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Proportioning of Members of Single layer Cylindrical Latticed Roofs under Non-Uniform Loadings

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Abstract

This paper shows a proportioning method for members of single layer cylindrical latticed roofs under several non-uniform loadings. Firstly, a proportioning method for members of cylindrical latticed roofs is presented. Secondly, the maximum load of cylindrical latticed roofs of which members designed based on the present proportioning method is investigated, based on the elastic plastic analysis. Finally, the effectiveness of the method presented here is discussed based on above investigations.

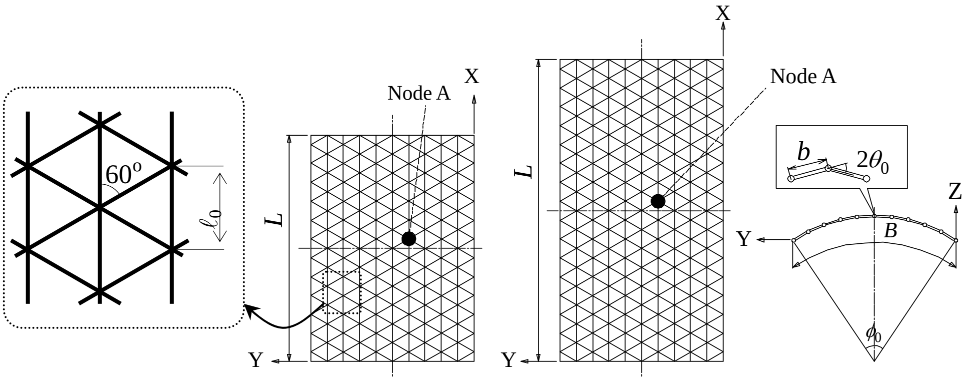
Keywords: Proportioning method for members, Single layer cylindrical latticed roofs, Non-uniform loadings

1. Introduction

The proportioning method for members of single layer cylindrical latticed roofs is necessary to design light cylindrical latticed roofs of high strength. And, studies on the proportioning method for members of single layer cylindrical latticed roofs have been conducted. Kato et al. have presented a proportioning method for single layer cylindrical latticed roofs, and, the method is available to design members' section for single layer cylindrical latticed roofs of short span [1]. Kato and Niho have presented a member proportioning method for roofs under uniform vertical loading[2], based on following four assumptions; (1) the elastic plastic buckling strength of longitudinal members of a roof is equal to that of a longitudinal member of an axially compressed cylindrical latticed roof, (2) the elastic plastic buckling strength of diagonal members of a roof is equal to that of a diagonal member of a pin-supported cylindrical latticed roof under vertical loading. (3) Member stresses are calculated based on the linear stress analysis, and after that, (4) the bending moment on members amplified with considerations of P-Δ effects. This method has shown to be effective to design member's section of roofs with long span under uniform vertical loading[2]. On the other hand, any proportioning method for members of cylindrical latticed roofs under several non-uniform loadings has not been presented.

This paper presents a member proportioning method for cylindrical latticed roofs under several non-uniform loadings, based on the proportioning method presented in Ref[2]. The proportioning method presented here is available to design members' section of cylindrical latticed roofs of equilateral triangle grid pattern (See Figure 1).

To develop the above proportioning method, elastic plastic buckling strength for members must be determined. Therefore, this paper shows first both the elastic plastic buckling strength for a longitudinal member of axially compressed cylindrical latticed roofs and that for a diagonal member of pin-supported cylindrical latticed roofs under uniform loading. Secondary, the proportioning method is proposed. Thirdly, maximum load of roofs designed based on the present method is investigated, based on elastic plastic analysis. And finally, the effectiveness of the method presented here is discussed based on above investigations.



(a) Plan(n_p = 12) (b) Plan(n_p = 16) (c) Elevation

Figure 1: Single layer cylindrical latticed roofs

2. Investigation on elastic plastic buckling strength for members

2.1. Elastic plastic buckling strength for longitudinal members of axially compressed cylindrical latticed roofs

2.1.1. Analytical models

A cylindrical latticed roof is assumed here to be applied axially compression $P(h)$ (=9.8kN) acting in X-direction at the each node on gabled edges (See Figure 2). The roof is composed of longitudinal members parallel to X-axis and diagonal members crossing the X-axis at an angle of 60 degrees. The number of divisions in longitudinal direction n_p is restricted to 12 or 16, and, that in circumferential direction n is 10. The member length ℓ_0 is assumed 400cm. The subtended half angle θ_0 is varied as 2, 3, 4, and, 5 degrees.

