total uplift load on the roofing sheet, which was then used to calculate the average wind pressure on the sheet prototype. Dial gauges, graduated to 0.01 mm, were arranged at screwed crests (or centre lines of the pans) of the test sheets to measure the upward deflections.

Figure: 12 Test arrangement of wind uplift load

5. TEST RESULTS AND DISCUSSIONS

The results were obtained by experimentally using hydraulic jack, load cell and dial gauges. The failure loads, failure modes and behaviour of profiled steel sheeting subjeted to wind uplift load are shown in Fig 13. The typical upward deflections of mid-point located on the screwed crest or rib at the mid span are plotted against the prototype average pressure for the roofing sheets which is shown in Fig. 14. When the prototype average pressure was below 10 psf, the overall structural behaviour of the roofing sheet was predominantly linear and elastic. With the increase of loading, the upward deflection of the unscrewed crest became larger than that of the screwed crest. The sheeting profile was distorted. Therefore, the non-linear characteristic of the sheeting was mainly attributed to the geometrical deformation. As the load increased further, local diamond-shaped deformations progressively developed around the screw fasteners at the central support. The deformations were plastic and significantly affected the overall sheeting deflection behaviour. When the average pressure was increased to about 25 psf, a local buckle with a clear sound occurred around the screw fasteners at the central support and caused a sudden drop of the loading. The local plastic buckling was followed by an overall cross-sectional distortion along the central support without any load increase. Correspondingly, the load-deflection curve exhibited an abrupt flattening.

Figure 13: Failure mode of uplift pressure

After the screwed crests at the central support totally flattened and the upward deflections of the unscrewed crests at the central support sufficiently increased, a different roof sheeting profile developed along the central support and caused a change in the deflection behavior. The structural stiffness of the roofing sheet suddenly increased from a nearly zero value and an approximate linear relationship between the load and the deflection was resumed. It was not occurred in the prototype roofing sheet results.

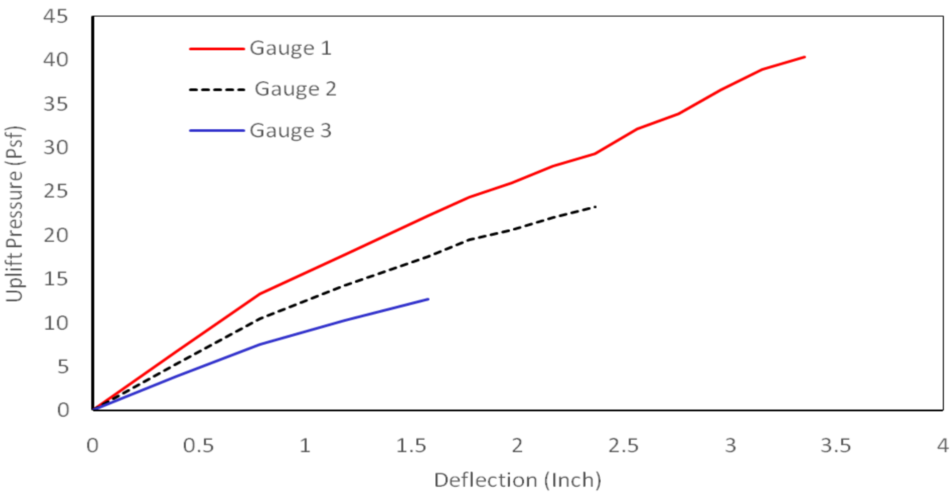


Figure 14: Comparison of uplift pressure vs. deflection at different point

According to BNBC code, the uplift pressure due to wind effect is 23.73 psf. Again according to ASCE code, the maximum wind force and suction pressure is 16.128 and 21 psf in wind ward and lee ward directions respectively. Based on the expremental results, it was found that the load carrying capacity of the proposed profiled steel sheet roofing sytem subjected to wind uplift load is 39.88 psf which is greter that BNBC and ASCE recommended wind uplift load. This roofing system satisfies BNBC code, ASCE code prescribed wind uplift load. Hence, this roofing system is suitable for housing construction in coastal areas also. Therefore, the proposed roofing system has a great potential to be exploited for the housing construction as well as disaster relief shelter.

5.1 Effect of Cyclone Washer

The local plastic failure of screw fastened profiled roofing sheets can be improved if the fastener is properly designed. The effectiveness of additional cyclone washers to the fastener was examined here. Although the cyclone washers are usually used in cyclone prone areas to resist sustained fluctuating wind and prevent roofing sheets from fatigue damage, the tests of the roofing sheets with the washers under static uplift load are useful for further understanding of the local plastic failure characteristic and for future work on cyclone-induced fatigue of the same profiled roofing sheets. Fig. 15 shows the comparison of the force-deflection curves of roofing sheet with and without the washers.

