1- Introduction

Circular roofs are the most common forms of suspended cable roofs since its roundness gives the architect the flexibility in both the planning and the usage of such structures. In addition to the dynamic loads, suspended roofs carry its own weight and small live loads applied during repair and maintenance .Circular roofs may be of radial (simply supported) or of intersecting (counter-stressed) cables/cable beams. Radial roofs include both simply suspended cable roofs and pretension cable beams roofs, Fig. (1). Intersecting cables form a pretension cable net roof while intersecting cable beams form a pretension cable grid, Fig. (2).The cables or cable beams in circular roofs are supported by an outer RC compression ring and, for radial roofs, a small steel tension ring at the center is needed. The design of such a roof basically consists of the design of the cables and the design of a RC ring beam. More details about the design of simply supported cable or cable beams roofs are given by [1, 2].

To understand the static behavior of circular cable nets and grids, many roofs were analyzed with tacking the design parameters into account. These parameters include the applied loads, the spacing between nodes, cable rigidity (EA), cable pretension (T_0), sag/span and rise/span ratios, the effect of hangars and the rigidity of the supporting structure. The relations between these factors and the response of such roofs to static loads are given in non-dimensional graphs and tables. These tables and graphs are made for (10×10) circular cables roofs, which mean that the diametrical cable is divided into 10 segments, Fig. (3).For simplicity, it is assumed that the supports are infinite rigid (fixed).

Based on these non-dimensional graphs and tables, many useful relationships are derived. These relationships form the fundamentals of a good technique for the preliminary design of circular cable suspended roofs.

Although simplification of the mathematical model by lumping cables or beams together is allowable [1], the new preliminary design method uses formulae, instead of lumping, to express the deflections and forces of any $(n\times n)$ roof by the guidance of (10×10) cable roof. The work done in this paper is made using computer program developed by [3]. This program is based on the minimization of the total potential energy using the conjugate gradient technique.

2- Design of circular cable nets

Calculation of uniformly distributed load along cable length

According to Fig. (3-d), the total load that assumed to be concentrated at joint j is equal to ($w \times s^2$) two successive cables or cable beams. If this concentrated load is assumed to be uniformly distributed along the two s-length cable segments intersected at joint j, then the uniformly distributed load per unit length of the cable or cable beam is:

$$w' = w\times\frac{S}{2} \qquad (1)$$

The pretension as an equivalent load

Assuming that the pretension is equivalent to a load per unit length w'', then the pretension in all cables are assumed to be equal to:

$$T_0 = \frac{w''L^2}{8d} \qquad (2)$$

Where: L is the roof diameter and d is the sagging of the roof.

Case of study (1):

Three circular cable nets of (10x10) spacing with the characteristics shown in Table (1) are solved for different values of steel area (A). Steel areas in examples (1) and (2) are chosen that the corresponding values of (EA/wL^2) .The cables are taken as strands with modulus of elasticity equal to 1663 t/cm2. Fixing other parameters, the structure is solved for different values of sag / span ratios and pretension. In the following, it is considered that:

$\delta = (d/L)\%$, $\tau = (T_{max}/T_{min.\ break.})\%$

And $f(\Delta z) = \left[wLS \Big/ EA(\frac{d}{L})^2(\frac{\Delta z}{L}) \right]$

in which:

Δz = The deflection of the central node of the roof;

$T_{max.}$ = The maximum final tension in cables; and

$T_{min.\ break.}$ = The minimum ultimate strength (14 t/cm^2) multiplied by the area of the cable.

Example (1) and (2) give the same results, Table (2), while results of example (3) is given in Table (3). These results and other solved example [4] reach the following deductions:

(a) Circular cable nets with the same arrangement $(n \times n)$ will act identically, i.e. $(\Delta z/L)$ and (τ) are invariable, under the following conditions:

1-The value (EA/wL^2) is constant.

2-The sag/span ratio (d/L) is constant.

3-The ratio of pretension to the applying load (w''/w') is constant.

(b) Condition (a-1) shows that the steel area is proportional to both the applying load and

the square of the roof diameter and is inversely proportional to its modulus of elasticity:

$$A \propto w \tag{3}$$

$$A \propto L^2 \tag{4}$$

$$A \propto \frac{1}{E} \tag{5}$$

Identical circular cable nets of arrangement $(n \times n)$ have a constant value of the following quantity

$$f(\Delta z) = \frac{wLS}{EA(\frac{d}{L})^2(\frac{\Delta z}{L})} = \frac{1}{n(\frac{EA}{wL^2})(\frac{d}{L})^2(\frac{\Delta z}{L})}$$

Where, n is the number of segments in the diametrical member; i.e. $n = L/S$ and S is the spacing between nodes.

According to the this deduction, it yields that the steel area is inversely proportional to both the required ratio of deflection to span, the square of the sag/span ratio, and to the number of the segments in the diametrical member:

$$A \propto \frac{1}{(\Delta z/L)} \tag{6}$$

$$A \propto \frac{1}{(d/L)^2} \tag{7}$$

$$A \propto \frac{1}{n} \tag{8}$$

$$\frac{\Delta z}{L} \propto \frac{1}{(d/L)^2} \tag{9}$$

If the equivalent pretension exceeds the applying load (w), deflection of the central node will reflect to be upward ,hence it is recommended to take the equivalent load of pretension less than that of the applying load.

$$[w'' = \frac{8T_0 d}{L^2}] < w' \tag{10}$$

For two circular nets $(n_1 \times n_1)$ and $(n_2 \times n_2)$ with the same properties (diameter, steel area, loading, modulus of elasticity and sag/span ratio), the relation between deflections and tensions in the two roofs may be approximately expressed as:

$$\Delta z_2 = \frac{n_1}{n_2} \times \Delta z_1 = \frac{S_2}{S_1} \times \Delta z_1 \tag{11}$$

$$(T_{max})_2 = \frac{n_1}{n_2} \times (T_{max})_1 = \frac{S_2}{S_1} \times (T_{max})_1 \tag{12}$$

The preliminary design of circular cable nets

The previous deductions may be used in making non-dimensional tables or graphs for the preliminary design of circular cable nets as follows:

1) Table (2) is non-dimensional table for the design of (10×10) circular cable nets.