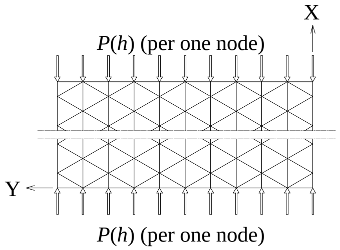


Figure 2: Axially compression

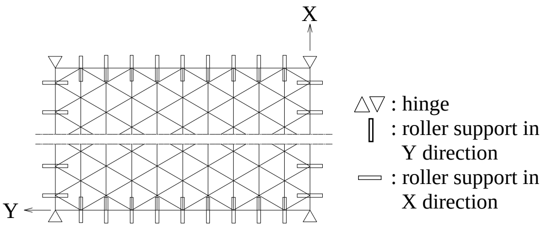


Figure 3: Boundary condition (simply support)

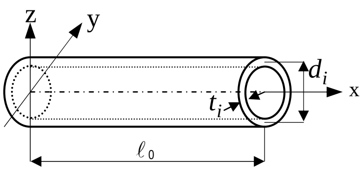


Figure 4: A steel tubular member

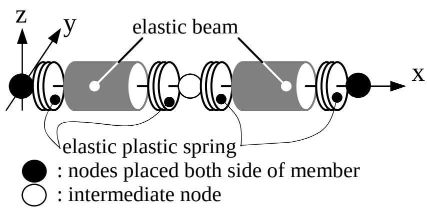


Figure 5: Modelling on members

The roof is supported as shown in Figure 3 with hinges and rollers. Nodes on peripheral edges that parallel to X-axis can move Y-direction. On the other hand, nodes on gabled edges can move in X-direction. Rotations are not restricted.

Members of each roof are steel tubular pipe of which Young's modulus E and yield stress σ_y are 2.06x10^5[N/mm^2] and 23.5[N/mm^2], respectively(See Figure 4). Both thickness t_i and diameter d_i of each member is determined, based on the proportioning method presented in Ref.[2].

2.1.2. Numerical Analysis

Buckling capacities of each roof are calculated numerically in this paper. The linear buckling capacity $P_{cr}^{lin}(h)$, elastic buckling capacity $P_{cr}^{ela}(h)$ are obtained respectively linear buckling analysis and nonlinear elastic buckling analysis.

Elastic plastic buckling capacity of each roof $P_{cr}^{epl}(h)$ is obtained based on elastic plastic analysis. One member is assumed to be composed of two elastic beams for numerical preciseness, as shown in Figure 5. To consider the plasticity of members, each elastic beam is connected by two elastic plastic springs placed at both ends. The stress interaction of the elastic plastic spring with in a plastic range is assumed as follows:

$$\left(\frac{N_i}{N_{yi}}\right)^2 + \frac{\sqrt{{M_{yi}}^2 + {M_{yi}}^2}}{M_{pi}} = 1.0 \qquad (1)$$

where, N_i, M_{yi} and M_{zi} are axial force, bending moment in y-axis and that in z-axis for i-th member, respectively. N_{yi} and M_{pi} are plastic axial and bending capacities, respectively.

2.1.3. The knock down factor for axially compressed cylindrical latticed roofs

The knock down factor for an axially compressed cylindrical latticed roof $\alpha_0(h)$ is defined by following equation:

$$\alpha_0(h) = \frac{P_{cr}^{\ ela}(h)}{P_{cr}^{\ lin}(h)} \tag{2}$$

Figure 6 shows the relationship between $\lambda_0\theta_0$ and the knock down factor $\alpha_0(h)$ (λ_0:member slenderness). In Figure 6, a triangular plot indicates $\alpha_0(h)$ of a cylindrical latticed roof composed of one same type of steel tubular member and is quoted from Ref.[2]. As shown in Figure 6, the knock down factor $\alpha_0(h)$ may be approximated by following equation:

$$\alpha_0(h) = 1 - \frac{1}{0.4(\lambda_0\theta_0)^{6/5} + 1} \tag{3}$$

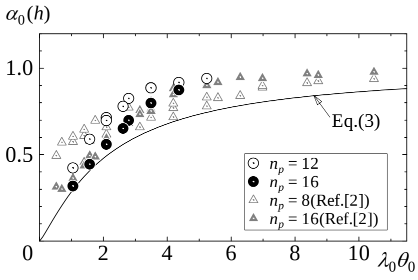


Figure 6: The knock down factor (roofs under axially compression)

