



Journal of Applied Sciences

ISSN 1812-5654

science
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Finite Element and Experimental Investigation on Profiled Steel Sheet to Develop Self-supporting Roofing Element

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Abstract: Profile steel shell structures are used popularly due to aesthetic and economical use of materials. The aim of this research work is to develop a self-supporting roofing element using profiled steel sheet such as zincalume, with potential for application in affordable quality housing. An analytical investigation using finite element method is carried out on the structural strength and behaviour of different types of self-supporting roofing elements. An experimental study on the structural strength and behaviour of a selected roofing element is conducted to validate the analytical investigation. Conventionally, profile steel sheet such as zincalume and galvanized iron sheet is using in roof as a covering materials using different type of internal support without any attention paid to their structural capability. It is an innovative system that is self-supporting roofing system where sheeting roofs run continuous lengths of roof sheeting from one end to other end support through eliminating internal support. This kind of roofing system has significant advantages of removing the internal trussing and support. An attempt has been made to find out efficient, economic and aesthetically pleasing shape of shell elements to provide self-supporting roofing system on the basis of present results. The load deflection, stress-strain and deflected shape profiles for investigated roofing element is showed that parabolic roofing element having crown height $1/6$ of chord length is more efficient than others. It is observed that a parabolic shape roofing element with optimum crown height is structurally and economically able to use as a supporting roofing system for 8 m span lengths using 1.25 mm thick profiled zincalume sheets. It can be concluded that the proposed roofing system has a great potential to be exploited for housing construction.

Key words: Finite element method, profiled steel sheet (Zicalume), self-supporting, roof

INTRODUCTION

Shelter, the second basic need of man, has been a preoccupation for many governments all over the world trying to house their growing population. The housing need is ever increasing due to rapid industrialization, urbanization and population explosion. The roof protects the building and its occupants from the effects of weather, but it are also is an architectural feature that gives the building a desired appearance. Jagannath^[1] mentioned that roof accounts to a substantial part (about 25%) of the total cost of a building whether it is residential or industrial. Therefore, it demands high technical and design specifications for both of the individual products elements and for the roof as a whole in order to achieve a satisfactory design life. The use of the corrugated metal thin shells in roofs, leads to considerable saving in materials, labour and cost.

The use of the corrugated metal sheet goes back to the beginning of this century. For a long time, corrugated metal sheets were used as covering materials, without any attention paid to their structural capability. The reason for not considering them as structural elements was the lack of sound basis for using these sheets together to form a continuous self-supporting medium. This approach provides particularly neat and attractive roofing whilst eliminating the ridge capping, thereby avoiding any possibility of leakage along this fitting. Nilson^[2] also showed the possibility of using these sheets in folded plate roofs. A study has been performed on structural analysis and practical applications of cylindrical shell roofs made of corrugated metal sheets by Atrouzy^[3]. The exact differential equations used to explain the behavior of orthotropic shells. More recently, Sakala^[4] develop a procedure for the design of steel roof subjected to non-uniform loads such as drifted snow using purlins frame. Self supporting concept was not considered. Rib steel deck was used as a covering material, without any

attention paid to their structural capability. Geometric and materials nonlinearity also was ignored. Extensive study on support settlement of cylindrical shell roofs was carried out by many researchers^[5-8]. Stekelenburg *et al.*^[9] investigated experimentally structural behaviour of ferrocement semicircular roofing elements. Theoretical studies relating to ferrocement have been reported in the literature observed and found out an optimum shape within selected five shapes by Imam *et al.*^[10] and Maity *et al.*^[11]. Thin cylindrical shell roof was solved by Scordelis and Lo^[12] and was extensively used for checking the performance of various types of shell elements. They used support along the circumferential edge not straight edge as a self-supporting concept. Nonlinear analysis was not carried out. Steel instead of ferrocement is very much use now a day in the design of lighter structures. Zinalume is lighter than ferrocement, which is easier for construction, handling and efficiently erection. Actually ferrocement have some drawbacks, being labour intensive and time consuming. Analytically critical loads of self-supporting cylindrical roofs can be found out by energy theorem^[13]. The self-supporting roofing element using profile steel sheeting (zinalume); a thin shell, lightweight structure, is a structural load bearing system describe in an earlier publication^[14,15].

