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Corrugated Metal Roof Cladding Sheets Subjected to Uplift Pressure

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Abstract— Corrugated metal roof cladding sheets are widely used in the industrial, residential and other buildings. In recent times corrugated metal roof cladding sheets are used in different geometries with different colors and have a wide range of applications in industrial structures. Corrugated steel sheets are frequently used for roofing and siding in buildings because the sheets are strong, lightweight, and easy to erect. In many cases they are used as shear diaphragms to replace conventional bracing and to stabilize entire structures or individual members such as columns and beams. These roofs during windstorms are subjected to intense fluctuating external pressures at windward roof edges. Loads on these areas can be gradually increased when combined with large positive internal pressures resulting from a breached windward wall, giving a large net uplift load, that is, large negative pressure is produced. In the present work design of arc tangent corrugated metal roof cladding sheets is attempted. The sectional properties of corrugated metal roof sheets of standard sizes as specified in IS277:1992 are computed using the method suggested by Blodgett. These standard sheets are subjected to wind loads as per IS 875:1997 (part 3) considering various parameters like height and width ratio of the building, angle of roof, wind zones, etc. Design tables are proposed which give the thickness of the arc corrugated sheets to resist safely the wind pressures due to the various combinations of the above parameters. A study is also made to find the influence of parameters like height to width ratio, width of building, roof angle, and basic wind speeds on the thickness of corrugated sheets. An attempt is also made to perform a linear static analysis of corrugated metal roofing sheets using the finite element software ANSYS 12.0. 'Quad 8 node 183' and 'Brick 20 node 186' elements are used for the discretization of the corrugated metal roof sheet. Stresses and deformations are computed for various corrugated metal roofing sheets. These values are found to be within the permissible limits. The numerical analysis suggests that the values of thickness given in the design tables are found to be adequate. The proposed design tables helps the designer to readily select a suitable thickness for the corrugated sheets in any wind zone of India. These tables are simple and convenient to use, and covers wide range of parameters encountered during the design.

Key words: Metal Roof Cladding Sheets, Corrugated Metal Roof Cladding Sheets

I. INTRODUCTION

A. Roofing and Cladding Systems

Thin, high strength steel cladding is widely used in commercial, industrial and residential low rise buildings. Roofs during windstorms are subjected to intense fluctuating external pressures at windward roof edges. Loads on these areas can be gradually increased when combined with large positive internal pressures resulting from a breached windward wall, giving a large net uplift load. Thus the roof envelope and fixing generally experience the highest wind pressures of the building's components, and are the components most susceptible to failure.

A common mechanism of roof cladding failure is the localized fatigue failure in the vicinity of the fasteners during severe wind events, such as cyclones. The highly fluctuating and prolonged loading experienced by the roof envelope during windstorms results in fatigue cracking beneath the fasteners. These fatigue cracks can propagate to a sizeable hole that is then large enough for the fastener to pull through the cladding, expediting the loss of entire cladding sheets.

Cyclone Tracy caused catastrophic damage in Darwin in 1974. Walker reported that over 90% of houses and 70% of other structures suffered significant loss of roof cladding as shown in Fig. 1(a). The extensive loss of light gauge metal roof cladding was caused by low cycle fatigue of the cladding adjacent to its fasteners. With the cracking allowing the cladding to pull over one fastener, led to an avalanche effect of overloading and failing the cladding at adjacent fasteners as shown in Fig. 1(b). Following Cyclone Larry's impact on Innisfail in 2006, fatigue failure of pierced fixed metal cladding was observed where the fixing centres exceeded typical product specifications (Henderson et al. 2006).

Fig. 1: (a) Catastrophic failure of metal (b) Cladding pulling over heads of roof cladding fasteners.

In recent times, very thin high-strength steel battens of various shapes have been used in residential, industrial and commercial buildings and this appears to be the fastest growing method in roof construction. These cladding systems can then suffer from another type of local failure when the screw fasteners pull out of the steel battens, purlins, or girts under wind uplift/suction loading. Such a pull-out failure also leads to a rapid disengagement of roof and wall claddings, causing severe damage to the entire building. It is important that the entire roof/wall cladding system be safe under high wind events. Traditionally timber purlins and battens have been used in buildings and hence pull-out failures have not been a common occurrence or a problem. This situation has changed because of the increasing use of high strength thin steel battens, purlins, and girts in roof and wall construction.

Therefore, it is very important to investigate the static and fatigue pull-out behavior of these steel cladding systems.

Fatigue is the term used to describe the material or structural failure caused by repeated loading. Wind pressures on roof cladding of low-rise buildings fluctuate heavily because of the natural turbulence in incident wind and the turbulence induced by flow-building interaction. A sustained strong wind may therefore cause fatigue damage to metal roofs.