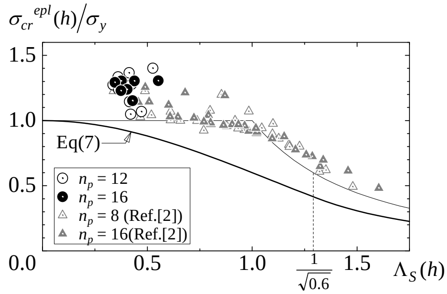


Figure 7: Elastic plastic buckling strength (roofs under axially compression)

2.1.4 The elastic plastic buckling strength for a longitudinal member

The elastic plastic buckling strength for the specific member (longitudinal member) of axially compressed cylindrical latticed roofs $\sigma_{cr}^{\ epl}(h)$ is defined by following equation:

$$\sigma_{cr}^{\ epl}(h) = \frac{P_{cr}^{\ epl}(h)}{P(h)} \cdot \sigma(h) \tag{4}$$

where, $\sigma(h)$ is the axial compressive stress of the specific member (longitudinal member) calculated based on linear elastic analysis. The specific member (longitudinal member) is selected as a compressive member of which ratio of axial force under axial compression $P(h)$ to its axial capacity N_{yi} is largest among all longitudinal members.

Figure 7 shows the relationship between the generalized slenderness of the specific member (longitudinal member) $\Lambda_S(h)$ and $\sigma_{cr}^{\ epl}(h)$. In Figure 7, a triangular plot indicates $\sigma_{cr}^{\ epl}(h)$ of a roof composed of one same type of steel tubular member and is quoted from Ref.[2]. And $\sigma_{cr}^{\ epl}(h)$ is normalized by yield stress σ_y in Figure 7. $\Lambda_S(h)$ is defined by following equation:

$$\Lambda_S(h) = \sqrt{\frac{\sigma_y}{\alpha_0(h) \cdot \sigma_{cr}^{lin}(h)}} \tag{5}$$

where, $\alpha_0(h)$ is calculated by Equation (3). $\sigma_{cr}^{lin}(h)$ is the linear buckling strength of the specific member (longitudinal member) calculated by following equation:

$$\sigma_{cr}^{lin}(h) = \frac{P_{cr}^{lin}(h)}{P(h)} \cdot \sigma(h) \tag{6}$$

As shown in Figure 7, the elastic plastic buckling strength of the specific member (longitudinal member) $\sigma_{cr}^{epl}(h)$ may be approximated by following estimation $\sigma_{cr}^{Est}(h)$ (Ref.[3]):

$$\left.\begin{aligned} \frac{\sigma_{cr}^{Est}(h)}{\sigma_y} &= \frac{1-0.24\Lambda_S(h)^2}{1+(9/13)\Lambda_S(h)^2} & \left(\Lambda_S(h) \le \frac{1}{\sqrt{0.6}}\right) \\ \frac{\sigma_{cr}^{Est}(h)}{\sigma_y} &= \frac{9}{13\Lambda_S(h)^2} & \left(\Lambda_S(h) > \frac{1}{\sqrt{0.6}}\right) \end{aligned}\right\} \tag{7}$$

2.2. Elastic plastic buckling strength of diagonal members of pin-supported cylindrical latticed roofs under uniform vertical loading

2.2.1. Analytical models

The roofs, shown in Section 2.1.1., are assumed here to be applied vertical downward load $P(d)$(=9.8kN) acting at the each node instead of axially compression shown in Figure 2(See Figure 8). And, each roof is supported as shown in Figure 8.