The main objective of this study was to develop a self-supporting roofing system, with potential and efficiency for application in affordable quality housing. Structural behavior of Inverted V shape, Cylindrical, Parabolic, Doubly curve, Single pitch and Flat plane shell roofing system are investigated analytically to provide as a self-supporting roofing system. This research was an attempt to investigate the contribution of corrugated sheet in reducing the buckling and displacement and enhances its load carrying capacity. An experimental program was undertaken in the course of present study to validate the analytical results. The experimental results showed good agreement with those obtained theoretically. The deflection and stress-strain behavior of different types of roofing elements are compared each other. The efficient and economic shape of self-supporting roofing elements has been found out after a through investigation on the basis of present results.

MATERIALS AND METHODS

Profile thin shell metal element is used popularly due to aesthetic and economical use of materials. Great variety of shell roofs have been designed and constructed in many part of the world^[16]. The use of the shells in roofs, leads to considerable savings in materials. Normally corrugated metal sheet such as zinalume is used in roofs

as a covering only, while depending on different types of intermediate support. A self-supporting roofing system is when a roof runs its continuous length from on end to other end support by eliminating internal supports such as purlins, rafter, fastener and truss. This method provides a particularly neat and attractive solution to roofing whilst eliminating the ridge capping, thereby avoiding any possibility of leakage along this fitting. This roof can save material, construction and erection cost. Finite element method is used for analytical work.

Zinalume: The shape and size of precast/prefabricated roofing element is chosen to satisfy the general requirements of strength and stiffness, lightness and economy, ease of handle and erection, proper seating and leak proof joint. There are different types of materials for construction of roof frame and roof covering. Common types of materials are metal sheet, ferrocement, plastic and concrete and clay tile for roof covering. Timber and metal are normally used for the trusses. For this investigation the corrugation metal sheet zinalume was chosen in an effort to develop the self-supporting roofing system. The main features of using of zinalume sheet as roofing material as according to Bluescope-Lysaght are as follows;

- Speedy installation; no shuttering required, less installation errors.
- 30-40% cost saving over RCC roofing.
- Lower dead load on the walls, light weight and easy handling.
- High strength to weight ratio.
- Easy to for into complex shapes, new shape more efficiently allowing to be used.
- Elegant profile and uniform sizes, large span possible with intermediate supports.
- Abundantly available and inexpensive and corrosion-resistant.
- Fire registrant and material consistency high.
- Unaffected by termites and longevity and does not required paint.
- No materials wastage and recycling system is applicable.
- Economical considering mean service life.

Zinalume sheet can be considered as the best and most durable roofing elements for affordable quality housing in the world. Zinalume consists of high strength steel substrate protected with corrosion inhibitive treatments and coatings designed to provide the broad spectrum of performance that is essential for long life and minimum maintenance. All steel sheets used in the