2) Figs. (4) to (6) are non-dimensional graphs corresponding to Table (2).

Using relations (11) and (12), the response of cable nets of different arrangements $(n \times n)$ may be estimated by using the above non-dimensional tables or graphs.

Case study (2):
Table (4) includes the data of example 4.

Preliminary design of example (4)

$w'' = 0.25 \times 0.30 = 0.075\ t/m'$,and

$(\Delta z)_{allowable} = 8000/250 = 32\ cm$

sag = 4% ,d = 4x80/100 =3.2 m

Using Equation (2):

$T_0 = 0.075 \times 80^2 /(8 \times 3.2) = 18.75\ ton$

Using Equation (11), the allowable deflection corresponding to (10×10) circular net is:

$$\Delta z_{10\times10} = 32 \times \frac{16}{10} = 51.2\ cm$$

$$\therefore (\frac{\Delta z_{10\times10}}{L})\% = \frac{51.2}{8000} \times 100 = 0.64\%$$

Using Table (2) or Fig. (5) Corresponding to 4% sag/span ratio and w'' equal to $0.25(D.L+L.L)$, it yields that

for $(\Delta z/L)\% = 0.64\%$:

$$EA/wL^2 = 65.52 \quad and$$

$$(T_{max.}/T_{min.\ break})\% = 26.578$$

Using Equation (12):

$$(\frac{T_{max.}}{T_{break.}})_{16\times16} = (\frac{T_{max.}}{T_{break.}})_{10\times10} \times \frac{10}{16} = 16.61\%$$

$$A_{req} = 65.52 \times 0.12 \times 80^2 / 1663 = 30.26\ cm^2$$

$$T_{max.} = 0.1661 \times (30.26 \times 14) = 70.37\ ton$$

Data of the example are used in the computer program mentioned before and the results are:

$\Delta z_{max.} = 33.19\ cm \rightarrow$

$(\Delta z/L) = 0.00414 = 0.414\%$

$T_{max.} = 73.48\ ton \rightarrow$

$(T_{max.}/T_{min.\ break.}) = 73.48/(30.26 \times 14)$

$= 17.34\%$

These results show how much the accuracy of the used method of the preliminary design is.

Investigation of factors affect the response of cable nets

a)The curvature of cables (sag/span ratio);

b)The cross-sectional area of the cables (the steel area);

c) The level of pretension; and

d)The stiffness of the boundary and supporting structure.

Summary of the results obtained by investigating these parameters is:

1) Increasing sag/span ratio for the same steel area and same pretension decreases the net deflections and consequently decreases the final cable tensions.

2) Increasing sag/span ratio for the same required deflection decreases the required steel area.

3) Increasing the steel area decreases the nodal displacements.

4) Increasing the pretension force decreases the nodal displacements and has a negligible effect. Comparing with increasing the steel area upon the relative final forces in cables. This means that the steel area, not the pretension, is the decisive in carrying the applying loads.

3- Design of circular cable grids

Many circular grids, either concave or convex, were analyzed in the same manner as done before for cable nets. The results are similar to these of circular cable nets as follows:

a) Circular cable grids with the same arrangement $(n \times n)$ will act identically, i.e. $(\Delta z_S/L$ and $\tau_S)$ and $(\Delta z_P/L$ and $\tau_P)$ for both suspension and prestressed cables respectively are invariable, if:

1) The values $(E_s A_s / wL^2$ & $E_p A_p / wL^2)$ are constant.

2) The sag/span and rise /span ratios $(d/L$ & $R/L)$ are constant.

3) The ratios of pretension to the applying load $(w''_s/w'$ & $w''_p/w')$ are constant.

b) Circular cable grids with the same arrangement $(n \times n)$, that act identically, have a constant value of the quantities $f(\Delta z_s)$ and $f(\Delta z_p)$ where

$$f(\Delta z_x) = \frac{wLS}{E_x A_x (\frac{d}{L})^2 (\frac{\Delta z_x}{L})} = \frac{1}{n(\frac{E_x A_x}{wL^2})(\frac{d}{L})^2 (\frac{\Delta z_x}{L})}$$

$$f(\Delta z_p) = \frac{wLS}{E_p A_p (\frac{R}{L})^2 (\frac{\Delta z_p}{L})} = \frac{1}{n(\frac{E_p A_p}{wL^2})(\frac{R}{L})^2 (\frac{\Delta z_p}{L})}.$$

Due to this, equations from (4) to (9) are still valid for both sagging and hogging cables.

a) For two circular grids ($n_1 \times n_1$) and ($n_2 \times n_2$), either concave or convex, with the same properties (diameter, steel area, loading, modulus of elasticity and sag (rise)/span ratio), approximate relations (11) and (12) are still valid, for both the suspension and the prestressed cables. Also, the forces in the hangers (struts or ties) are approximated as:

$$\frac{(F/EA)_{hang\,2}}{(F/EA)_{hang\,1}} = (\frac{n_1}{n_2})^2 = (\frac{S_2}{S_1})^2 \qquad (13)$$

This equation is satisfied as long as the steel area of the suspension cable is more than or equal to that of the prestressed cable ($A_S \geq A_P$).