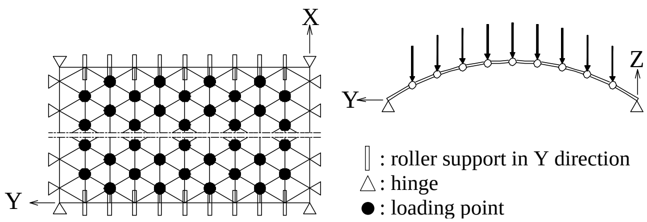


Figure 8: A pin-supported cylindrical latticed roofs under uniform vertical loading

2.2.2. Numerical Analysis

Buckling capacities of each roof are calculated numerically in this paper. The linear buckling capacity $P_{cr}^{lin}(d)$, elastic buckling capacity $P_{cr}^{ela}(d)$ are obtained respectively linear buckling analysis and nonlinear elastic buckling analysis. Elastic plastic buckling capacity of each roof $P_{cr}^{epl}(d)$ is obtained based on elastic plastic analysis. Details on the elastic plastic analysis refer to Section 2.1.2.

2.2.3. The knock down factor for pin-supported cylindrical latticed roofs

The knock down factor for pin-supported cylindrical latticed roofs under uniform vertical loading $\alpha_0(d)$ is defined by following equation:

$$\alpha_0(d) = \frac{P_{cr}{}^{ela}(d)}{P_{cr}{}^{lin}(d)} \tag{8}$$

Figure 9 shows the relationship of a parameter ξ and $\alpha_0(d)$. In Figure 9, a triangular plot indicates $\alpha_0(d)$ for a cylindrical latticed roof composed of one same type of member and is quoted from Ref.[2]. The parameter ξ is calculated by following equation:

$$\xi = \frac{2\sqrt{2}(3\gamma)^{1/4}\cos\alpha}{\pi(\sin\alpha)^{3/2}} \cdot \sqrt{\lambda_0\theta_0} \cdot n_p \tag{9}$$

where, $\gamma = 0.5$, and $\alpha = 60$ degrees. As shown in Figure 9, $\alpha_0(d)$ is greater than 0.6 for every roof. Therefore, $\alpha_0(d)$ may be assumed to be 0.6 from practical point of view.

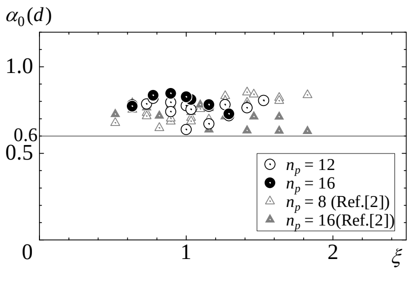


Figure 9: The knock down factor (pin-supported roofs)

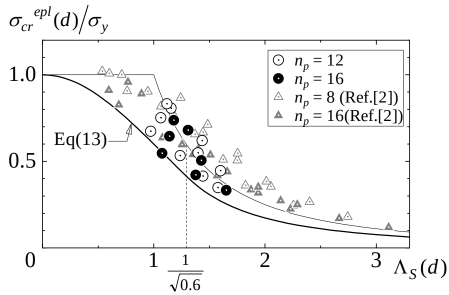


Figure 10: Elastic plastic buckling strength (pin-supported roofs)

2.2.4. The elastic plastic buckling strength for a diagonal member

For the specific member (diagonal member) of pin supported cylindrical latticed roofs under uniform vertical loading, the elastic plastic buckling strength $\sigma_{cr}{}^{epl}(d)$ is calculated by following equation:

$$\sigma_{cr}{}^{epl}(d) = \frac{P_{cr}{}^{epl}(d)}{P(d)} \cdot \sigma(d) \tag{10}$$

where, $\sigma(d)$ is the axial compressive stress of the specific member (diagonal member) under uniform vertical loading $P(d)$. The specific member (diagonal member) is selected as the one of which ratio of axial force to its axial capacity N_{yi} is largest among all diagonal members.

Figure 10 shows the relationship of the generalized slenderness $\Lambda_S(d)$ and $\sigma_{cr}{}^{epl}(d)$. In Figure 10, a triangular plot indicates $\sigma_{cr}{}^{epl}(d)$ for a cylindrical latticed roof composed of one same type of steel tubular member and is quoted from Ref.[2]. And, $\sigma_{cr}^{epl}(d)$ is normalized by yield stress σ_y in Figure 10. $\Lambda_S(d)$ is defined by following equation:

$$\Lambda_S(d) = \sqrt{\frac{\sigma_y}{\alpha_0(d) \cdot \sigma_{cr}^{lin}(d)}} \tag{11}$$