Traditionally, engineers have used laboratory testing to investigate the structural behavior of steel building products and systems subject to the expected wind and earthquake loads and to develop appropriate design methods. Laboratory testing was also used to develop new building products and systems. However, such reliance on time consuming and expensive laboratory testing has hindered progress in this area. The product manufacturers and designers often decided on conservative designs in order to avoid expensive and time consuming laboratory testing. However, advances in the field of computer aided engineering during the last two decades have changed this situation significantly in many engineering industries. In the building industry, the use of advanced finite element tools has not only allowed the introduction of innovative and efficient building products, but also the development of accurate design methods.

B. Corrugated Metal Roofing Sheets

Corrugated galvanized iron (colloquially corrugated iron or pailing (in Caribbean English), commonly abbreviated CGI) is a building material composed of sheets of hot-dipped galvanized mild steel, cold-rolled to produce a linear corrugated pattern in them. The corrugations increase the bending strength of the sheet in the direction perpendicular to the corrugations, but not parallel to them. Normally each sheet is manufactured longer in its strong direction.

CGI is lightweight and easily transported. It was and still is widely used especially in rural and military buildings such as sheds and water tanks. Its unique properties were used in the development of countries like Australia from the 1840s, and it is still helping developing countries today.

II. OBJECTIVES OF THE STUDY

The important objectives of the present study are

- To review the existing procedure for analysis and design of corrugated metal roof cladding sheets
- To develop standard tables for design of corrugated metal roof cladding sheets considering various terrains, geometry of the frame, inclination of corrugated sheets and basic wind speeds.
- To study the influence of parameters like height to width ratio, width of building, roof angle, and basic wind speeds on the thickness of corrugated metal roof cladding sheets.
- To model and perform numerical analysis of corrugated metal roof cladding sheets using finite element software (ANSYS 12).
- To validate design tables by comparing it with the results from numerical analysis.

III. SCOPE OF THE PRESENT WORK

In the present work design tables are generated for arc and tangent corrugated metal roof sheets of depths 17.5 mm and 12.5 mm for standard sheet sizes specified in IS 277: 1992. The sectional properties of these sheets are computed using the method suggested by Blodgett method. The design tables are generated for wind loads as per IS 875:1997 (part 3) considering different parameters like height and width ratio of the building (0.5, 1.0, 1.5, and 2), width of building (5 m, 10 m, 15 m, and 20 m), angle of roof (100, 200, 300, 450, and 600), wind zones (33 m/s, 39 m/s, 44 m/s, 47 m/s, 50 m/s and 55 m/s) etc. The linear static finite element analysis of corrugated metal roofing sheets is performed using ANSYS 12.0. ‘Quad 8 node 183’ and ‘Brick 20 node 186’ elements are used for the discretization of the corrugated metal roof sheet. Young’s modulus and Poisson’s ratio are kept constant throughout the thickness of the sheet. The pressure is applied on the sheet by giving suitable boundary conditions to fix the sheet by bolts to the purlin. The corrugated sheets are supported by three purlins, two at the ends and one at the midspan. The end purlins are kept at a distance of 150 mm from the edge of the sheet. The numerical analysis is carried out to determine the stresses and the deformations in the sheets.

IV. VARIATION OF THICKNESS WITH RESPECT TO SPAN LENGTH

Figures 2 to 5 show the variation of thickness with respect to span lengths of corrugated sheets. The study is made for basic wind speeds considering the roof angle θ as 10° , height to width ratio as 0.5 and width of the building as 5m, 10 m, 15 m and 20 m. The thickness of corrugated sheet increases with the increase in span length for all wind speeds. However the rate of increase in thickness with increase in length is larger for higher basic wind speeds. Further the change in thickness with respect to change in basic wind speed keeps increasing with an increase in the length of the corrugation sheet. This observation is also seen for other roof angles of 30° and 60° (refer Figs. 6 and 7). The study is extended by considering other values of height to width ratios of 1.0,1.5 and 2.0, with width w equal to 5, 10, 15 and 20 m, and roof angles of θ = 10° , 30° and 60° . In all these cases the observations made are similar to those discussed in Fig. 2

V. VARIATION OF THICKNESS WITH BASIC WIND SPEED

Figure 8 shows the variation of thickness of corrugated sheets with basic wind speed. This study is made for different length of corrugated sheets considering roof angle θ as 10° , height to width ratio as 0.5 and width of the building was 5 m. The thickness of sheet increases with an increase in basic wind speed for all lengths. However the rate of increase in thickness with increase in basic wind speed is larger for higher length of the sheets. Further the change in thickness with respect to change in length keeps increasing with an increase in basic wind speeds. This observation is also seen for other roof angles i.e. 30° and 60° as shown in Fig. 9 and 10.