The preliminary design of circular cable grids

Horizontal components of the pretension in both suspension and prestressed cables are:[1]

$$H_{S_0} = \frac{w'L^2}{16(d_S + \Delta d)} = \frac{w''L^2}{8(d_S + \Delta d)} \qquad (14)$$

$$H_{P_0} = H_{S_0}(\frac{d_S}{d_P}) \qquad (15)$$

Where: d_P = The rise of the prestressing cable, and the value (Δd) may be determined as:

$$\Delta d = \frac{15L^3}{8(10L^2 d - 5Z^2 d - 48d^3)} \Delta l \qquad (16)$$

$$\Delta l = \frac{1}{2}\frac{H}{EAL}(L^2 + \frac{16}{3}d^2)$$

$$\& \; H = \frac{w'L^2}{8d} \qquad (17)$$

Due to Eqn. (14), the pretension in the suspension cable is approximately equivalent to a uniformly distributed load equal to $0.5(DL + LL)$ while the value (Δd) can be neglected.

According to Eqns (14) & (15) and to the examples solved [4], the relation between the pretension of the suspension cables and the minimum final tension of the prestressed cables is as follows:

At

$$w''_{S_0} > [0.5w' = 0.5(DL + LL)] \quad \Rightarrow \quad T_{P'_{min}} > 0.0 \qquad (18a)$$

And at:

$$w''_{S_0} < [0.5w' = 0.5(DL + LL)] \quad \Rightarrow \quad T_{P'_{min}} < 0.0 \qquad (18b)$$

Since compression is not allowable, it yields that the pretension of suspension cables has to be in the range of value given by equation (18a).

Useful notes

The following notes, observed and examined, are corresponding to an equivalent pretension load in the suspension cables equal to $w'' = 0.5w'$ and its corresponding pretension in the prestressed cable due to Equation (15).

1) For cable grid of ($sag = rise$): the deflections of both sagging and hogging cables are approximately equal and equal these of a circular cable net with the same sag, equivalent pretension and other characteristics. In such a case, final forces in suspension cables are approximately equal to these of the corresponding cable net, while the final forces in the prestressed cables are nearly zero.

2) For cable grid with ($sag \neq rise$):

$$(\Delta z_S \cong \Delta z_P) \leq \frac{1}{2}(\Delta z_{Sag} + \Delta z_{Rise}) \qquad (19)$$

And

$$T_S \cong \frac{1}{2}(T_{Sag} + T_{Rise}) \qquad (20)$$

Where: Δz_S = The deflection of the suspension cable of the grid.

Δz_P = The deflection of the prestressed cable of the grid.

Δz_{Sag} = The deflection of a cable net of sag equal to this of the suspension cable of the grid.

Δz_{Rise} = Deflection of a cable net of sag equal to the rise of the prestressed cable of the grid.

T_S = The final tension in the suspension cable of the grid.

T_{Sag} = The final tension in a cable net of sag equal to this of the suspension cable of the grid.

T_{Rise} = Final tension in a cable net of sag equal to the rise of the prestressed cable of the grid.

Due Eqn (9), it yields that:

$$\frac{\Delta z_{Sag}}{\Delta z_{Rise}} = \frac{Rise^2}{Sag^2} \qquad (21)$$

So, Eqn (19) may be rewritten as follows:

$$(\Delta z_S \cong \Delta z_P) \le [\frac{\Delta z_{Sag}}{2}(1 + \frac{Sag^2}{Rise^2})] \qquad (22)$$

Or

$$\Delta z_{sag} = 2\Delta z_{all}(\frac{Rise^2}{Sag^2 + Rise^2}) \qquad (23)$$

Where: Δz_{all} = The allowable deflection in both suspension and prestressed cables.

According to Eqs (21) and (23), it yields that:

$$\Delta z_{Rise} = 2\Delta z_{all}(\frac{Sag^2}{Sag^2 + Rise^2}) \qquad (24)$$

According to the above notes, the non-dimensional tables or graphs for the preliminary design of circular cable nets can be used in the preliminary design of circular cable grids as will be shown.

For struts of convex grid

$$A_{strut} = wS^2 / f_C = 2w'S / f_C \qquad (25)$$

For ties of concave grid

$$A_{tie} = wS^2 / f_t = 2w'S / f_t \qquad (26)$$

where: f_C and f_t are the allowable compression and tension stresses, respectively.

Case of study (3):

Data are shown in table (5):

Circular cable grid (10×10) with the following characteristics:

L = Diameter = 32m & S = Spacing between nodes = 3.20m.

Dead load $(D.L.) = 70\ kg/m^2$ - Live load $(L.L.) = 30\ kg/m^2$ & $E = 1663\ t/cm^2$.

$w = D.L + L.L = 0.10\ t/m^2 \Rightarrow$

$w' = 0.1x(3.2/2) = 0.16\ t/m'$

Sag = 1.60 m = 5% of the span & Rise = 0.96 m = 3% of the span.

The pretension is equivalent to a load equal to $0.50(DL+LL) \Rightarrow w'' = 0.08\ t/m'$

The allowable central deflection is (1/250) or (0.4%) of the span.