where, $\sigma_{cr}^{lin}(d)$ is the linear buckling strength of the specific member and calculated by following equation:

$$\sigma_{cr}^{lin}(d) = \frac{P_{cr}^{lin}(d)}{P(d)} \cdot \sigma(d) \tag{12}$$

In Figure 10, the bold line indicates the estimation of the elastic plastic buckling strength $\sigma_{cr}^{Est}(d)$ calculated by following equation (Ref.[3]):

$$\left.\begin{aligned} \frac{\sigma_{cr}^{Est}(d)}{\sigma_y} &= \frac{1-0.24\Lambda_S(d)^2}{1+(9/13)\Lambda_S(d)^2} & \left(\Lambda_S(d) \le \frac{1}{\sqrt{0.6}}\right) \\ \frac{\sigma_{cr}^{Est}(d)}{\sigma_y} &= \frac{9}{13\Lambda_S(d)^2} & \left(\Lambda_S(d) > \frac{1}{\sqrt{0.6}}\right) \end{aligned}\right\} \tag{13}$$

3. Proportioning method for members of single layer cylindrical latticed roofs under several non-uniform loadings

A flow chart of the present method is shown in Figure 11. In Figure 11, suffixes i and j mean ID number of a member and that of a type of a design load, respectively. And, parameter ML is the total of types of design loads.

3.1. Calculation of initial value of thickness t_i

The initial value of thickness t_i is calculated as follows:

(Step 1-1) Determination on geometry of the roof

(Step 1-2) Assuming both member slenderness λ_0 and the initial value of the thickness t_i

(Step 1-3) Calculation of the structural characteristics for i-th member by following equations:

$$d_i = 2\sqrt{2} \cdot \frac{\ell_0}{\lambda_0}, \quad A_i = \pi \cdot d_i \cdot t_i, \quad I_i = \frac{\pi \cdot d_i^3 \cdot t_i}{8} \tag{14.1, 14.2, 14.3}$$

$$N_{yi} = A_i \cdot \sigma_y, \quad M_{ei} = \frac{\pi \cdot d_i^2 \cdot t_i}{4} \cdot \sigma_y \tag{14.4, 14.5}$$

where, d_i, A_i, I_i, N_{yi}, and M_{ei} are diameter, sectional area, moment of inertia, plastic axial capacity, and, elastic bending capacity, respectively.

(Step 1-4) Calculation of linear buckling strength of the specific member (longitudinal members) $\sigma_{cr}^{lin}(h)$ (See Equation (6))

