



## EXPLORING THIN SHELL PROFILED STEEL SHEET ROOFING ELEMENT FOR ARCHITECTURAL AND STRUCTURAL CONTEXT

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### Abstract

Many governments all over the world are trying to fulfill the second basic need of shelter of human being by the affordable quality housing. Roofing is an important part of building in structural, architectural and aesthetic point of view. Due to rapid increasing different types of industry as well as growing cities and population, thin shell profiled steel sheet roofing element are using for architectural and structural purpose. Its lightness, corrosion resistance, high strength-to-weight ratio properties make them attractive to engineer and architect. Nowadays, profiled steel sheet thin shell roofing element is used in buildings, stadiums, airports, and industrial factories and other architectural applications. Innovative shapes of roofs using profiled steel sheet can be used aesthetic and structurally efficient. The objective of this study is to investigate thin shell profiled steel sheet roofing element for architectural and structural context. An extensive lab testing and finite element studies on parabolic and doubly curve shape profile steel sheet roofing has been conducted. Mode of failure, load of ultimate failure and deformation-load performance of parabolic and doubly curve shape thin shell profile steel roofing is presented in this study. It is observed that the specimens tended to fail in the concave portion for curve portion of roofing. It was a great attempt to find out aesthetically pleasing as well as structurally efficient parabolic and double curve shape of shell roofing on the basis of present results. It is showed that parabolic doubly curve roofing element is suitable for architectural and structural point of views. So, those innovative shapes of roofs using profiled steel sheet can plays an important role and explore innovation idea for different construction industries.

**Keywords:** Experiment and numerical, Parabolic and curved shape, Profiled steel sheet, Roofing, Thin shell

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## Introduction

Now a days, Architect and Engineer's both are looking for architecturally pleasing shape as well as structurally efficient, lightweight roofing element. Profiled steel sheet not only used as a roof covering material it also used as architectural purpose as well as structural elements. Curve shape thin shell profiled steel sheet roofing is using increasingly in building roofing (workshop, factory), stadium, airport hanger etc. The roof is an architectural feature that gives the building a desired appearance and protects the building as well as its occupants from the effects of weather. It is found by Jagannath and Sekar that roof contributes to a substantial part (about 25%) of the total cost for both residential and industrial building. The profiled steel shell structures are used widely in roofing elements due to their lightweight, corrosion resistance, high strength-to-weight ratio, ease of production, recyclability, and availability, which also ensure the aesthetics and economical use of materials. Atrouzy (1999) performed structural analysis and studied the practical applications of corrugated cylindrical metal sheets shell roofs. Extensive experimental and analytic study was carried out by Rao and Rao (1998), Kostem (1977) and Simmonds (1979) to find the support settlement of cylindrical shell roofs. Structural behaviour of semicircular roofing elements made by ferrocement was experimentally investigated by Stekelenburg et al. (1980). An optimum shape was found out from five selected shapes by Imam et al. (2002) and Maity et.al (2003) by performing a theoretical investigation related to ferrocement. Islam et al. (2006) had performed extensive laboratory tests on cylindrical profiled steel sheet roofing elements to recognize the structural strength and behaviour. Based on test result, it was revealed that significant improvements structural performance was found in the parabolic profiled steel sheet roofing element. However, there is no research on structural strength and behaviour on parabolic and doubly curve shape thin shell profile steel sheet roofing. It is required to explore structural behaviour and strength of parabolic and doubly curve shape thin shell profile steel sheet roofing. It is a novel approach to investigate on doubly curve profiled steel sheet roofing for architectural feature and cost effective.

The prime objective of this study is to investigate thin shell profiled steel sheet roofing element for architectural and structural context steel sheet roofing system, with effective and efficient application in inexpensive housing. Structural strength and performance of on parabolic and doubly curve shape thin shell profile is investigated experimentally and numerically. An experimental program was carried out in the course of present study to authenticate the numerical results. The experimental results showed good symphony with numerical findings. The deflection and stress-strain behavior are compared on parabolic and doubly curve shape thin shell profile steel sheet roofing elements. The efficient as well as economic parabolic and doubly curve shape thin shell profile steel sheet roofing shape has been found out after a thorough experimental and numerical investigation on the basis of present results.