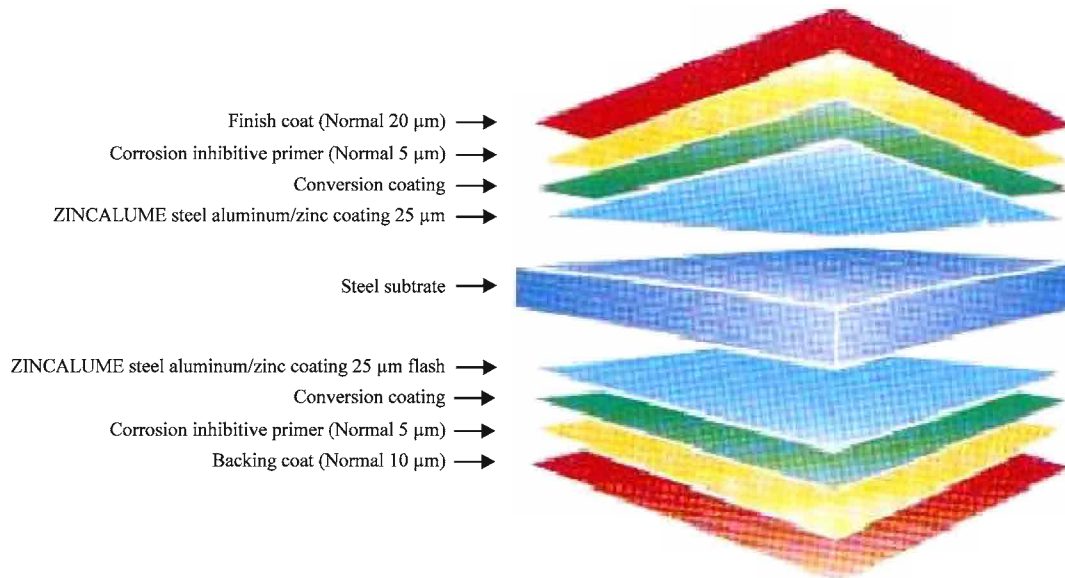


Fig. 1: Different composition layer of zincalume sheet

manufacture of the roofing sheets shall have a protective metallic alloy coating of zinc (43.5%) aluminium (55%) and silicon (1.5%), applied by the hot dip process and having a coating thickness of 0.05 mm as stipulated in AS1397-1993 for coating class AZ 150. Chromic acid sealed, zinc phosphate pretreatment is applied after alkaline cleaning for coating. Galvanized steel is treated on both sides with phosphate conversion coating followed by application of an impervious epoxy primer incorporating a corrosion inhibiting compound. Modified polyester coating of 20 µm is used for finish coat to ensure maximum durability. Composition layer of zincalume is shown in Fig. 1. Zincalume, which is used in the investigation, are locally available in Malaysian, Singapore and Australian market. It is obtained strength as steel grade ASTM A446 E, minimum yield strength 550 Mpa, Modulus of elasticity $E=210$ Gpa, poisons ratio $\nu=0.30$: mass= 4.7 kg m^{-2} (for thickness of 0.47 mm sheet). Zincalume obtained two basic strength grades G 550 and G 300. High tensile steel G550 was used in this study to develop self-supporting roofing elements.

Finite element models: The shell roofing element were models and analysed employing the finite element software LUSAS^[17]. The shell-roofing element was analysed as a 3-D problem. It was discretised by means of 8-noded semi-loof elements having three translational displacements in the global axes at the corner and mid side nodes and one rotation with respect to axes in the plane of middle surface. The semi-loof element is probably one of 8 the most efficient elements for the solution of thin shell of arbitrary geometry^[18,19]. At first an arc was

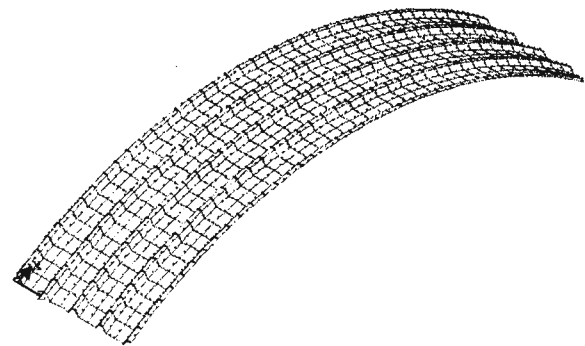


Fig. 2: Finite element model of profile of parabolic shell roof

drawn by three Cartesian points and then translate required width and corrugation for profile sheet. Width of different types of roofing elements was considered as 0.76 and 8.0 m for analysis. Thickness of flat sheet and profile sheet were assigned as 1.2 and 0.47 mm, respectively. A nonlinear analysis was carried out assuming zincalume to be elastic-plastic material. The model was subjected to global distributed load along the vertical direction. Different types of roofing element such as Inverted V shape, cylindrical, parabolic, doubly curve; single pitch and flat plane have been subjected to incremental global distributed load. The boundary conditions for the roofing element were assumed as fixed, pin and simple supported to make a comparative study of effect of boundary condition. Different mesh sizes and different numbers of element were tried so that accurate results could be obtained. Material and geometric

nonlinearity were considered in FEM analysis. Three different types of profile sheet such as Trim, Spendeck and Klip-lok are model. Trim profile is shown in Fig. 2.