$(\Delta z)_{allowable} = 3200/250 = 12.80\ cm$

$$\therefore T_{S_o} = \frac{0.08 \times 32^2}{8 \times (1.6 + 0.128)} = 5.926\ ton$$

So, according to Eqn

$$(15) \Rightarrow T_{P_o} = 5.926 \times \frac{1.60}{0.96} = 9.877\ ton$$

Using eqn (23):

$$\Delta z_{Sag} = 2 \times 12.80 \times (\frac{3^2}{5^2 + 3^2}) = 6.78\ cm$$

$$\therefore (\frac{\Delta z}{L})\% = \frac{6.78}{3200} \times 100 = 0.21\%$$

Using Table (2)or Figs (6), corresponding to the preliminary design of (10×10) circular net with 5% sag/span ratio and T_0 corresponding to $0.50w'$, it yields that for $(\Delta z / L)\% = 0.21\%$:

$$\frac{EA}{wL^2} \cong 92.7\ and$$

$$(T_{max.} / T_{min.\ break.})\% \cong 16.30\%$$

$$A_{req} = 92.7 \times 0.10 \times 32^2 / 1663 = 5.7\ cm^2$$

$$\therefore T_{Sag} = 0.163 \times (5.7 \times 14) = 13.0\ ton$$

Using Table (2) or Figs (4) corresponding to the preliminary design of (10×10) circular net with 3% sag/span ratio and T_0

corresponding to $0.50w'$, it yields that for

$(\frac{EA}{wL^2} = 92.7)$:

$(\Delta z / L)\% = 0.493$ &

$(T_{max} / T_{min\ break.}) = 24.3\%$

$\therefore\ \Delta z_{Rise} = 0.00493 \times 3200 = 15.78\ cm$

& $T_{Rise} = 0.243 \times (5.7 \times 14) = 19.39\ ton$

According to Eqn (19)

$(\Delta z_P = \Delta z_S) \leq [0.5(6.78 + 15.78) = 11.28\ cm]$

$T_S = [0.5(13 + 19.39) = 16.20\ ton]$

Data of the example used in the computer program are:

L = 32 m, S = 3.2 m, Sag = 1.60 m, Rise = 0.96 m, w = 0.10 t/m², $T_{S_0} = 5.926\ ton$, $T_{P_0} = 9.877\ ton$, A = 5.7 cm² and E = 1663 t/cm².

The results are approximately the same for both concave and convex grids as follow:

$\Delta z_S \cong \Delta z_P \cong 10\ cm$

$\rightarrow\ (\Delta z / L) = 0.003125 = 0.3125\%$

$T_{S\,max.} \cong 15.6\ ton\ \rightarrow$

$$\frac{T_{S\,max}}{T_{min\ break.}} = 15.6/(5.7 \times 14) = 19.55\ \%$$

The exact results confirm the efficiency of this preliminary method.

Notice

This example may be resolved with unequal steel area of both suspension and pretension cables as follows:

Using eqn (24):

$$\Delta z_{Rise} = 2 \times 12.80 \times (\frac{5^2}{5^2 + 3^2}) = 18.82\ cm$$

$$\therefore (\frac{\Delta z}{L})\% = \frac{18.82}{3200} \times 100 = 0.588\%$$

Using Table (2) or Figs (4), corresponding to the preliminary design of (10×10) circular net with 3% sag/span ratio and T_0 corresponding to $0.50w'$, it yields that for $(\Delta z / L)\% = 0.588\%$:

$\frac{EA}{wL^2} \cong 72.85$ *and* $(T_{max.} / T_{min\ break})\% \cong 30.12\ \%$

$\therefore A_{P\,req} = 72.85 \times 0.10 \times 32^2 / 1663 = 4.48\ cm^2$

Resolving the problem using the computer program for the previous data

With $A_S = 5.7\ cm^2$ & $A_P = 4.48\ cm^2$, it yields that:

$\Delta z_S \cong \Delta z_P \cong 10.6\ cm$

$\rightarrow\ (\Delta z / L) = 0.00331 = 0.331\%$

$T_{S\,max.} \cong 16.0\ ton$

$$\rightarrow\ \frac{T_{max.}}{T_{min.\ break.}} = 16.0/(5.7 \times 14) = 20.05\ \%$$

Factors affect the response of cable grids

a) The cross-sectional area of the cables and the hangers (ties or struts);

b) The curvature of the cables (sag/span and rise/span ratios);

c) The level of pretension in both sagging and hogging cables and the ties;

d) The number of the hangers (ties / struts) or the spacing between nodes; and

e) The stiffness of the boundary and supporting structure

Summary of the results obtained by investigating these parameters is:

1) The suspension cable is the main-load carrying cable.
2) The cross section of the suspension cable has to be greater than or equal to this of the prestressed cable.
3) The steel areas of ties/struts have negligible effect on both deflections and forces.
4) The sagging of the suspension cable is the principal factor compared with rise of the prestressed cable. The sagging of the suspension cable has to be greater than or equal to the rise of the prestressed cable.

5) The rise of the prestressed cable has to be taken as minimum as the grid reaches required stiffness (rigidity).
6) The values of pretension in either the prestressed or the suspension cables have not to allow compression in the prestressed cable.
7) It is more economic and efficient to increase the pretension of the suspension cable only than to concurrently increase the pretension in both cables.