## Field Application of Profiled Steel Sheet for Roofing

The trend of modern architecture is now changing from traditional flat surface towards curved shapes that encloses a volume of space. Shells are structures that can be idealized mathematically as curved surface for building roofs. Shells are being used on an increasing scale for roof. Thin shell element is appropriate for roofing to build artistic and aesthetically pleasing structure due to its structural efficiency. This type of structural element is used increasingly due to the structural integrity, lightweight and comparatively very low thickness. The parabolic shell is the simplest form of shell formed by rendering a curved line along a straight longitudinal axis and which span longitudinally between supporting diaphragms. The parabolic shell can be used as efficient roofing material for its singly curved surface. In a doubly curve roofing two curve are present. Parabolic and doubly curve shape thin shell profile steel sheet roofing is using increasingly in building roofing (workshop, factory), auditorium, convention centre, stadium, airport hanger etc. as shown in Figure 1.

## Material Properties

Now a days, profiled steel sheet not only used as a roof covering material it also used as artistic , architectural feature purpose as well as structural elements. Due to structural point of view, this sheet is more effective in



Figure 1. Parabolic and doubly curve thin shell profiled steel sheet roofing.

term of load carrying capacity. Profile steel sheet is colorful, lightweight and corrosion resistant which is added extra beauty in structures. The key advantages of profile steel sheet are speedy construction and attractive architectural styles as a roofing element. As profiled steel sheet have seven layers of coating, it is tremendously durable against corrosion. Figure 2 presents the profile steel sheet and different composition layer of profiled steel sheet.

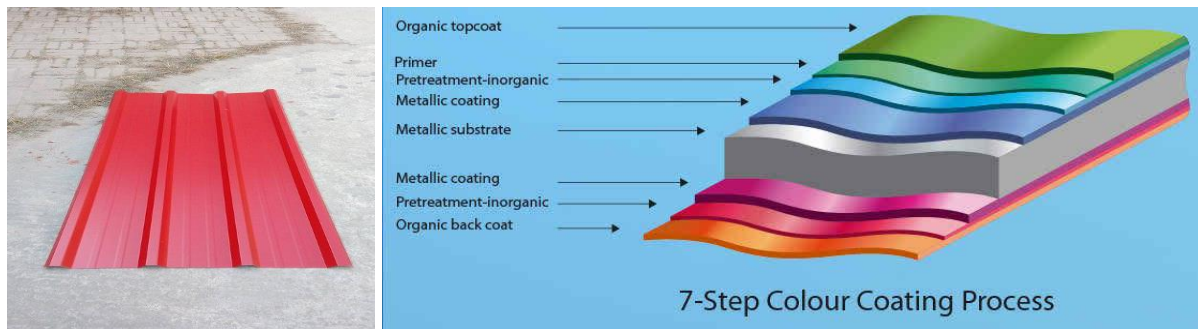


Figure 2. Profile steel sheet and its composition.

### Specimen for Numerical Analysis

Parabolic, doubly curve shape, inverted V shape, single pitch shape and flat plane shape roofing element was investigated numerically to find the structural efficiency as shown in Figure 3. Parabolic and doubly curved shape roofing element was found to meet the functional requirements of the structure. Structural efficiency of parabolic curved roof form was found more compared to other shapes.

