STATIC AND DYNAMIC ANALYSES OF SUSPENDED CABLE ROOFS FOR HALLS HAVING A RECTANGULAR SHAPE DUE TO WIND LOADS

التحليل الإستاتيكى والديناميكى لشبكات الأسقف المعلقة للصالات ذات الأشكال المستطيله المعرضة لقوى الرياح

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الخلاصة:الهدف الرئيسي لهذا البحث هو دراسة التحليل الاستاتيكي والديناميكى للأسقف المعلقة ذات الكابلات للصالات ذات الأشكال المستطيله تحت تأثيرقوى الرياح أخذاً فى الإعتبار الإستجابة اللاخطية لأسقف تلك المنشآت وعلى الرغم من أن النهج يتطلب حتمية وقت وجهد في تحليل العلاقة لوضع النماذج ومعالجة البيانات يبدو انه البديل الوحيد للحصول على دقة عالية. و تفاصيل التحليل الإستاتيكى والديناميكى لشبكة سقف الكابلات هو عمل معقد ويتطلب خبرات متقدمة في مجال النمذجة . ولكن العمل بنهج العنصر المحدود يعتبر بديل للتحليل في مراحل التصميم الأولية أو يمكن استخدامه في التحقق من صحة النتائج التى تم الحصول عليها من أكثر النماذج العددية علما بان نتائج التحليل باستخدام هذه الطريقة قد اظهرت توافقا كبيرا مع تلك التي تم الحصول عليها ببرنامج الحاسب الآلى.

وقد تمت دراسة و تحليل العديد من الأسقف المستطيلة المعلقة ذات الكابلات باستخدام برنامج ساب 2000 الإصدار 14 ثم استخدام نتائج التحليل في استنباط التأثيرات المختلفة للعوامل المؤثرة على مثل هذه المنشات , و كذلك العلاقات المستنبطة شكلت وسيلة جيدة و فعالة للتصميم الإبتدائي للأسقف المستطيلة ذات الكابلات.ونموذج المحاكاة المقترح تم توضيحه بإستخدام البرنامج المشار إليه سابقاً.

Abstract: The main aim of the present work is to investigate the static and dynamic analysis of suspended cable roofs for halls having rectangular shapes due to wind load. The responses of nonlinear analysis are taken into consideration. The deterministic approaches require considerable analysis time and effort in relation of modeling, running, and data processing. Detailed static and dynamic analysis of cable roof networks is sophisticated and requires advanced modeling expertise. The approach can be considered as alternative to analysis in the preliminary design phase, or can be used to validate results obtained from more elaborated numerical models. This good preliminary technique was examined using several examples and the results are in good agreement with these solved using the computer program.

Many rectangle cable roofs have been studied and analyzed using a computer program Sap 2000 version 14.0.0 [1]. The results are used to investigate the factors that affect the design and the response of cable suspended roofs. Also, the results, graphs and relationships form a good technique for the preliminary design of rectangle cable suspended roofs. Proposed model is illustrated with program which is mentioned before.

1. Introduction

Cables are light and have a high strength to weight; its lightness provides an expanded impression of space and the smoothly curving cables that create structures with soft outline provide a desirable alternative to the traditional orthogonal building, cable has also proven to be an economical proposition for large structures. With the continuing rise of the steel cost, the development of the high tensile steel cable has it possible for man to transmit large axial force in tension at a relative low cost. Cable roofs have a wide field of application and have been used to cover such different building such as stadia and sports halls, swimming pools and water

Accepted December 30, 2010.

reservoir, concert halls and theaters, cooling tower, hangers and factories.

This work investigates the static and dynamic responses for convex cable roof net having a 200 m long, 100 m wide, and 24 m height .The analysis of wind load is taken according to [ECP-building –loads]. Several parameters are studied in static and dynamic analysis and the results are showed for some selected joints, members, and column bases.

2.The static and dynamic analyses for cable roof nets

2.1 Static analysis.

The static analysis for cable roof convex beams are carried out taking the following effect into consideration as study parameters with reference to Fig.(1) [2,3,4,and5]:-

1. The spacing between vertical cable elements (distance a).
2. The initial tension in cable elements (all group of cables).
3. The value of both sag and rise to span ratios (sag and rise).
4. The inclination of stayed cable elements with horizontal (angle θ_1).
5. The inclination of columns with vertical (angle θ_2).
6. With and without diagonal elements.