5. The values of pretension in either the prestressed or the suspension cables have not to allow compression in the prestressed cable. The pretension of the prestressed cable has to be as minimum as possible with the value that allow no compression in it.
6. Increasing the pretension of the suspension cable is economic and the efficient way for decreasing the nodal deflections comparing with increasing the pretension in both the cables in the same time.

4- Conclusions

1.The technique for the preliminary design of circular cable suspended roofs built on non-dimensional tables / graphs and a small number of equations shows an efficiency, accuracy and speed comparing with other new preliminary methods.
2. Suspension cables is the main-load carrying cable and the steel area of suspension cable have not to be less than the steel area of the prestressed cable and the sag/span ratio has not to be less than rise/span ratio.
3. Rise must be as minimum as the grid reaches the required stiffness (rigidity).
4. Hangars must be as minimum as to allow the proper distribution of forces in cables.

5- References

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2) Krishna, P.," Cable-Suspended Roofs ", McGraw-Hill, New York, 1978.

3) Naguib, M. "Buckling Strength and dynamic response of guyed tower", Ph. D. Thesis, Polytechnique of Central London, 1989.
4) Mohie-Eldin, M. "Static and Dynamic Analysis of Circular Cable Suspended Roofs", M. Sc. Thesis, Mansoura University, Egypt, 2003.

Table (1): Data assumptions for case of study (1):

Ex.	Types of arrangement	Diameter (*m*)	(D.L+L.L) kg/m^2	w' (*t/m*)	Group of areas in (cm^2) with modulus E =1663 t/cm^2	Sag/Span % ratios
1	10×10	40.00	100.00	0.20	5.031, 5.722, 6.55, 7.64, 9.058, 11.03, 13.92, 18.48, 27.07, 50.10	3%, 4% & 5%
2	10×10	60.00	150.00	0.45	16.98, 19.31, 22.11, 25.79, 30.57, 37.23, 46.98, 62.37, 91.36, 169.10	
3	16×16	40.00	100.00	0.125	5.031, 5.722, 6.55, 7.64, 9.058, 11.03, 13.92, 18.48, 27.07, 50.10	4%

Table (2): Non-dimensional coefficients for circular cable net with (10×10) spacing

Equivalent pretension w''/w'	$\frac{EA}{wL^2}$	$\delta = 3\%$			$\delta = 4\%$			$\delta = 5\%$		
		$\frac{\Delta z}{L}\%$	$\tau\%$	$f(\Delta z)$	$\frac{\Delta z}{L}\%$	$\tau\%$	$f(\Delta z)$	$\frac{\Delta z}{L}\%$	$\tau\%$	$f(\Delta z)$
0 %	52.291	1.42	36.00	149.7	1.00	31.66	119.5	0.704	27.59	108.7
	59.473	1.30	32.94	143.9	0.90	28.34	116.8	0.624	24.53	107.8
	68.079	1.18	29.14	138.4	0.80	25.19	114.8	0.548	21.64	107.2
	79.408	1.054	25.70	132.8	0.70	22.00	112.4	0.471	18.74	107.0
	94.147	0.927	22.32	127.3	0.60	18.87	110.6	0.396	15.94	107.3
	114.64	0.794	18.91	122.0	0.50	15.77	109.0	0.323	13.20	108.2
	144.68	0.656	15.49	117.0	0.40	12.71	108.0	0.251	10.53	110.1
	192.08	0.514	12.07	112.6	0.30	9.72	108.5	0.183	7.974	113.6
	281.36	0.362	8.54	109.3	0.20	6.72	111.1	0.119	5.457	120.0
	520.73	0.194	4.78	109.8	0.10	3.66	120.0	0.058	2.941	133.0
25 %	52.291	1.085	37.75	195.8	0.770	32.37	155.3	0.541	27.83	141.5
	59.473	0.995	33.93	187.9	0.692	28.89	151.8	0.479	24.69	140.5
	68.079	0.905	30.31	180.4	0.618	25.60	148.7	0.420	21.64	139.9
	79.408	0.810	26.61	172.9	0.540	22.28	145.9	0.360	18.79	139.8
	94.147	0.713	23.00	165.6	0.463	19.07	143.5	0.303	15.97	140.5
	114.64	0.611	19.39	158.6	0.385	15.89	141.8	0.246	13.20	142.0
	144.68	0.505	15.79	152.1	0.306	12.76	141.1	0.191	10.51	144.7
	192.08	0.395	12.23	146.5	0.229	9.73	141.9	0.139	7.947	149.8
	281.36	0.277	8.60	142.6	0.152	6.71	146.1	0.090	5.436	158.8
	520.73	0.148	4.78	144.2	0.076	3.65	159.0	0.044	2.931	176.6
50 %	52.291	0.733	40.11	290.1	0.527	33.27	226.9	0.370	28.11	206.6
	59.473	0.674	35.84	277.4	0.474	29.57	221.7	0.328	24.88	205.4
	68.079	0.615	31.83	265.6	0.423	26.12	217.3	0.287	21.86	204.9
	79.408	0.551	27.78	253.8	0.369	22.63	213.2	0.246	18.86	205.0
	94.147	0.486	23.86	242.8	0.316	19.30	209.9	0.206	15.98	206.2
	114.64	0.418	19.98	232.1	0.263	16.01	207.7	0.167	13.18	208.9
	144.68	0.345	16.16	222.4	0.209	12.82	206.9	0.129	10.49	213.9
	192.08	0.270	12.43	214.4	0.156	9.74	208.9	0.092	7.92	227.0
	281.36	0.189	8.67	209.2	0.103	6.70	215.7	0.060	5.415	236.0
	520.73	0.100	4.78	212.8	0.051	3.63	235.3	0.029	2.921	262.6
75 %	52.291	0.369	43.30	576.6	0.272	34.40	439.8	0.192	28.45	398.9
	59.473	0.341	38.42	548.7	0.245	30.43	429.8	0.170	25.0	396.8
	68.079	0.312	33.86	523.1	0.218	26.75	420.6	0.148	22.00	396.3
	79.408	0.281	29.32	497.5	0.191	23.07	413.2	0.1237	18.93	397.4
	94.147	0.249	24.98	474.4	0.163	19.58	406.7	0.106	16.00	400.8
	114.64	0.214	20.74	452.4	0.135	16.18	403.1	0.086	13.18	406.9
	144.68	0.178	16.62	432.7	0.107	12.88	402.8	0.064	10.46	432.0
	192.08	0.139	12.67	416.9	0.080	9.752	408.0	0.048	7.893	436.1
	281.36	0.097	8.75	407.1	0.053	6.684	423.1	0.031	5.391	466.1
	520.73	0.051	4.78	416.3	0.026	3.618	466.1	0.015	2.91	524.3