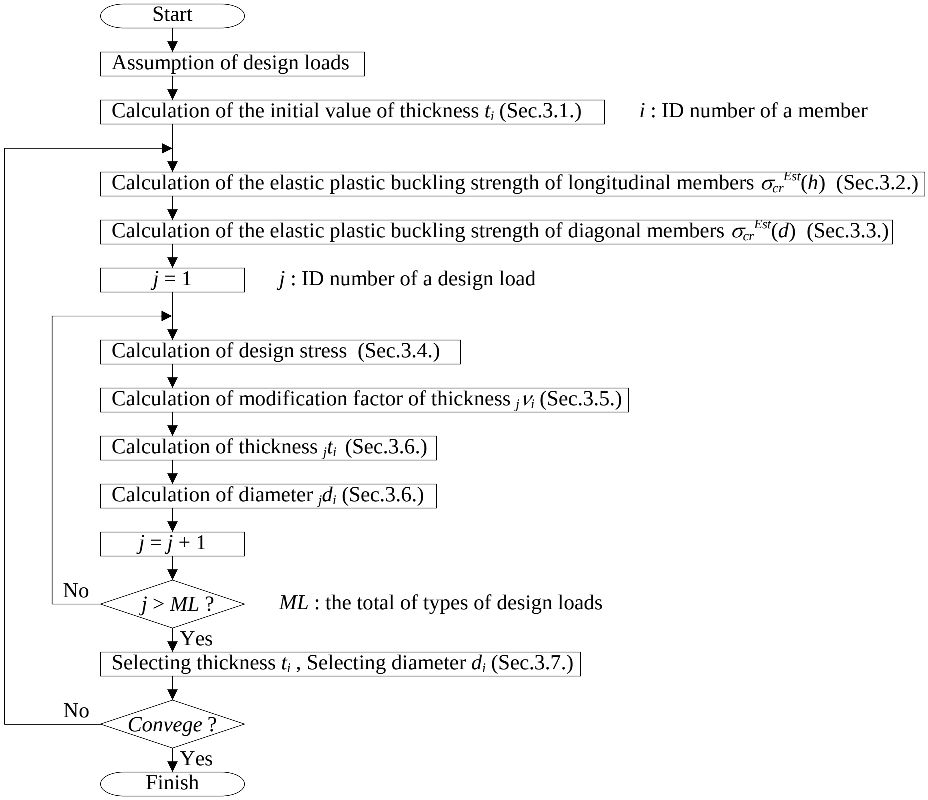


Figure 11: Flow chart of the present proportioning method

The roof is assumed here to be applied to axially compression $P(h)$ (=9.8kN) acting at each node on gabled sides, as shown in Figure 2.

(Step1-5) Calculation of linear buckling strength of the specific member (diagonal members) $\sigma_{cr}^{lin}(d)$ (See Equation (12))

The roof is assumed here to be applied to vertical load $P(d)$ (=9.8kN) at each node and supported with hinges and rollers, as shown in Figure 8.

(Step 1-6) Calculation of the axial force for *i*-th member ${}_jN_i$

The roof is assumed here to be applied to a design load No. *j*.

Step 1-6 is repeated from $j = 1$ to ML (ML is the total of design loads).

(Step 1-7) Calculation of the axial force for *i*-th member N_i by following equation:

$$N_i = \max|\ {}_jN_i\ | \tag{15}$$

If ${}_jN_i$ is tensile, ${}_jN_i$ is assumed to be zero in Equation (15).

(Step 1-8) Modification of the thickness t_i by following equation:

$$t_i \leftarrow \beta_1 \cdot \beta(h) \cdot t_i \quad \text{(longitudinal members)} \tag{16.1}$$

$$t_i \leftarrow \beta_1 \cdot \beta(d) \cdot t_i \quad \text{(diagonal members)} \tag{16.2}$$

where, β_1 is 5/4. $\beta(h)$ and $\beta(d)$ are calculated respectively as follows:

$$\beta(h) = \max\left| N_i \middle/ \left(\frac{9}{13} \cdot \alpha_0(h) \cdot \sigma_{cr}{}^{lin}(h) \cdot A_i \right) \right| \tag{17.1}$$

$$\beta(d) = \max\left| N_i \middle/ \left(\frac{9}{13} \cdot \alpha_0(d) \cdot \sigma_{cr}{}^{lin}(d) \cdot A_i \right) \right| \tag{17.2}$$

$\alpha_0(h)$ is calculated by Equation (3). And, $\alpha_0(d) = 0.6$.

(Step 1-9) Calculation of the structural characteristics of all members by Equations (14.1, 14.2, 14.3, 14.4, and 14.5)

3.2. Calculation of the elastic plastic buckling strength for longitudinal members

(Step 2-1) Calculation of the linear buckling capacity of the roof $P_{cr}{}^{lin}(h)$

The roof is assumed here to be applied to axially compression $P(h)$ (=9.8kN) acting at each node on gabled sides, as shown in Figure 2.

(Step 2-2) Calculation of the linear buckling strength of the specific member (longitudinal member) $\sigma_{cr}{}^{lin}(h)$ (See Equation (6))

(Step 2-3) Calculation of the generalized slenderness of the specific member (longitudinal member) $\Lambda_S(h)$ (See Equation (5))

(Step 2-4) Calculation of the elastic plastic buckling strength of the specific member (longitudinal member) $\sigma_{cr}{}^{Est}(h)$ (See Equation (7))

$\sigma_{cr}{}^{Est}(h)$ is applied as the elastic plastic buckling strength for all longitudinal members. In addition, for tensile members, $\sigma_{cr}{}^{Est}(h)$ is assumed to be σ_y.

3.3. Calculation of the elastic plastic buckling strength for diagonal members

(Step 3-1) Calculation of the linear buckling capacity of the roof $P_{cr}{}^{lin}(d)$

The roof is assumed here to be applied to vertical load $P(d)$ (=9.8kN) at each node and supported with hinges and rollers, as shown in Figure 8.