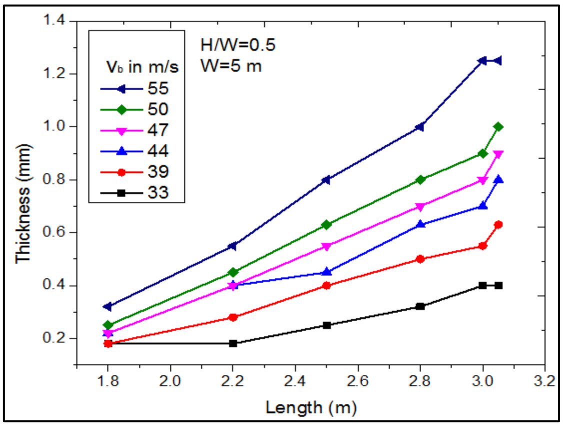

Fig. 2: Variation of thickness with respect to span length for θ= 10°

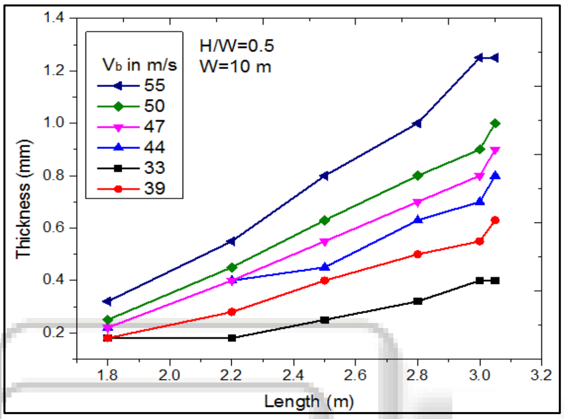

Fig. 3: Variation of thickness with respect to span length for θ= 10°

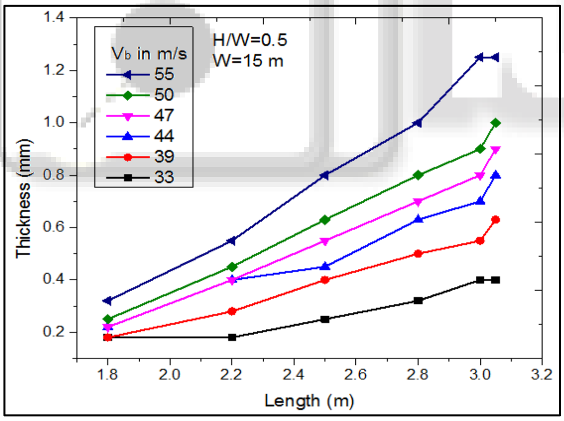

Fig. 4: Variation of thickness with respect to span length for θ= 10°

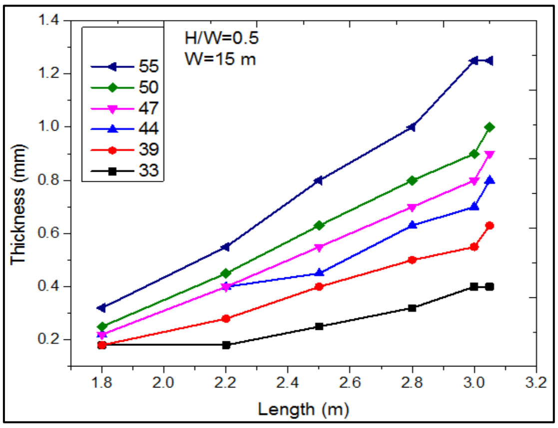

Fig. 5: Variation of thickness with respect to span length for θ= 10°

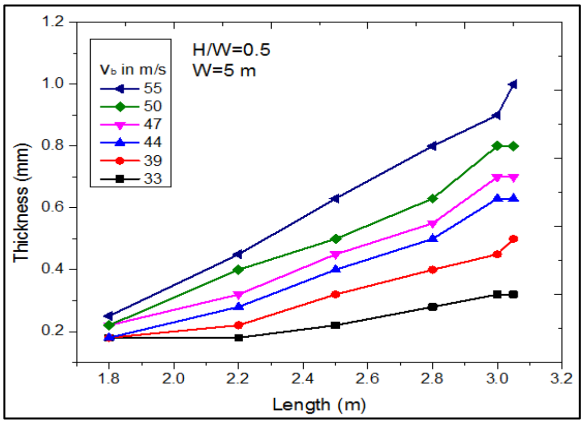

Fig. 6: Variation of thickness with respect to span length for θ= 30°

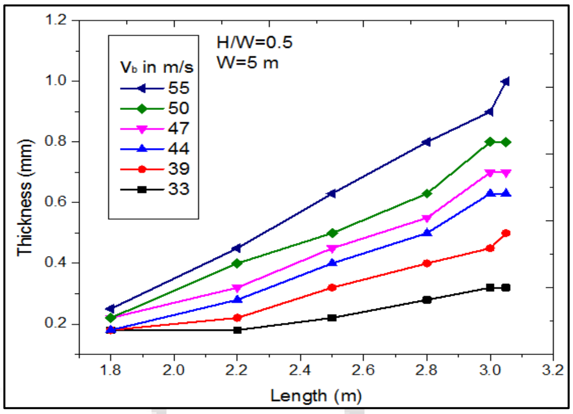

Fig. 7: Variation of thickness with respect to span length for θ= 60°

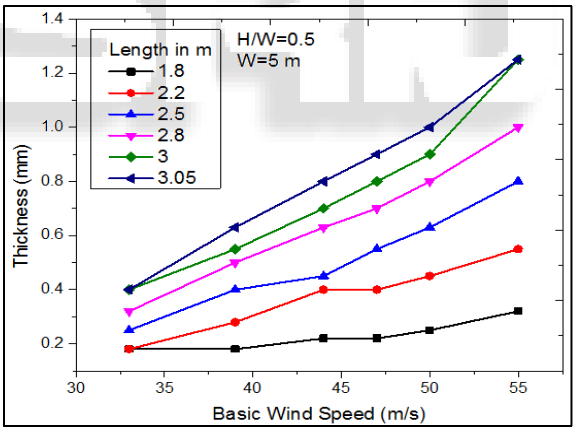

Fig. 8: Variation of thickness with basic wind speed for θ= 10°

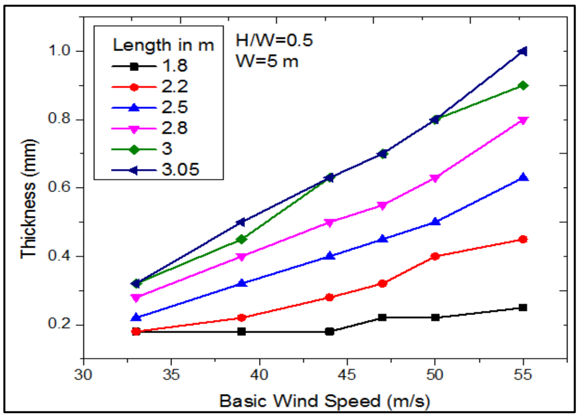

Fig. 9: Variation of thickness with basic wind speed for θ= 30°

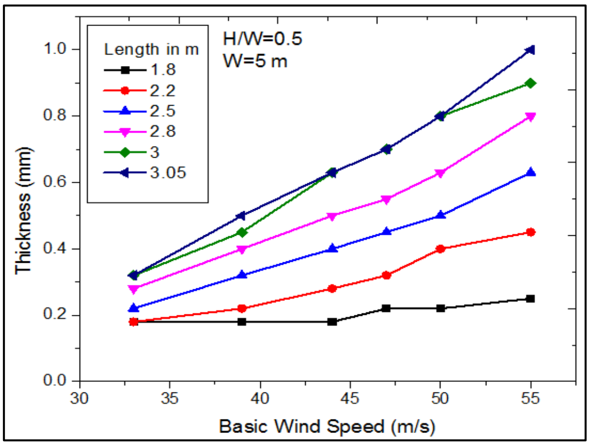

Fig. 10: Variation of thickness with basic wind speed for θ= 60°

VI. VARIATION OF THICKNESS WITH ROOF ANGLE

Figure 11 shows the variation in thickness of corrugated sheet with the roof angle ‘θ’. This study is made for various basic wind speeds considering the length as 1800mm, height to width ratio as 0.5 and width equal to 5m. The corrugation sheet roof angle does not influence the thickness of the sheet for higher values of roof inclinations. This observation is true even for higher corrugated sheet lengths [refer Figs. 12 to 22] having height to width ratios as 1.0, and 1.5. However when height to width ratio is 2, the thickness remains constant for all roof angles except 30° . When the roof angle is 30° the thickness of the sheet increases. Hence a roof slope of 30° should be avoided for all height to width ratio equal to 2.

VII. VARIATION OF THICKNESS OF CORRUGATED SHEET WITH HEIGHT TO WIDTH RATIO

Figure 23 shows the variation of thickness of corrugated sheet with height to width ratio. The study is made for different widths of building, considering the corrugated length as 1.8m, basic wind speed as 44m/sec and roof angle as 10° . The study indicates that the thickness remains constant up to a height to width ratio of 1 for all widths. When the height to width ratio is increased further, it results in higher thickness especially when the width is 20m. However the thickness reduces when height to width ratio is equal to 2. Hence it can be concluded that larger width of the building should be avoided when the height to width ratio exceeds 1. This observation is found to be true for other roof angles also (refer Fig. 24 and 25).