Table (3): (16×16) Circular net with $\delta = 4\%$ and $[w'' = 0.25(D.L+L.L)]$

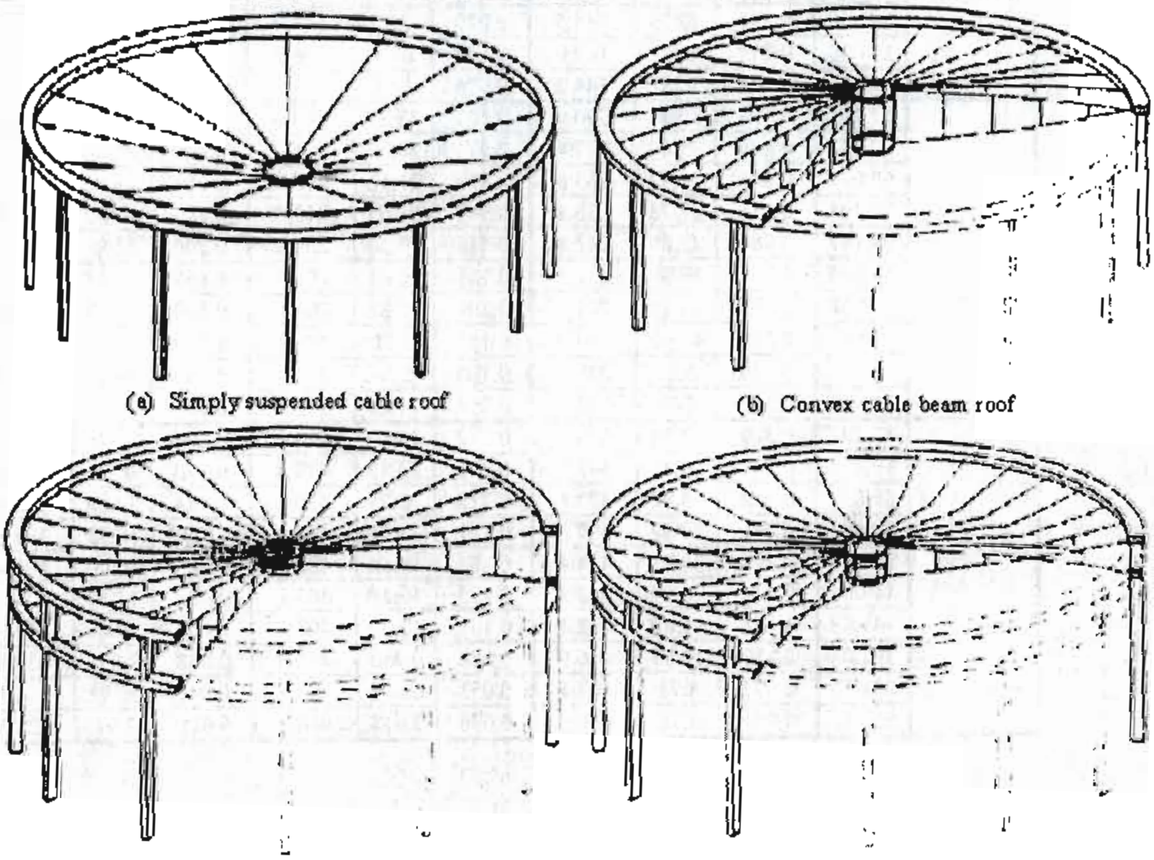
(EA/wL^2)	52.291	59.473	68.079	79.408	94.147	114.64	144.68	192.08	281.36	520.73
$(\Delta z/L)\%$	0.511	0.455	0.400	0.345	0.291	0.237	0.185	0.135	0.086	0.041
τ %	21.35	18.97	16.74	14.49	12.34	10.22	8.164	6.184	4.238	2.287
$f(\Delta z)$	155.3	151.8	148.7	145.9	143.5	141.8	141.1	141.9	146.1	159.0

Table (4): Data assumptions for case of study (2).

Ex	Arrange	Diam (m)	Spacing (m)	D.L kg/m^2	L.L kg/m^2	w t/m^2	w' t/m	Sag	$\frac{w''}{w'}$	$\frac{\Delta z_{allow}}{L}$	E t/cm^2
4	16×16	80.0	5.0	80	40	0.12	0.3	4%	25%	1/250	1663

Table (5): Data assumptions for case study (3).