It is seen that the initial slope of the reaction force-deflection curve of the sheeting with the washers was steeper than that without the washers. As the uplift load was increased further, however, the steel washers of only 1 mm thick were distorted and were unable to prevent large local plastic deformations and large cross-sectional distortions. The yielding stage and the deflection hardening stage still remained. The final failure loads were also attributed to the overall buckling across the entire width of the sheeting at the mid span. For the roofing sheet with the washers, the upper limit value of reaction force per fastener at the central support for the initial failure was 1.12 times that for the sheeting without the washers. The lower limit value was approximately the same as the lower limit value for the sheeting without the washers. The limit value of reaction force per fastener was approximately increased by a factor of 1.26. The roofing sheet with the washers, the uplift load carrying capacity was increased 12% to 26% than without washers.

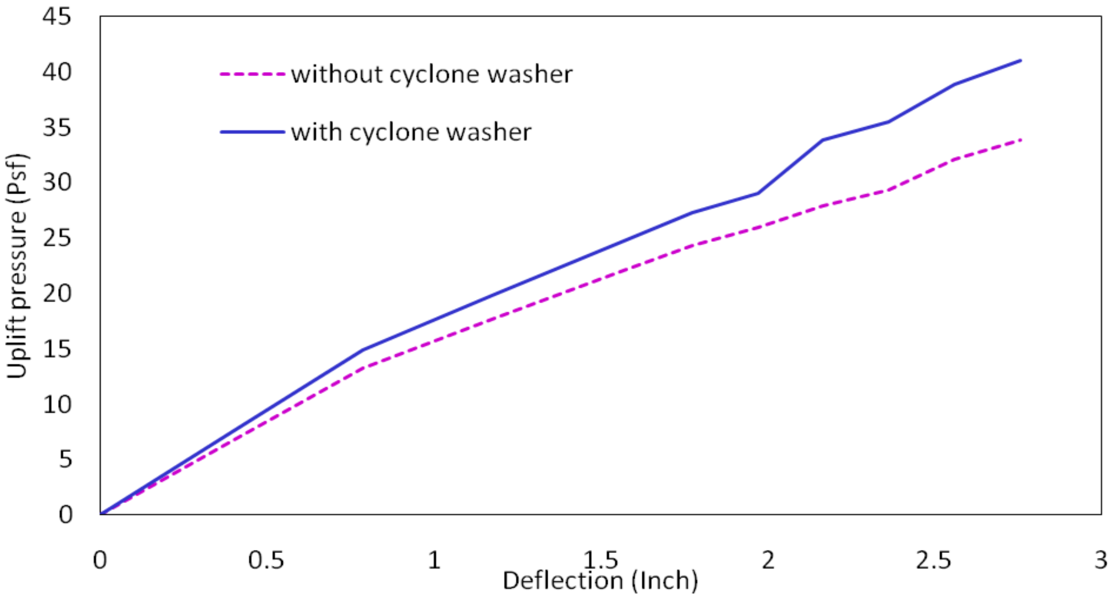


Figure 15: Comparison the effect of cyclone washer at mid point of the specimen

6. CONCLUSIONS

The paper presents an experimental investigation on the structural strength and behaviour of profiled steel sheet roofing elements under simulated wind uplift forces. A series of tests was performed on profiled steel sheet roofing subjected to wind uplift simulated pressure. The optimum diameters of 4.7 and 4.3 mm for screw connections were found for single shear and double shear respectively. Based on test results, two screwed parallel connections provided better performance than vertical arrangement. The failure loads, failure modes and the load-deformation behaviour of screwed fastened profile steel sheet under simulated wind load were presented. It was observed that during the increase of loading, the upward deflection of the unscrewed crest became larger than that of the screwed crest. It was found that the local diamond-shaped deformations progressively developed around the screw fasteners at the support due to uplift load. The use of cyclone washers with screw fasteners reduced local plastic deformations and, in general, increased initial failure loads of the roofing sheets. The roofing sheet with the washers, the uplift load carrying capacity was increased 12% to 26% than without washers. Based on the exprememtal results, it was found that the load carrying capacity of the proposed profiled steel sheet roofing sytem subjected to wind uplift load is 39.88 psf which is greter that BNBC and ASCE recommended wind uplift load. It was found that, the structural behaviour of the roofing sheets under uplift loads was greatly dependent on the diameter of the screw and span length of profiled steel sheet.

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