Theoretical formulation of degenerated shell element: A good number of finite elements have been developed for the analysis of thin, circular cylindrical shells. These include flat elements and curved elements. Flat elements are lower-order elements and hence may require refined mesh, where as curved elements are higher-order elements and may more efficient than flat element^[5,6]. Semi-loop element was originally published by Irons and since then it has been the object of much research with respect to its philosophy and performance in various structural situation. Finite element modeling of general shells has been using semi-loop elements, elements formulated on the basis of curved shell theory and by means of degenerated isoparametric elements. The Semi-loop shell element is a thin, doubly curved, isoparametric element formed by applying Kirchhoff constraints to a three-dimensional degenerated thick shell element^[17]. It is able to take care properly the bending performance of thin shell structures. The final nodal configurations are obtained corner and mid-side nodes at which displacement U, V, W along, respectively the axis X, Y, Z is used as parameter: loof nodes at which the parameters are θ_i (rotation) which is shown in Fig. 3.

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

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

Equation 1 often written in the partitioned form

$$\begin{bmatrix} \varepsilon_f \\ \varepsilon_s \end{bmatrix} = \begin{bmatrix} \sum_{k=1}^n B_{fi} d_i \\ \sum_{k=1}^n B_{si} d_i \end{bmatrix} \quad (2)$$

In which ε_f and ε_s is the in plain strains and the transverse shear strains. The total potential energy can be written as:

$$\begin{aligned} \Pi &= \frac{1}{2} d^T \left[\int_{v_e} B^T D B dv \right] d = \frac{1}{2} d^T \left[\int_{v_e} B_f^T D_f B_f dv \right] d \\ &+ \frac{1}{2} d^T \left[\int_{v_e} B_s^T D_s B_s dv \right] d \end{aligned} \quad (3)$$

Where, the elasticity matrix D is divided into an in plane part D_f and a transverse part D_s . Upon finite element

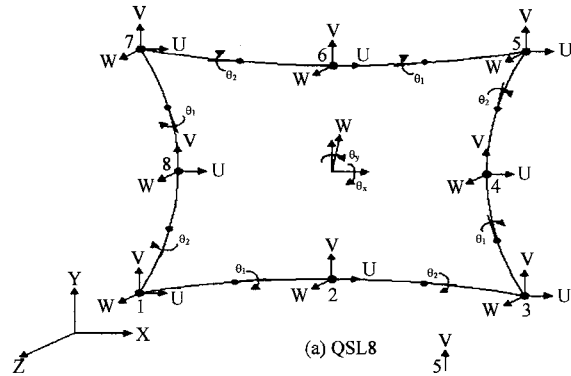


Fig. 3: Final nodal configuration for semi-loop elements

discretisation and subsequent minimization of total potential energy^[20-22] with respect to nodal variables the following equations are obtained:

$$K_{ij} d_j = f_i \quad (4)$$

In which the stiffness matrix K_{ij} linking nodes I and j has the following typical contributions emanating from the in plane and transverse shear strain energy terms, respectively.

$$\begin{aligned} K_{fij}^e &= \int_{v_e} B_{fi}^T D_f B_{fj} dv \\ K_{sij}^e &= \int_{v_e} B_{si}^T D_s B_{sj} dv \end{aligned} \quad (5)$$

A 2-point integration rule through the shell thickness and a full integration rule in the ζ - η surface can be used and

$$dv = dx dy dz = |J| d\zeta d\eta d\zeta \quad (6)$$

Where, $|J|$ is determinant of the Jacobian matrix

If the axes of the local coordinate system are parallel to those of the global coordinate system at all points in the shell mid surface, then the formulas for the shell element are the same as those of the Mindlin plate element.

Experimental testing specimen: In order to verify the validity of the finite element analysis on the selected types of roofing elements a limited number of experimental model tests were conducted. The dimension of the model was span 3 m, width 0.76 m and varying crown heights 0.125, 0.25, 0.5, 1.0 and 1.5 m, respectively. When a inverted V shape, doubly curve shape, single pitch shape and flat plane shape roofing element did not meet the functional requirements of the structure, parabolic and cylindrical curved roof form was found to be the more



Fig. 4: Setting of deformation gauge, LVDT and strain gauge



Fig.6: Sand bag loading on cylindrical element



Fig. 5: Test setup for cylindrical shell roofing elements



Fig.7: Sand bag loading on parabolic element

efficient structure. These nonlinear, nonplanar systems owe their efficiency to their unique capacity to resist applied loads primarily by direct stress as opposed to flexural or shear stress. The structural action and advantage of arches were easily recognized by considering a two hinge arch. As a further development of the arch principle, shell surfaces provided a structurally efficient solution to the problem of carrying roof loads as a self-supporting condition. Five selected parabolic roofing elements were considered in order to find out the optimum crown height.