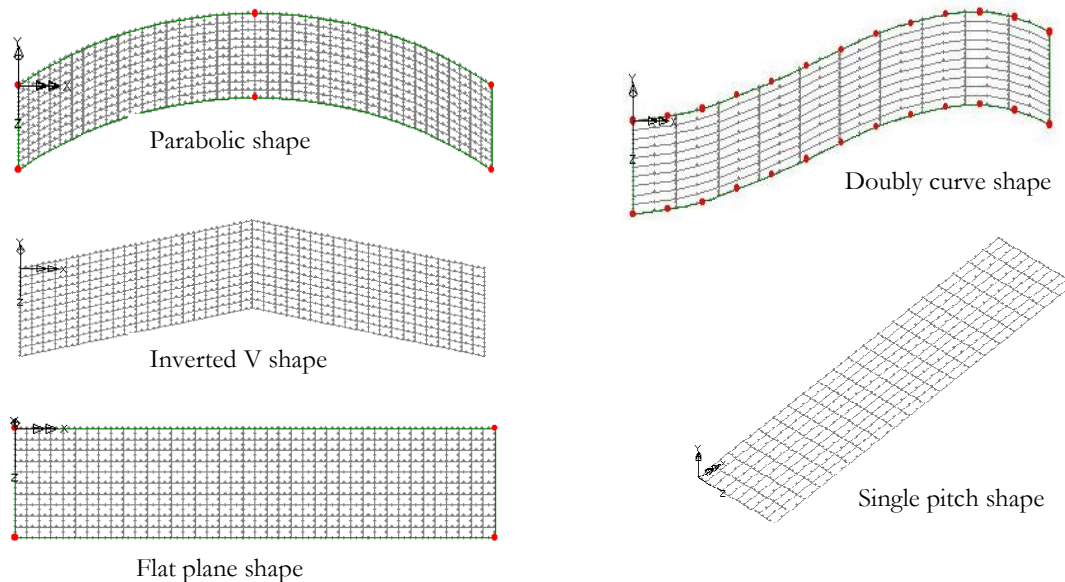


Figure 3. Different types of roofing element.

### Test Specimen and Test Procedure

Parabolic and doubly curved shaped roofing elements were considered for test in laborites. The span of the parabolic roofing element was 3 m, where width was 0.76 m and crown heights vary as 0.125 m, 0.25 m, 0.5 m a.10 m and 1.5 m respectively. The profile sheet was designed in the shape of doubly curve by manual procedure in the mechanical workshop. The upper and lower edge of the specimen connected with the frame. The steel sheet was connected to the frame by using simple mechanical connectors, for example self-tapping screws and welding. Height of the frame in the upper and lower side was 4 ft and 3 ft respectively. Test setup and sand bag loading on parabolic and doubly curved of roofing element is shown in Figure 4. Uniformly distributed load was ensured by sand bag loading technic where each bag contained 5 kg of load. The gradual load increment was applied manually until the tested specimen is failed by yielding or buckling.



Figure 4. Test setup and sand bag loading on parabolic and doubly curved of roofing element.

### Test Results and Discussions

The failure modes of profiled steel sheet parabolic and doubly curved of roofing element are shown in Figure 5. Deflection was found as the main design criteria for checking geometrical stability of the roofing element. Because geometrical failure due to exceed permissible limit was predominant than buckling failure and material failure. The weak point or critical zone of different crown height parabolic shell roof was different place. Central or crown point was common weak point due to maximum moment as well as deflection. In higher crown height such as parabolic shell obtained to two weak points. It was seen that addition one weak point was generated at the point where shear is changed. Maximum deflection was found at crown 31.38, 10.68, 4.45, 7.52, 16.69 mm due to service load 0.528 kN/m<sup>2</sup> for 1.5 m, 1.0 m, 0.5 m, 0.25 m and 0.125 m crown height respectively. Load carrying capacity was found 1.06, 2.11, 2.80, 2.51, 1.68 kN/m<sup>2</sup> of crown height 1.5 m, 1.0 m, 0.5 m, 0.25 m and 0.125 m respectively. It is observed that the specimens tended to fail in the central portions of roofing elements where there is no internal support. Load- deformation behaviour of doubly curved profile steel sheet is presented in Figure 6. Central point gauge provided higher deflection those others. Based on the

test results, it found that internal support provided higher load carrying capacity than without internal support. The observed load bearing capacity of the profile sheet with internal support was found  $1.86 \text{ kN/m}^2$  which is greater than based on BNBC code specified wind loading  $1.54 \text{ kN/m}^2$  for doubly curve profile sheet roofing.



Figure 5. Failure mode of parabolic and doubly curved of roofing element.