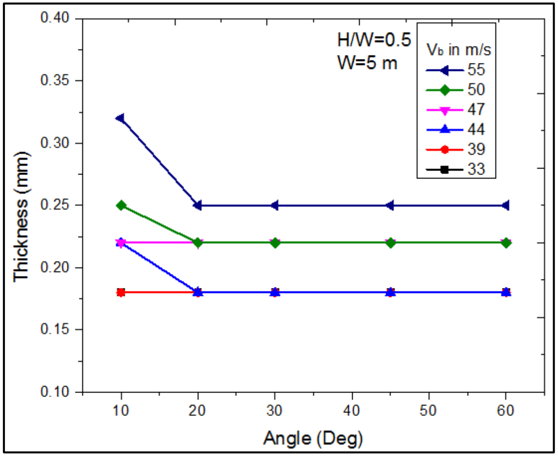

Fig. 11: Variation of thickness with roof angle for l=1.8 m

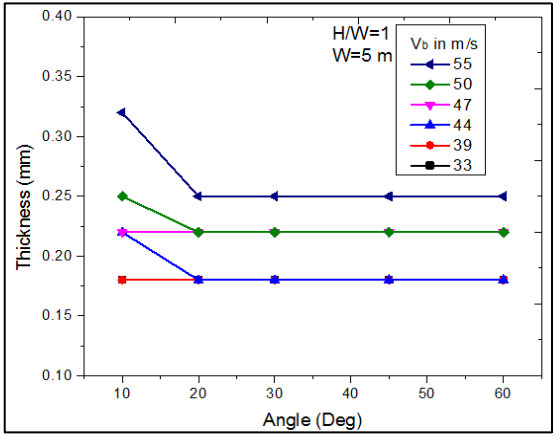

Fig. 12: Variation of thickness with roof angle for l=1.8 m

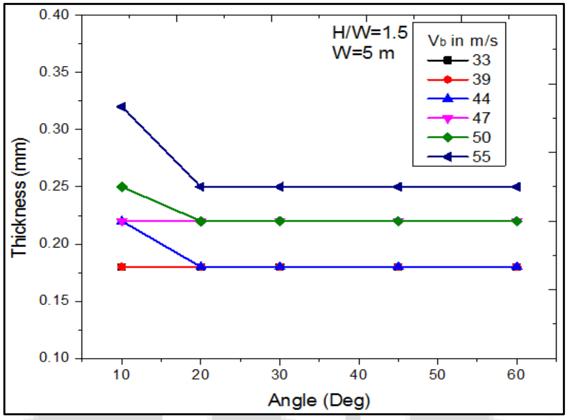

Fig. 13: Variation of thickness with roof angle for l=1.8 m

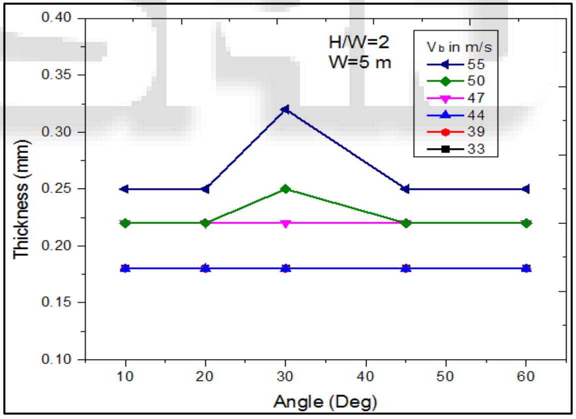

Fig. 14: Variation of thickness with roof angle for l=1.8 m

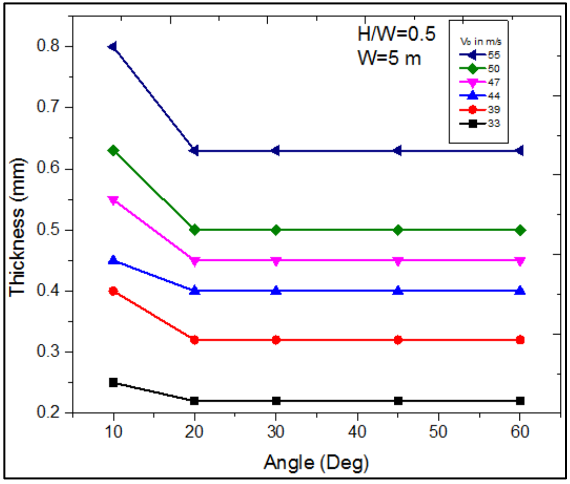

Fig. 15: Variation of thickness with roof angle for l=2.5 m

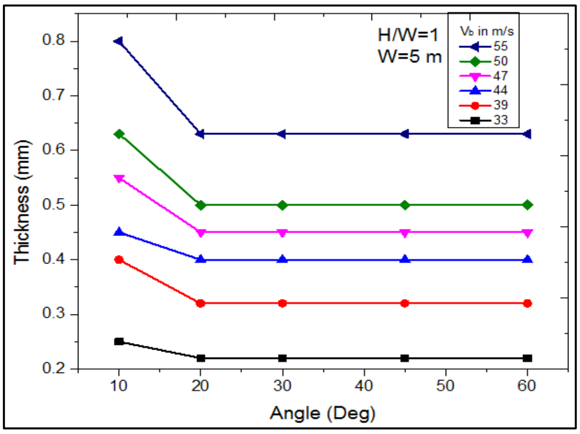

Fig. 16: Variation of thickness with roof angle for l=2.5 m

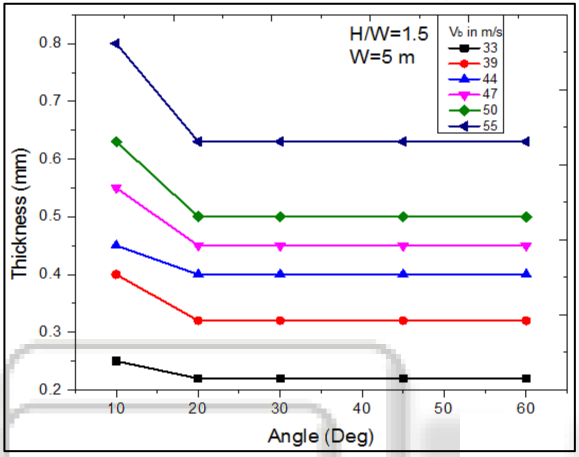

Fig. 17: Variation of thickness with roof angle for l=2.5 m

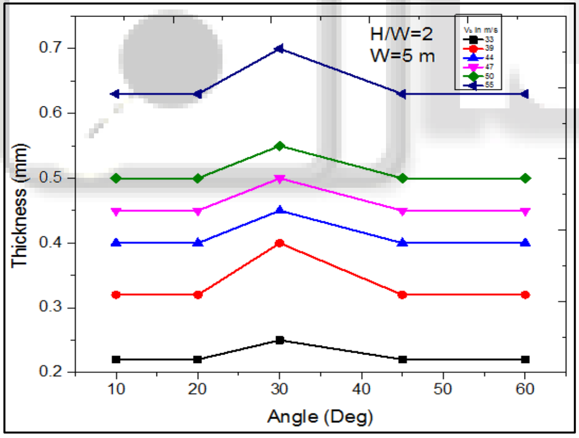

Fig. 18: Variation of thickness with roof angle for l=2.5 m

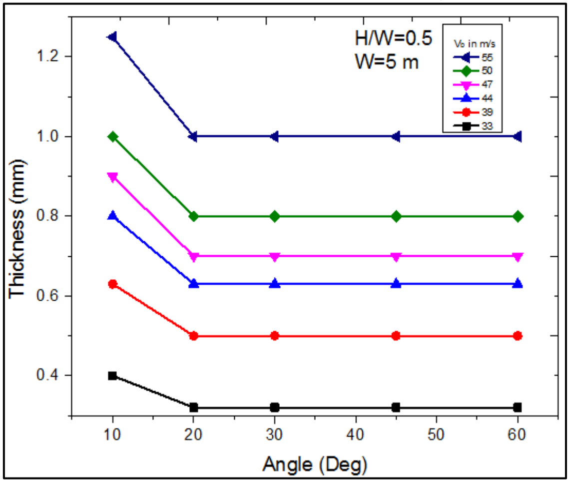

Fig. 19: Variation of thickness with roof angle for L=3.05 m

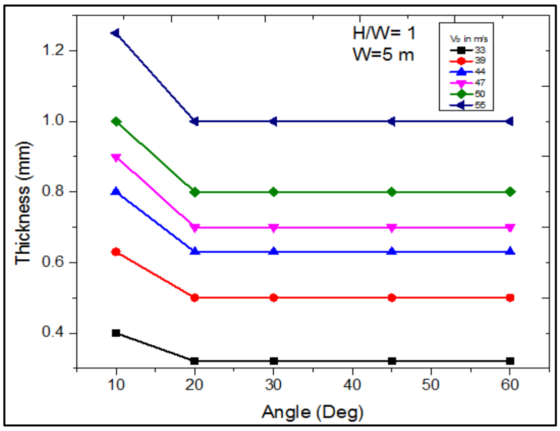

Fig. 20: Variation of thickness with roof angle for L=3.05 m

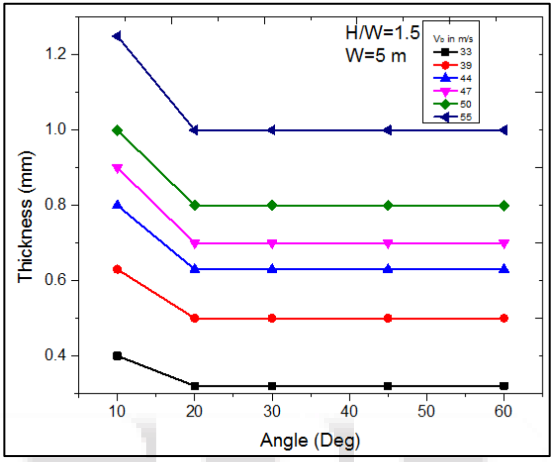

Fig. 21: Variation of thickness with roof angle for l=3.05 m

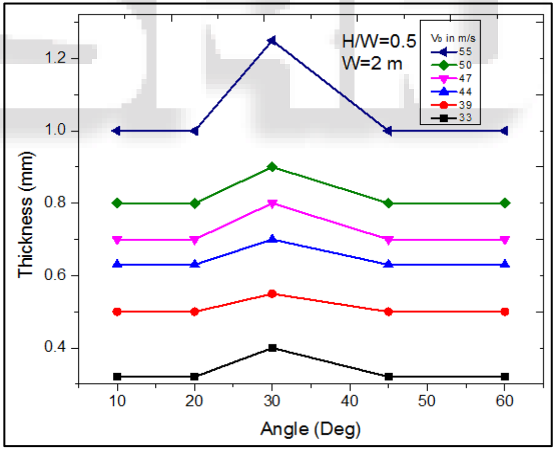