Fabrication, test setup and procedure: Zincalume made from high strength steel substrate, which was protected with corrosion inhibitive treatments and designed coatings. These steel sheets used in the manufacture of the roofing sheets shall have a metallic alloy coating of zinc (43.5%) aluminium (55%) and silicon (1.5%), applied by the hot dip process. All specimens were tested with the curve edge free and straight edge hinged supported.

U type metal channel were used to provide hinge support at straight of the cylindrical and parabolic shell roofing elements to maintain hinge-supported condition. All the specimens were tested in the vertical position. Sand bag loading was used to provide uniformly distributed loads. Each bag contained 5 kg load. The loads were applied manually by gradually increasing until yield failure of the model. Four deformation gauge, two LVDT and ten electronic strain gauges were used to measure deflections and stains. Deformation gauges and LVDT were set at the center of the bottom surface for the specimen with required stand. Strain gauges were used at the mid position of the top surface of the specimen. Detailed setting of deformation gauges, LVDT and strain gauges are shown in Fig 4. Test setup for cylindrical shell roofing elements is shown in Fig. 5. Sand bag loading was used to provide uniformly distributed load. Each bag contained 5 kg load. The load was applied manually by gradually increment until yield failure of the tested specimen. Sand bag loading are shown in Fig. 6 and 7.

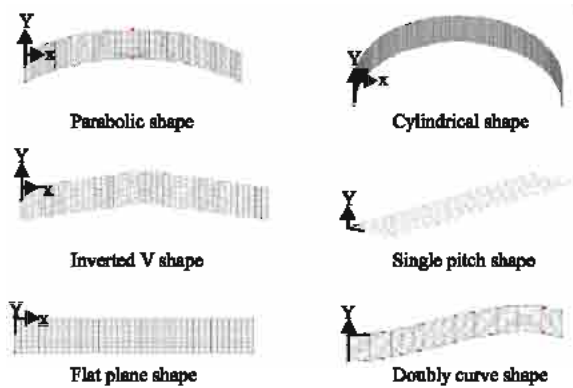


Fig. 8: Different types of roofing elements

Numerical examples: The primary effect of wind is visualized in the form of pressures normal to the structure's exterior surfaces. In this paper, the assessment of imposed load and wind loading was carried out according to Uniform Building by Law and the British code of Practice^[23-26]. With the help of well-known FEM based software package LUSAS, different bench problem are solved. The LUSAS is used for the evaluation of deflection and stress behavior of different types of roofing elements. The numerical results are studied for Parabolic, Cylindrical, Doubly Curve, Flat Plane and Single pitch roofing System. The roofing shell elements are analyzed with span length 3 m, width 0.76 m and thickness 0.47 mm and 1.2 m for profile sheet and flat sheet, respectively^[27]. Different types of roofing elements are shown in Fig. 8.

RESULTS

Basic behaviour of different types roofing element in elastic-plastic range is studied checking for deflection and stress as the main controlling design factor. The graphical representation of load deflection and stress-strain behavior of different types of roofing element is shown in Fig. 9 and 10, respectively. According to the non-linear finite element analysis, parabolic roofing element is more efficient than other types of roofing element due to its lower deflections and stresses. Parabolic and cylindrical roofing elements obtain arch action that causes load carrying capacity is higher then those others as self-supporting conditions. Nonlinear and nonplaner parabolic system resist applied loads by direct stress as opposed to membrane stress and bending stress.

Crown displacement is occurred due to two causes (i) bending and (ii) shortening of shell. Bending of curved shell roofing element is created by bending field such as M_x , M_y , M_{xy} , M_{yx} , Q_x and Q_y and on the other shortening