Ex.	The grid arrangement	Diam (m)	S (m)	D.L. (t/m^2)	L.L. (t/m^2)	Sag/span & Rise/span	Equivalent pretension w''/w'	Allowable deflection
5	(10×10)	32.0	3.2	0.07	0.03	Sag =5% Rise =3%	50 %	(1/250) of the span



(a) Simply suspended cable roof
(b) Convex cable beam roof
(c) Concave cable beam roof
(d) Concave-convex cable beam roof

Fig. (1) Radial cable roofs with inner tension ring and outer compression ring / rings.

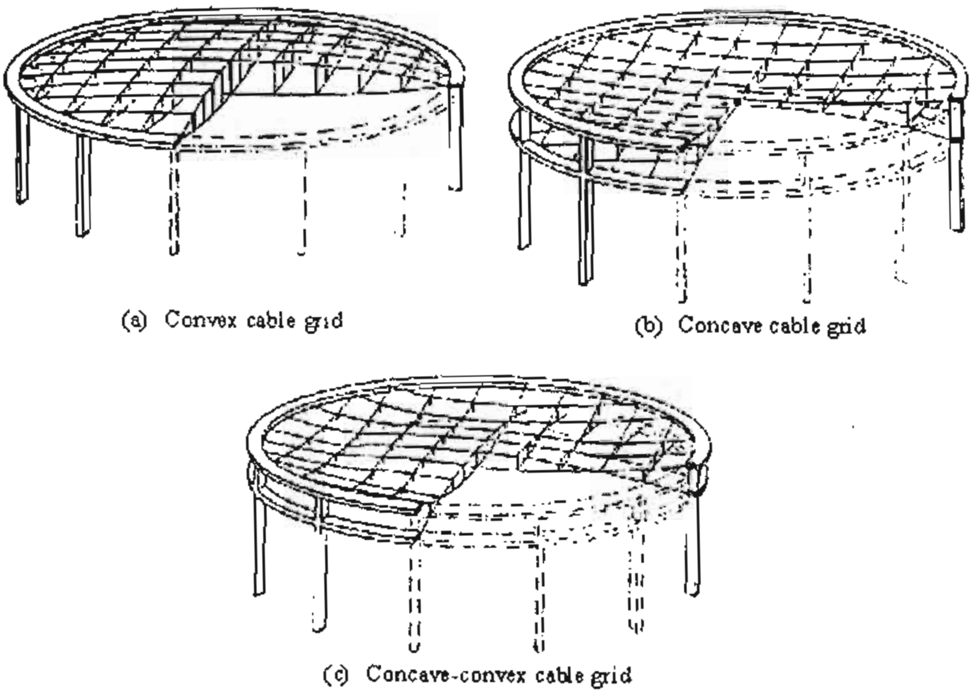


Fig. (2): Counter-stressed cable grid roofs.