Fig. 22: Variation of thickness with roof angle for l=3.05 m

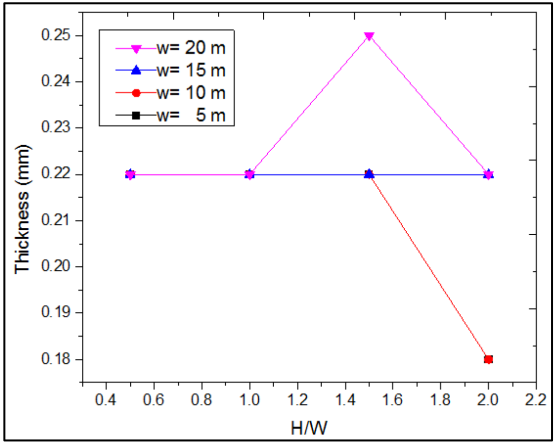

Fig. 23: Variation of thickness with roof angle 10°

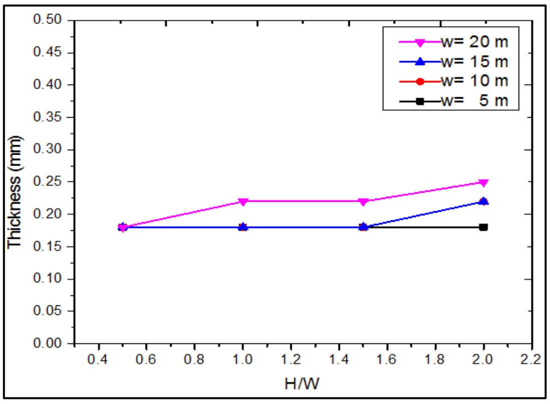

Fig. 24: Variation of thickness with roof angle 30°

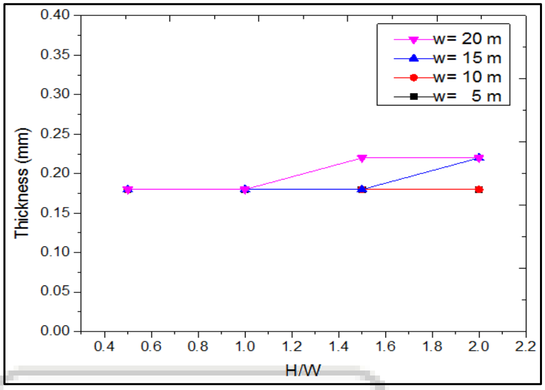

Fig. 25: Variation of thickness with roof angle 60°

VIII. NUMERICAL RESULTS

To support analytical results, numerical analysis is also carried out in the present study. Table 6.17 shows the geometrical dimensions of the two reference arc and tangent type corrugated metal roof cladding sheets which are analysed in this section. The dimensions of the two corrugated metal roof cladding sheets are considered from design Tables 6.2 and 6.13. The respective pressure loads from Tables 4.6 and 4.17 are applied on the corrugated metal roof cladding sheets. The lengths of the two sheets considered in the study are 1800 mm and 2200 mm. For each of the reference sheets the pressure loads are arrived separately considering the permissible pressure on the arc and tangent type corrugated metal roof cladding sheet which are given in Tables 3.3 and 3.4. These pressure loads are applied on the top surface of the corrugated metal roof cladding sheet in negative Y-direction since the analysis is carried out for uplift pressure loads.

Reference corrugated sheet	H/W	Width of building (m)	θ deg	V_b (m/s)	Length (mm)	Thickness of sheet (mm)
1	0.5	10	30	55	1800	0.25
2	2	5	10	55	2200	0.45

Table 6.17: Geometrical dimensions of two reference arc and tangent type corrugated metal roof cladding sheets

Generally the stress concentration in corrugated metal roof cladding sheet exists in regions near the support particularly surrounding the bolt hole. The pressure loads applied in both the cases are 3000 N/m2 (Tables 4.6 and 4.17).

The numerical results obtained using ANSYS for the reference corrugated metal roof sheets 1 of length 1800 mm subjected to uniformly distributed pressure load of 0.003 N/mm2 are presented in Fig. 26 to 27. The yield stress and Poisson's ratio of the material is taken as 250 MPa and 0.3 respectively.

Figure 26 shows the distribution of Von-Mises stresses in reference corrugated sheet 1. Figure 27 shows the deformation of corrugated metal roof sheet in Y-direction. The maximum values of stresses and deformations obtained in the numerical study are 130.36 MPa and 0.62 mm which are less than permissible values.