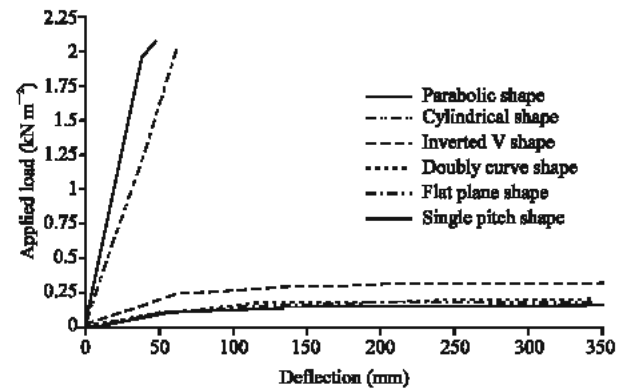


Fig. 9: Load-deflection profile of different types of roofing element

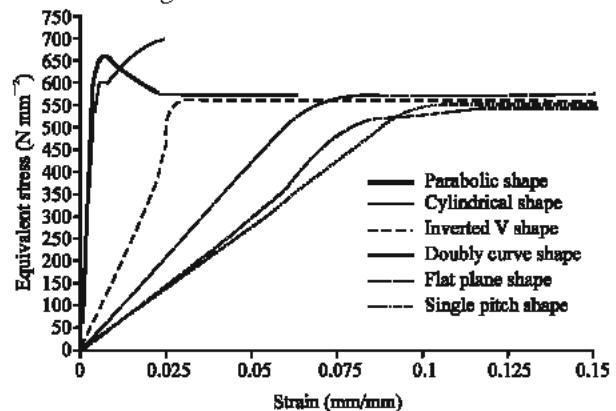


Fig. 10: Stress-strain profile of different types of roofing element

is created by membrane field N_x , N_y , N_{xy} and N_{yx} . At crown height 1/6 of chord width membrane field is predominant than bending field. As a result deflection is least. When crown height is lower, membrane force also lower than bending force. When crown height increased membrane forced also increased. After a certain limit of crown height membrane force also decrease due to buckling impact. Therefore, least and optimum deflection is obtained at crown height 1/6 of chord width. Experimental work is carried out to validate the analytical results. Good agreement is found between the results from nonlinear finite element analysis and those obtained experimentally that is shown in Fig. 11. The load-deflection, stress-strain and deflected shape profiles for investigated roofing element showed that parabolic roofing element having crown height 1/6 of chord width is more efficient than others as a self supporting condition. It is found that when the crown height of parabolic shape is increased, the central deflection decreased until optimum crown height. After the optimum crown height, slenderness ratio and geometric nonlinearity increased and buckling impact become predominant than shorting. Deflection along the

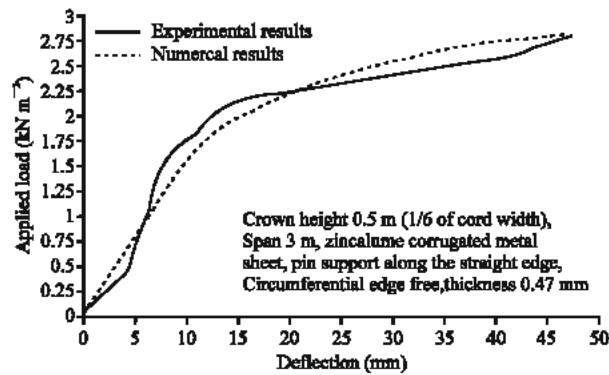


Fig. 11: Comparison between experimental and numerical deflection for parabolic roofing element

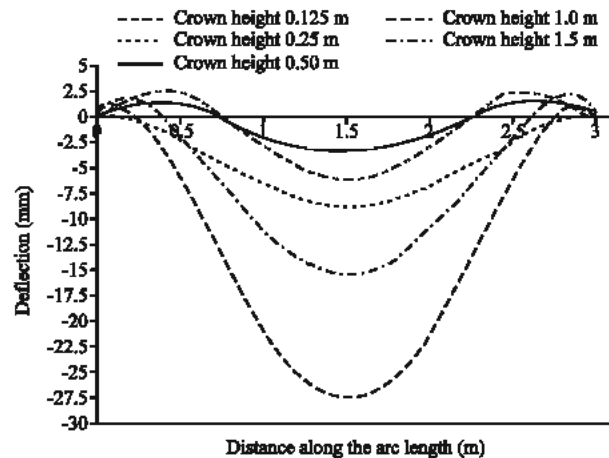


Fig. 12: Deflection profile of different crown height parabolic roofing element along the arc length