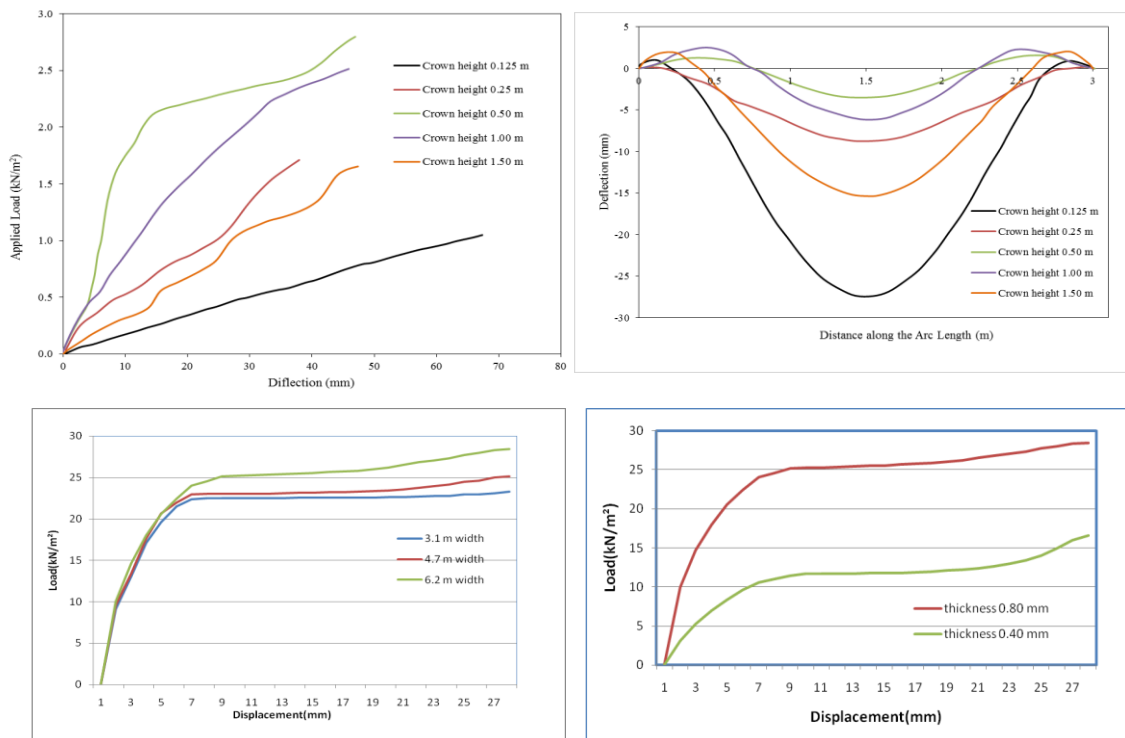


Figure 6. Load- displacement and displacement along arc parabolic and doubly curved of roofing element.

### Finite Element Modeling and Results

Finite element model of parabolic and doubly curve profile sheet roofing was developed by LUSAS and STAAD.Pro software as shown in Figure 7 respectively. The proposed FEM model ensure a reasonable degree of accuracy in forecasting structural performance of different types of roofing elements. This FEA analysis was extended to explore the viability to use doubly curve as a roofing system. The Semi-loof shell element was used for FEA. This element isoparametric, doubly curve, thin three dimensional elements. Figure 7 shows nodal configuration of semi-loof element, its obtained self-governing rotations and displacement. Semi-loof element consists three types of nodes. This element having corner and mid-side nodes which displacement U,V,W along respectively the axis X, Y and Z. The loof nodes at which the parameters are  $\theta_x, \theta_y$  (rotations of the through thickness normal): central node combining two types of parameters, displacements (W) and rotation  $\theta_x$  and  $\theta_y$  along the local axes as shown in Figure 7.