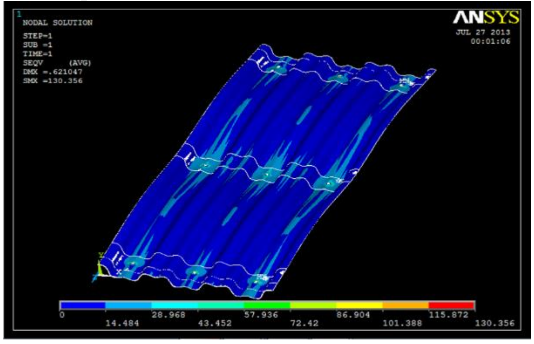

Fig. 26: Distribution of Von-Mises stresses in reference corrugated metal roof sheet 1

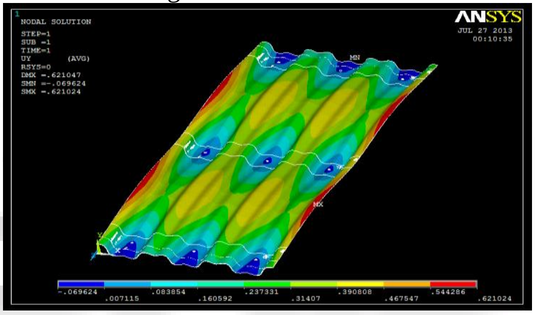

Fig. 27: Deformation of reference corrugated metal roof sheet 1 in Y-direction

Similarly, the numerical results obtained using ANSYS for the reference corrugated metal roof sheets 2 of length 2200 mm subjected to uniformly distributed pressure load of 0.003 N/mm2 are presented in Figs. 6.27 to 6.28. The yield stress and Poisson's ratio of the material is taken as 250 MPa and 0.3 respectively.

Figure 28 shows the distribution of Von-Mises stresses in reference corrugated sheet 2. Figure 29 shows the deformation of corrugated metal roof sheet in Y-direction. The maximum values of stresses and deformations obtained in the numerical study are 242.82 MPa and 1.02 mm which are less than permissible values

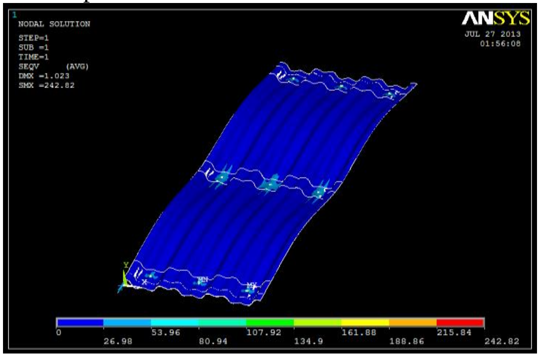

Fig. 28: Distribution of Von-Mises stresses in reference corrugated metal roof sheet 2

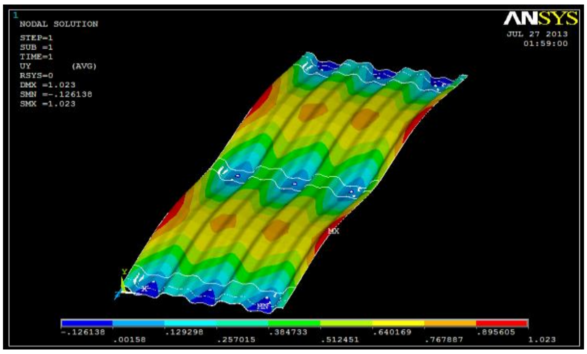

Fig. 29: Deformation of reference corrugated metal roof sheet 2 in Y-direction

IX. CONCLUSIONS

Based on the results from the present study the following conclusions are arrived.

1) The thickness of corrugated metal roof cladding sheets increase with increases in the length of the corrugated sheet and the basic wind speed.
2) The uplift pressure is maximum when the roof angle is 10^0 for all height to width ratios up to 1.5. However for the height to width ratio of 2, the uplift pressure is maximum when the roof angle is 30^0.
3) For a given basic wind speed, the uplift pressure is maximum on the windward slope of roof when compared with the leeward slope.
4) The choice of corrugated sheet lengths influences the thickness of the sheets. Longer sheet lengths result in higher percentage increase in thickness of sheets due to an increase in the basic wind speed. Hence, in higher wind zones, longer sheet lengths result in the use of thicker corrugated sheets.
5) The thickness of the corrugated sheets does not change significantly when the roof angle exceeds 10^0 for height to width ratios of 0.5, 1.0 and 1.5. For these ratios, the roof angle should be above 10^0.
6) When the height to width ratio is 2, the critical roof angle is 30^0 where the thickness required for the roofing sheet is maximum. Hence, it is appropriate to reduce the roof angle below 30^0 when the height to width ratio is 2, to reduce the thickness of the sheet.
7) The roof angle governs the thickness of the corrugated sheet and also the length of the purlin supporting the corrugated sheet. Hence proper roof angle should be selected to minimize the above parameters.
8) The thickness of the corrugated sheet is influenced by height to width ratio and the width of the building. The width of the building does not influence the thickness of the corrugated sheet when the height to width ratio is less than one. However, when height to width ratio exceeds one, the width of the building governs the thickness of the corrugated sheet. Hence, it is appropriate to choose smaller widths for the buildings when height to width ratio is more than one.
9) The numerical results carried out in the present study indicate that the stresses and deformations in the corrugated sheets considered from the proposed design tables are within the allowable limits. Hence, the proposed design tables can be used for the design of metal corrugated roof sheets.

The proposed design tables are simple and convenient, and covers wide range of parameters encountered during the design.

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