2.2 Dynamic analysis for cable roof nets

The dynamic analysis contained [2,6]:

1. Frequency domain analysis.
2. Time domain analysis.

3. Static and dynamic modeling with reference to Fig. (1)

Both static and dynamic analyses are carried out for a rectangular convex roof net having a dimension of 200 m long, 100 m wide, and 24m height.

The properties of used cable for all cable groups are taken as given in Table (1).

Arrangements of grid are 5 m center to center in the two principal directions; the spacing between columns is 5m in the two directions. The columns are steel I-beam built up section with fixed supports having a properties shown in Fig.(2a).The arrangement of columns with lateral beams in both directions (plane and out of plane) is shown in Fig.(2b),The rise of cable is fixed as 3 m (3% from short span) and the sag of cable varies from 3% to 6% with step 1% of short span .

3.1 Loading

The following assumptions for loads are taken into consideration to carry out both static and dynamic analyses:-

Dead load: - For cables (self-weight for all cable groups of 0.66 KN/m are considered and uniform distributed cladding of 0.150 KN/m^2 is taken for upper cables that carry the cladding) and for beams (own weight +wall load) equal 28.8 KN/m

Live load:-a uniform distributed live load equal 0.55 KN/m^2 according to [E.S.S]

Wind load: - Two cases of loading as shown in Fig. (3) due to [ECP-building – loads] are considered.

Windward pressure and leeward section was calculated with respect to [ECP-building –loads] using the following equation, Table (2) shows the value of them for columns.

$$P = C\,K\,q \qquad (1)$$

Table (3) shows the properties of cables for all groups.

All the loading assumptions regarding the wind effects on the network and the self-weight of the roof are also considered to be the same.

3.2 Modeling of damping

From ref. [7, 8, and 9] it was concluded that varying the damping ratio between 0.5 to 5% critical does not have a significant effect on the total response. Finally, an equivalent translational viscous damper with 2% of the critical viscous damping was selected.

4. Analysis of Results

The results are considered from the envelop solution of wind load directions in Fig.(3), it was noted that the maximum values of straining actions acquired when

Table (1):- Cable properties

Diameter (m)	0.116
Minimum breaking load (KN)	10487
Weight (KN)	0.66
Steel area (m^2)	7.862×10^{-3}
Elastic Modulus (KN/m^2)	14720