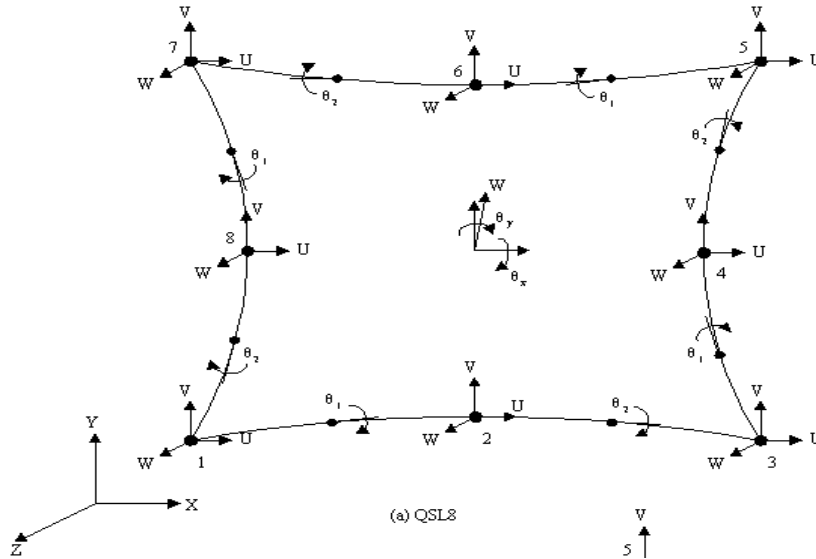


Figure 7. Formation nodal point of semi-loof element (theory manual of LUSAS software).

The displacements  $u, v,$  and  $w$  (or  $u_i$ ) obtained from the global derivatives are as follows:

$$\begin{bmatrix} \frac{\partial u}{\partial x} & \frac{\partial v}{\partial x} & \frac{\partial w}{\partial x} \\ \frac{\partial u}{\partial y} & \frac{\partial v}{\partial y} & \frac{\partial w}{\partial y} \\ \frac{\partial u}{\partial z} & \frac{\partial v}{\partial z} & \frac{\partial w}{\partial z} \end{bmatrix} = J^{-1} \begin{bmatrix} \frac{\partial u}{\partial \xi} & \frac{\partial v}{\partial \xi} & \frac{\partial w}{\partial \xi} \\ \frac{\partial u}{\partial \eta} & \frac{\partial v}{\partial \eta} & \frac{\partial w}{\partial \eta} \\ \frac{\partial u}{\partial \zeta} & \frac{\partial v}{\partial \zeta} & \frac{\partial w}{\partial \zeta} \end{bmatrix} \quad (1)$$

where the Jacobian matrix J is

$$J = \begin{bmatrix} \frac{\partial x}{\partial \xi} & \frac{\partial y}{\partial \xi} & \frac{\partial z}{\partial \xi} \\ \frac{\partial x}{\partial \eta} & \frac{\partial y}{\partial \eta} & \frac{\partial z}{\partial \eta} \\ \frac{\partial x}{\partial \zeta} & \frac{\partial y}{\partial \zeta} & \frac{\partial z}{\partial \zeta} \end{bmatrix} \quad (2)$$

The displacement derivatives in the equation 1 are obtained whereas the Jacobian matrix results from the definition of element geometry.

The strain components in the local system to the element nodal variable can be constructed by the strain matrix B as

$$\varepsilon = \sum_{k=1}^n B_k d_k \quad (3)$$

Equation 3 is often written in the portioned form

$$\begin{bmatrix} \varepsilon_f \\ \varepsilon_s \end{bmatrix} = \begin{bmatrix} \sum_{k=1}^n B_{fk} d_k \\ \sum_{k=1}^n B_{sk} d_k \end{bmatrix} \quad (4)$$

In which  $\varepsilon_f$  and  $\varepsilon_s$  are the in plane strains and the transverse shear strains. The total potential energy can be denoted as

$$\Pi = \sum \Pi_e \quad (5)$$

$$\Pi = \frac{1}{2} d^T \left[ \int_{v_e} B^T D B dv \right] d = \frac{1}{2} d^T \left[ \int_{v_e} B_f^T D_f B_{fdv} \right] d + \frac{1}{2} d^T \left[ \int_{v_e} B_s^T D_s B_s dv \right] d \quad (6)$$

Where D indicate the elasticity matrix, divided into an in plane part Df and a transverse part Ds.