(Step 3-2) Calculation of the linear buckling strength of the specific member (diagonal member) $\sigma_{cr}{}^{lin}(d)$ (See Equation (12))

(Step 3-3) Calculation of the generalized slenderness of the specific member (diagonal member) $\Lambda_S(d)$ (See Equation (11))

(Step 3-4) Calculation of the elastic plastic buckling strength of the specific member (diagonal member) $\sigma_{cr}{}^{Est}(d)$ (See Equation (13))

$\sigma_{cr}{}^{Est}(d)$ is applied as the elastic plastic buckling strength for all diagonal members. In addition, for tensile members, $\sigma_{cr}{}^{Est}(d)$ is assumed to be σ_y.

3.4. Calculation of design stress for members

(Step 4-1) Calculation of an axial force ${}_jN_i$, a bending moment in y-direction ${}_jM_{yi}$ and that in z-direction ${}_jM_{zi}$ of *i*-th member of the structure applied to a design load No.*j*. Member stresses ${}_jN_i$, ${}_jM_{yi}$ and ${}_jM_{zi}$ are calculated based on linear elastic analysis.

(Step 4-2) Calculation of member design stresses by following equations:

$$ {}_jN_{0i} = {}_jN_i \tag{18.1} $$

$$ {}_jM_{0i} = \sqrt{{}_jM_{yi}{}^2 + {}_jM_{zi}{}^2} \Bigg/ \left\{ 1 - \left| {}_jN_{0i} \Bigg/ \left(\frac{9}{13\Lambda_S(h)^2} \cdot N_{yi} \right) \right| \right\} \quad \text{(longitudinal members)} \tag{18.2} $$

For diagonal members, ${}_jM_{0i}$ is calculated by substituting $\Lambda_S(d)$ to $\Lambda_S(h)$ in Equation (18.2). And, for tensile members, let

$$ {}_jM_{0i} = \sqrt{{}_jM_{yi}{}^2 + {}_jM_{zi}{}^2} \tag{18.3} $$

3.5. Calculation of modification factor of thickness

(Step 5-1) The Modification factor ${}_j\nu_i$ is calculated by following equations:

$$ {}_j\nu_i = \left| \frac{{}_jN_{0i}}{\sigma_{cr}{}^{Est}(h) \cdot A_i} \right| + \frac{{}_jM_{0i}}{M_{ei}} \quad \text{(longitudinal members)} \tag{19} $$

For diagonal members, ${}_j\nu_i$ is calculated by substituting $\sigma_{cr}{}^{Est}(d)$ to $\sigma_{cr}{}^{Est}(h)$ in Equation (19).

(Step 5-2) If the factor ${}_j\nu_i$ is less than 1.0, ${}_j\nu_i$ is modified by following equation:

$$ {}_j\nu_i \leftarrow 1 - 0.5 \cdot (1 - {}_j\nu_i) \tag{20} $$

If ${}_j\nu_i$ is assessed to be 0.5 by Equation (19), ${}_j\nu_i$ is modified to 0.75 by Equation (20). This modification is to avoid designing a member of which thickness t_i is extremely thin.

3.6. Calculation of thickness ${}_jt_i$ and diameter ${}_jd_i$

(Step 6-1) Calculation of thickness ${}_jt_i$ and diameter ${}_jd_i$:

$$ {}_jt_i = {}_j\nu_i \cdot t_i \quad , \quad {}_jd_i = d_i \tag{21.1, 21.2} $$

If ${}_jt_i / {}_jd_i > 0.1$, both ${}_jd_i$ and ${}_jt_i$ are modified respectively by following equations:

$$ {}_jd_i = 1.1 \cdot d_i \quad , \quad {}_jt_i = 0.085 \cdot (1.1 \cdot d_i) \tag{22.1, 22.2} $$

(Step 6-2) Calculation of elastic bending capacity ${}_jM_{ei}$ by following equation:

$$ {}_jM_{ei} = \frac{\pi \cdot {}_jd_i{}^2 \cdot {}_jt_i}{4} \cdot \sigma_y \tag{23} $$

3.7. Selecting thickness t_i and diameter d_i

(Step 7-1) Selecting the elastic bending capacity ${}_kM_{ei}$ which satisfies following equation:

$$ {}_kM_{ei} = \max({}_jM_{ei}) \tag{24} $$

(Step 7-2) Calculation of both thickness t_i and diameter d_i by following equations:

$$ t_i = {}_kt_i \ , \ d_i = {}_kd_i \qquad (25.1,\ 25.2) $$

(Step 7-3) Calculation of the structural characteristics of all members by Equations (14.1, 14.2, 14.3, 14.4, and 14.5)

(Step 7-4) If the thickness t_i is very close to former thickness, a convergence is assumed to be obtained. If not, the procedure is repeated from Step 3-1 till an enough convergence is reached.