arc length of different crown height of parabolic shell roof is shown in Fig. 12 due to service load 0.528 kN m^{-2} . In order to validate the proposed models a comparison between analytical and experimental deflected shape are carried out. Good agreement is found between both results. Analytical and experimental deflected shape of cylindrical roofing elements is shown in Fig. 13 and 14, respectively. It is interesting to note that both the central deflection and stresses are least parabolic shape of roofing element with crown height of 0.5 m. When crown height decreased then deflection and stresses increased i.e., valid for lower crown height. The results showed optimum crown height, deflection and stresses in parabolic roofing elements. Load carrying capacity is 1.059, 2.108, 2.80, 2.508 and 1.684 kN m^{-2} without any geometrical and material failure for 0.125, 0.25, 0.5, 1.0 and 1.5 m crown height parabolic and cylindrical roofing element, respectively. Geometrical as well as yield failure load was found due to 1.283, 2.23, 3.164, 2.71,

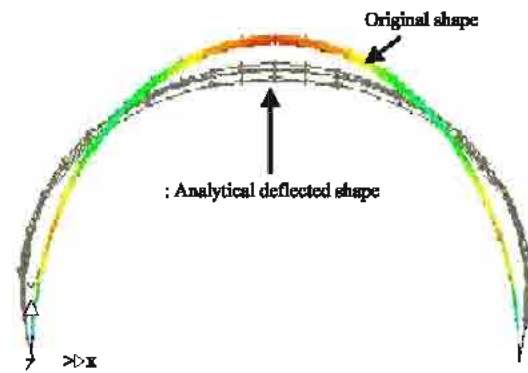


Fig. 13: Analytical deflected shape of cylindrical roofing element



Fig. 14: Experimental deflected shape of cylindrical roofing element

1.739 kN m^{-2} for 0.125, 0.25, 0.5, 1.0 and 1.5 m crown height parabolic and cylindrical roofing element, respectively. Load carrying capacity of parabolic roofing element having crown height 1/6 of chord width is higher than others. This crown height is considered as optimum crown height due to higher load carrying capacity and least deflection and stress. Since the surface area also increases with the crown height, it is found that optimum crown height will be more economical in order to lower surface area and material saving.

Nine types of roofing elements are studied in the present research. The presence of corrugation in the metal roofing element resulted in a significant improvement on the roof's structural performance compared to flat sheet element. Profile sheet is several times stiffer than flat plane sheet. Different boundary condition is analysed in this study. Both end fixed and pin support roofing element is showed almost same results with minor changes. Horizontal displacement of simple supported condition was more than that of pin and fixed supporting condition. Doubly curve shape of roofing element is architecturally

beautiful. On the basis of the present analysis, it is found that the corrugated parabolic shell element is the most economical, efficient, architecturally pleasing shape in self-supporting condition. The FEM investigation is extended to explore the feasibility of usage of zincalume as a self-supporting roofing system. Based on FEM investigation and experimental validation, this study is extended up to 8 m span using 1.33 m crown parabolic roofing element for using as self-supporting condition for affordable quality housing. According to the FEM results analysis, it is observed that the parabolic roofing element can be used efficiently as a self supporting roofing system using 8 m span and 1.25 mm thick profile zincalume sheet due to obtain permissible deflection and stress.

CONCLUSIONS

Conventionally, metal sheet such as zincalume is using in roof covering through intermediate support truss. It is an innovative system that is self-supporting roofing system. This kind of roofing system has significant advantages of removing the internal trussing and support. The behavior of nine different types of roofing element is studied to find out an economical, efficient, architecturally pleasing shape in self-supporting condition. Nonlinear effect has been adopted in the finite element analysis. From the parametric study, it is found that the central deflection and stresses are least and load carrying is higher in parabolic shape of roofing element with crown height about 1/6 of chord length. On the basis of the present analysis, it is found that the parabolic profiled zincalume shell element is the most economical, efficient, architecturally pleasing shape in self-supporting condition. The experimental results showed good agreement with those obtained analytically using Finite Element Method (FEM). It was observed that corrugated parabolic shell element which, have 8 m span and 1.25 mm thickness could be used efficiently as self-supporting roofing system in housing construction.

ACKNOWLEDGEMENTS

The authors would like to thank the Construction Industry Development Board (CIDB) Malaysia for financial support and Blue scope Lysaght (Malaysia) Sdn Bhd for the supply of experimental test specimens. The present study is part of graduate research of civil engineering department, Universiti Putra Malaysia (UPM) and National Research Programme on Affordable Quality Housing.

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