The isotropic modulus and resultant modulus (elasticity) matrices are defined as explicit

$$D = \begin{bmatrix} D_{=membrane} & 0 \\ 0 & D_{=bending} \end{bmatrix} \quad (7)$$

$$D_{=membrane} = \frac{E}{1-\nu^2} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{(1-\nu)}{2} \end{bmatrix} \quad (8)$$

$$D_{=bending} = \frac{Et^3}{12(1-\nu^2)} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{(1-\nu)}{2} \end{bmatrix} \quad (9)$$

Numerical integration for elasticity matrix of shell element was computed by the following formula. That matrix is used to find out material rigidity.

$$D = \int_t \frac{E}{1-\nu^2} \begin{bmatrix} 1 & \nu & u & z & \nu z & u \\ \nu & 1 & 0 & \nu z & z & 0 \\ 0 & 0 & \frac{(1-\nu)}{2} & 0 & 0 & \frac{(1-\nu)}{2} \\ z & \nu z & 0 & z^2 & \nu z^2 & 0 \\ \nu z & z & 0 & \nu z^2 & z^2 & 0 \\ 0 & 0 & \frac{(1-\nu)z}{2} & 0 & 0 & \frac{(1-\nu)z^2}{2} \end{bmatrix} \quad (10)$$

After minimization of  $\Pi$  with respect to the nodal variables D the following equation are obtained

$$K_{ij} d_j = f_i \quad (11)$$

The stiffness matrix  $K_{ij}$  connected nodes  $i$  and  $j$  which has indicated the in plane and transverse shear strain energy terms respectively.

$$K_{fij}^e = \int_{v_e} B_{fi}^T D_f B_{fi} dv \quad (12)$$

$$K_{sij}^e = \int_{v_e} B_{si}^T D_s B_{sj} dv$$

The shell thickness and a full integration rule in the  $\zeta - \eta$  surface can be obtained by 2-point integration rule

$$dv = dx dy dz = |J| d\xi d\eta d\zeta \quad (13)$$

where  $|J|$  denote the Jacobian matrix

The formulas for the shell element are the same as those of the Mindlin plate element theory were incorporated to predict shell behavior in LUSAS software by the following matrix:

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} D_1 & D_2 & D_4 & D_7 & D_{11} & D_{16} \\ D_2 & D_3 & D_5 & D_8 & D_{12} & D_{17} \\ D_4 & D_5 & D_6 & D_9 & D_{10} & D_{18} \\ D_7 & D_8 & D_9 & D_{10} & D_{14} & D_{19} \\ D_{11} & D_{12} & D_{13} & D_{14} & D_{15} & D_{20} \\ D_{16} & D_{17} & D_{18} & D_{19} & D_{20} & D_{21} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \Gamma_{xy} \\ \Psi_x \\ \Psi_y \\ \Psi_{xy} \end{bmatrix} - \begin{bmatrix} \varepsilon_{xo} \\ \varepsilon_{yo} \\ \Gamma_{xyo} \\ \psi_{xo} \\ \psi_{yo} \\ \psi_{xyo} \end{bmatrix} + \begin{bmatrix} N_{xo} \\ N_{yo} \\ N_{xyo} \\ M_{xo} \\ M_{yo} \\ M_{xyo} \end{bmatrix} \quad (14)$$

where, N= resultant membrane stress (Force per unit width), M = the resultant flexural stress (Moments per unit width), D= Flexural and shear rigidities; E= membrane strains ;  $\psi_x$ ,  $\psi_y$ , and  $\psi_{xy}$  the flexural strains in the local Cartesian system,  $\Gamma$  = Shearing strain

Figure 8. presents comparison of tested and numerical deflection and variation of equivalent stress-strain for parabolic roofing element. Displacement and stress distribution of parabolic curve profiled steel sheeting roofing is shown in Figure 9. Comparison of tested and numerical deflection and variation of equivalent stress- strain for parabolic roofing element is shown in Figure 10.