4. Investigations on the present proportioning method

4.1. Analytical model

An analytical model is a single layer cylindrical latticed roof of an equilateral triangle grid pattern(See Figure 1). The roof is supported by hinges and rollers as shown in Figure 3. The number of division in circumferential direction n is restricted to be 10. And meanwhile, the number of division in longitudinal direction n_p is varied as 12 and 16. The length of the member ℓ_0 is 400cm. The member slenderness λ_0 is varied as 30, 40, 50, 60, and, 70. The subtended half angle θ_0 is varied as 2, 3, 4 and 5 degrees.

Each member of the roofs is steel tubular pipe of which two ends are connected to rigidity to nodes. Both the thickness t_i and the diameter d_i for each member are determined to bear the design stress N_{0i} and M_{0i}, based on the present proportioning method.

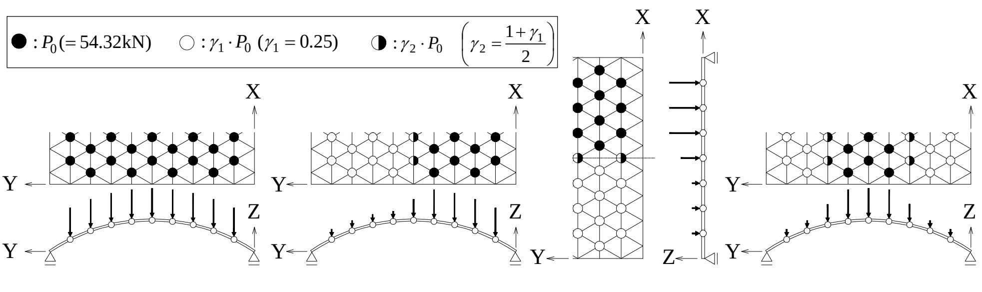


Figure 12: Design Loads

4.2. Design load

Four types of design loads, shown in Figure 12, are considered here. Any combination between these design loads is not taken into account.

4.3. Results

40 roofs are designed based on the present proportioning method. The maximum load P_{cr} is calculated numerically based on the nonlinear elastic plastic analysis. Details on the numerical analysis refer Section 2.1.2.

Figure13 shows the ratio of the maximum load P_{cr} on Node A (See Figure1) to design load P_0 (= 54.32kN per one node). As shown in Figure 13, P_{cr} is greater than P_0 for every roof.

5. Conclusion

This paper shows a new proportioning method for members of single layer cylindrical latticed roofs of long span under several non-uniform loadings. And this paper also investigates the maximum load of the cylindrical latticed roofs of which members' section is designed based on the present proportioning method. As a result, the maximum load satisfies the design load in every case. Consequently, the present proportioning method is considered practical from engineering point of view.

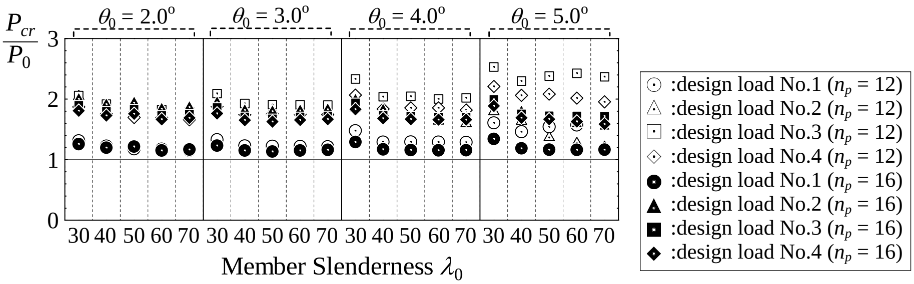


Figure 13: Maximum load P_{cr} (Node A)

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