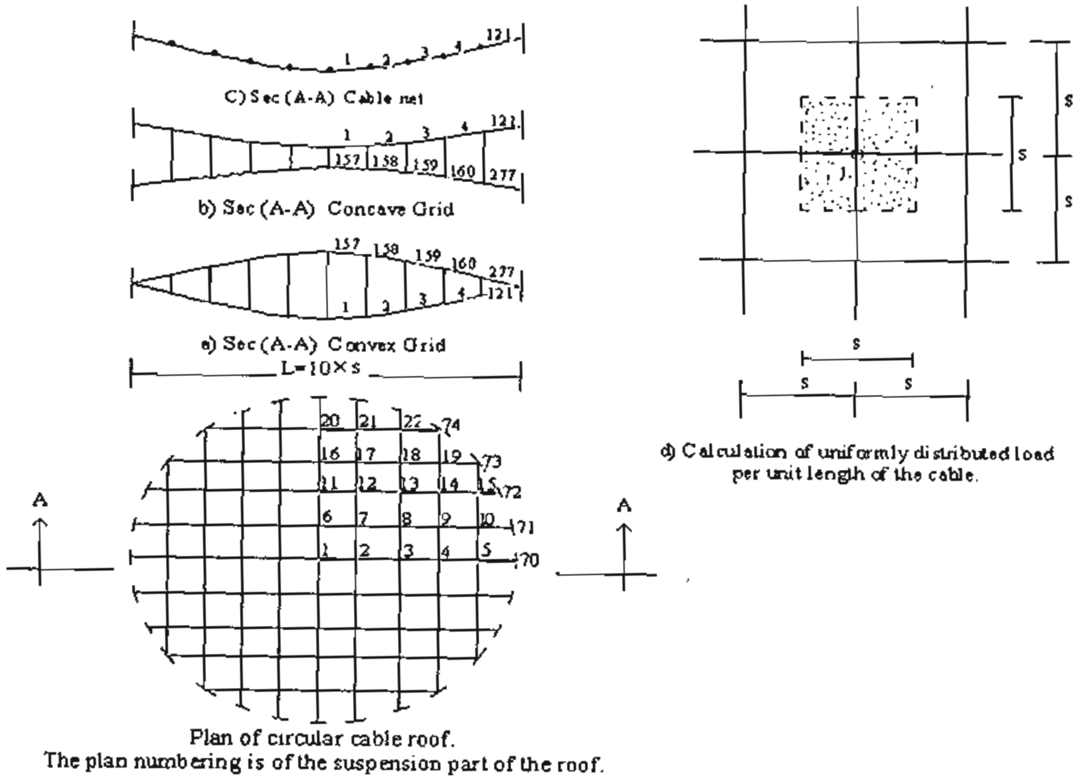
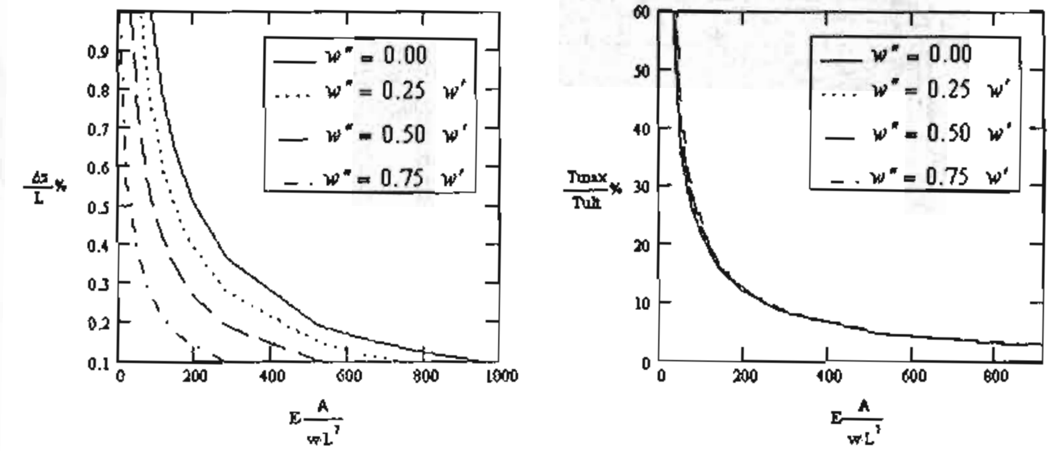
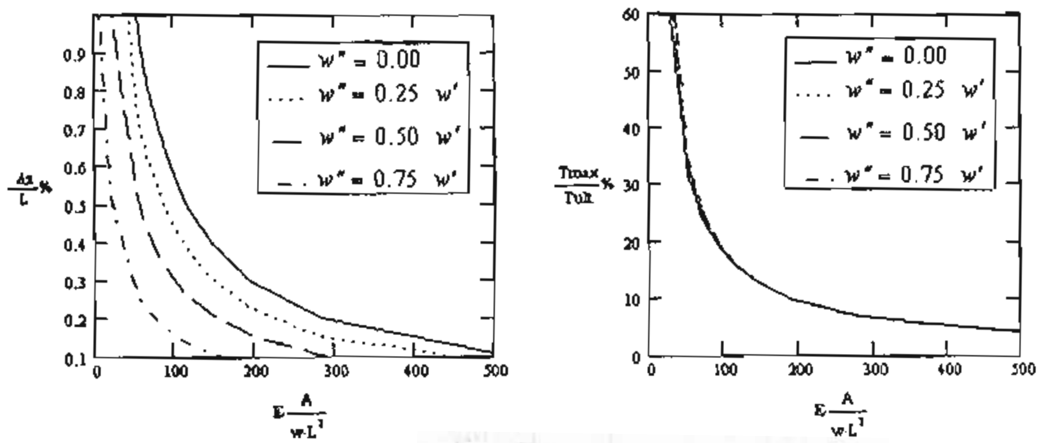


Fig. (3): (10×10) Circular cable roof and concentrating the applying loading at joints.



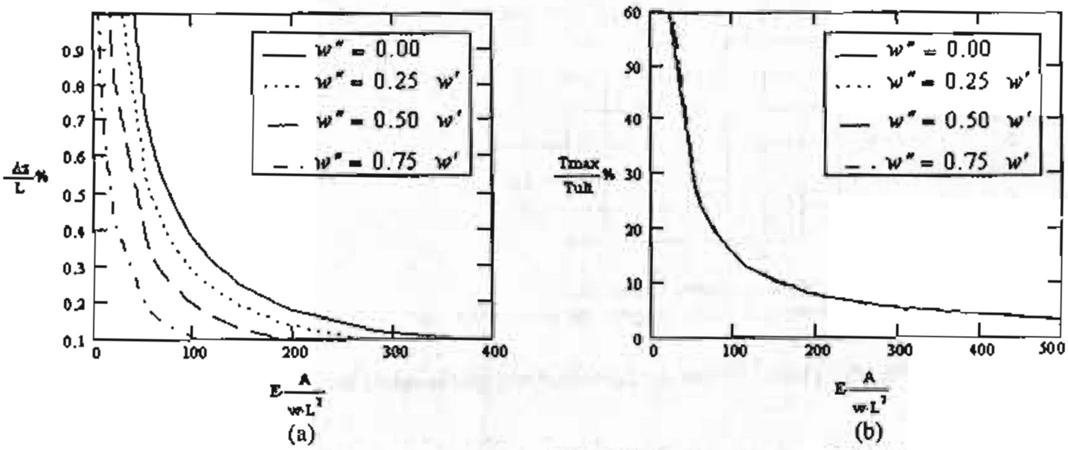
(a) (b)

Fig. (4): The relation between the design parameters, in (10×10) circular cable net with sag/span ratio of 3%: (a) the central deflections, (b) the maximum cable forces.



(a) (b)

Fig. (5): The relation between the design parameters, in (10×10) circular cable net with sag/span ratio of 4%: (a) the central deflections, (b) the maximum cable forces.



(a) (b)

Fig. (6): The relation between the design parameters, in (10×10) circular cable net with sag/span ratio of 5%: (a) the central deflections, (b) the maximum cable forces.