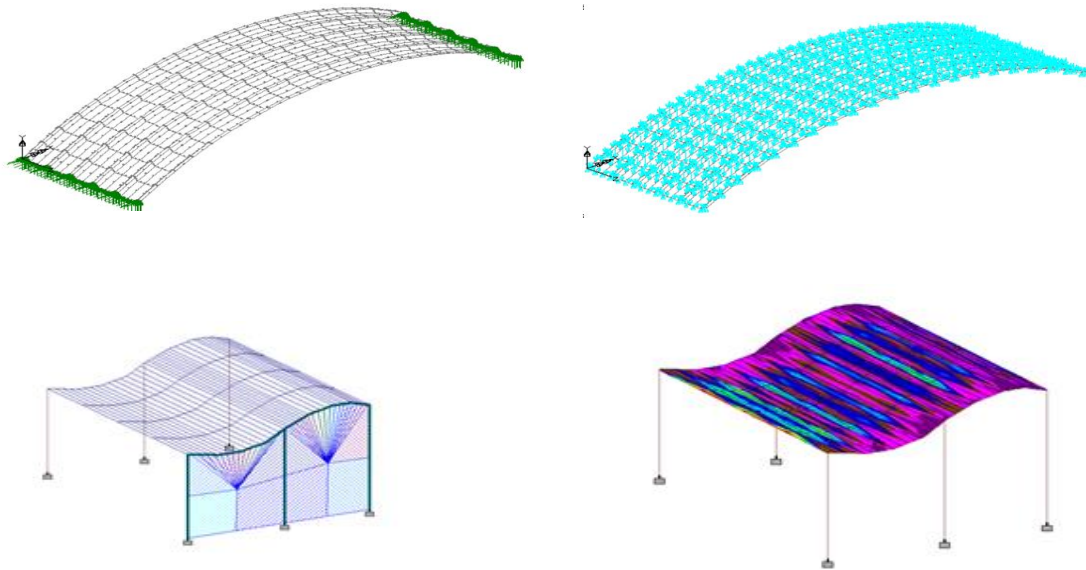


Figure 8. Finite element model and stress distribution of parabolic doubly curve profiled steel sheeting roofing.

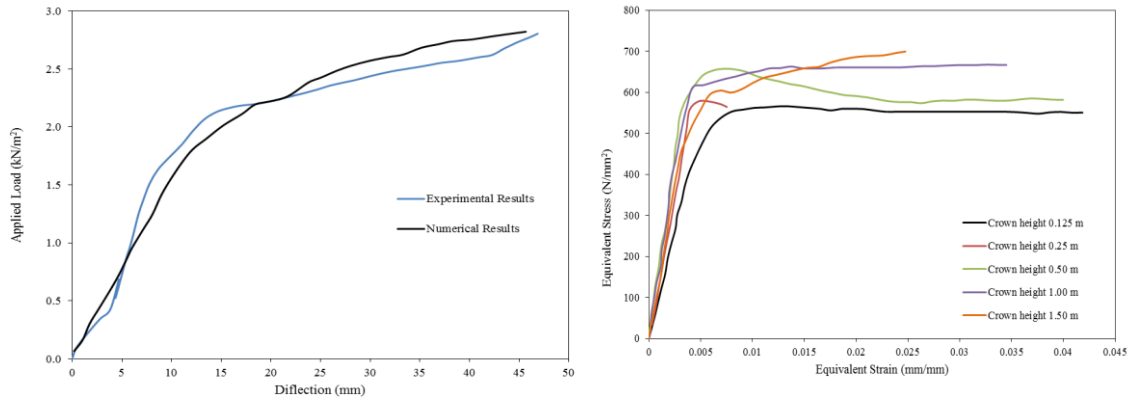


Figure 9. Comparison of tested and numerical deflection and variation of equivalent stress- strain for parabolic roofing element.

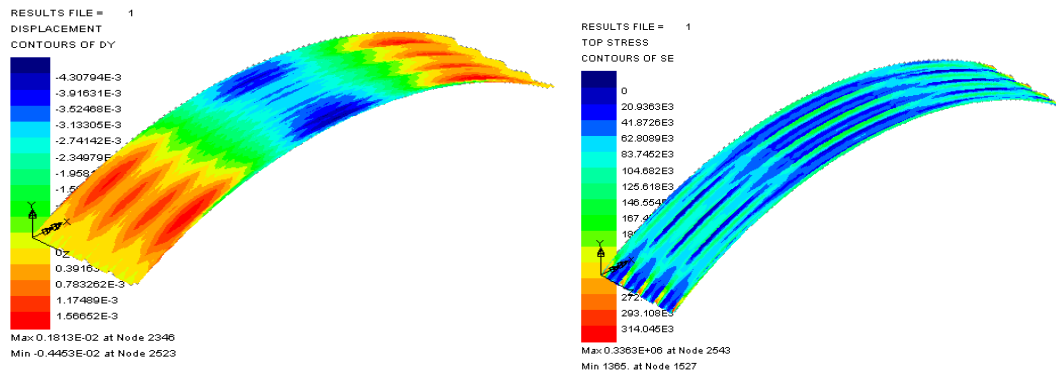


Figure 10. Displacement and stress distribution of parabolic curve profiled steel sheeting roofing.

## Conclusion

In this paper, an extensive lab testing and finite element studies on the structural strength and behaviour of profiled steel sheet parabolic and doubly curve shape profile steel sheet roofing has been conducted presented. Mode of failure, load of ultimate failure and deformation-load performance of parabolic and doubly curve shape thin shell profile steel roofing is also presented in this research. Parabolic and doubly curve shape profile steel sheet can be used efficiently for large span structures not only for economical purpose but also due to aesthetic view. LUSAS and STAAD.Pro software were used for the finite element analysis. It is found that the specimens tended to fail in the concave portion for curve portion of roofing. It was a great, novel and new attempt to find out aesthetically pleasing as well as structurally efficient parabolic and double curve shape of shell roofing on the basis of present results. It is found that parabolic and doubly curve roofing element is suitable for architectural and structural point of views. Higher thickness and providing internal support can be used in field application as doubly curve roofing element So, those innovative shapes of roofs using profiled steel sheet can plays an important role and explore innovation idea for different construction industries. It can

be concluded that those artistic and innovative shapes of roofs using profiled steel sheet can play an important role and explore innovation idea for different construction industries.

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### References

- Standard, A. (1991). Methods for tensile testing of metals, AS 1391. Sydney (Australia): Standards Association of Australia.
- ASTM, E. 9. (2001). Standard test methods for tension testing of metallic materials. Annual book of ASTM standards. ASTM.
- EL-Atrouzy, M. N. (1999). Cylindrical Shell Roofs Made of Corrugated Metal Sheets. The Fourth International Symposium on Roofing Technology, (pp. 138-141).
- IMAM, N., MAITY, D., & Kalita, U. C. (2002). An investigation on the shape of ferrocement roofing elements. *Journal of ferrocement*, 32(4), 271-286.
- Jagannath, V., & Shekar, U. C. (1989). Precast L-pan roof elements for low cost housing. D. Venkateshwarlu and Vijay Raj Ferrocement Gasifiers: A New Development in Low Cost Gasifier Fabrication 339, 351.
- Kostem, C. N., & Garrabrant, M. E. (1977). The Effect of vertical support settlements on cylindrical shells. In IASS Conference on Light-Weight Shell and Space Structures for Normal and Seismic Zones, Alma-Ata (pp. 187-191).
- Maity, D., Imam, N., & Kalita, U. C. (2003). Finite element analysis of ferrocement roofing shell elements. In CONMAT 2003: International Workshop and Conference on Construction and Materials (pp. 285-294).
- Rao, P. S., & Rao, A. P. (1988). Behavior of Cylindrical Shells Subjected to Support Settlements. *Journal of Structural Engineering*, 114(4), 931-941.
- Simmonds, S. H. (1989). Effect of support movement on hyperbolic paraboloid shells. *Journal of Structural Engineering*, 115(1), 19-31.
- Stekelenburg, P. V., Walraven, J. C., & Mathews, M. S. (1980). Development of a semi-cylindrical ferrocement roofing system. *JOURNAL OF FERROCEMENT-BANGKOK*, 10(2), 111-119.
- Islam, S. Z., Abang-Abdullah, A. A., & Jafor, M. S. (2006). An Investigation on structural performance of profiled steel sheet to develop self-supporting roofing system." *Journal of Advance Steel Construction*, 2(2006), 87-108.