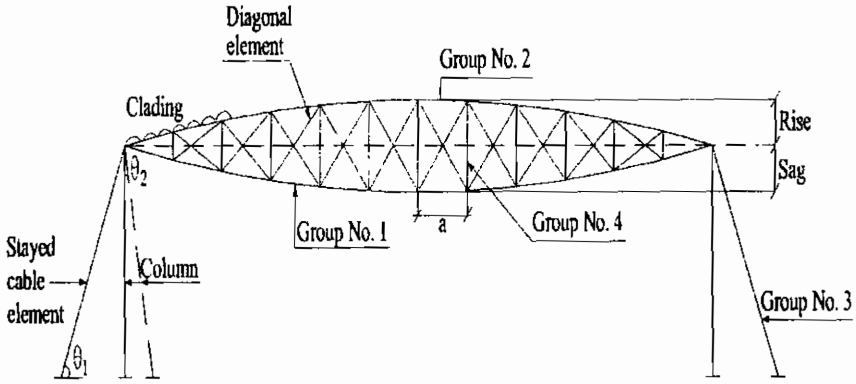


Fig. 1: Configuration of convex cable roof with all group members

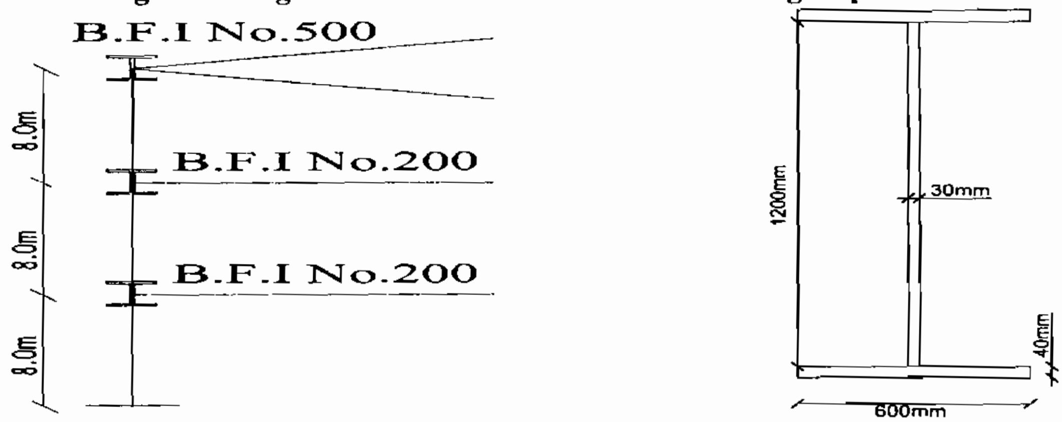


Fig.2a: Columns and beams properties

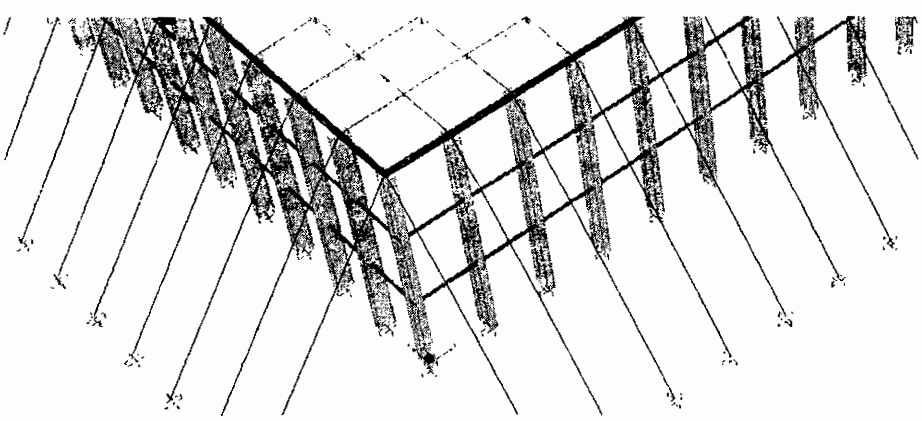


Fig.2b: Columns and beams arrangements in plane and out plane

the wind load direction is perpendicular to the long span (L=200m).For all results the axes direction assumed to be as in Fig. (4).

The output results for mid span joint, four members and four column bases joints as in Fig. (5).

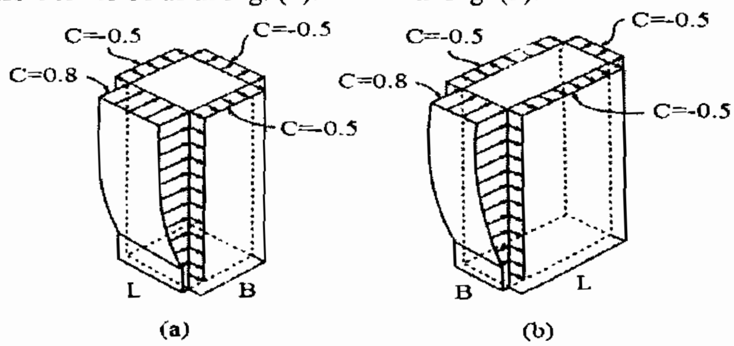


Fig.3: (a) Wind pressure direction perpendicular to long span (L)
(b) Wind pressure direction perpendicular to short span (B)

Table (2):- Wind pressure and suction calculation for columns.

Height above ground (m)	K	q KN/m^2	C		Windward pressure KN/m	Leeward section KN/m
			Windward	Leeward		
0-10	1.0	0.90	0.80	-0.50	3.6	2.25
10-20	1.10				3.96	2.475
20-24	1.3				4.68	2.925

Table (3): Configuration for each cable group

Group number	Location	T_{OF}	W KN/m
Group No.(1)	Sagging cables	5% which equal to 550 KN	0.66
Group No.(2)	Rising cables	20% which equal to 2097.4 KN	4.16
Group No.(3)	Stayed cable element	25% which equal to 2621.8 KN	0.66
Group No.(4)	Vertical element	20% which equal to 2097.4 KN	0.66

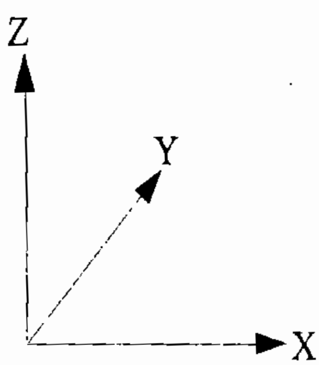


Fig.4: Assumed axes direction

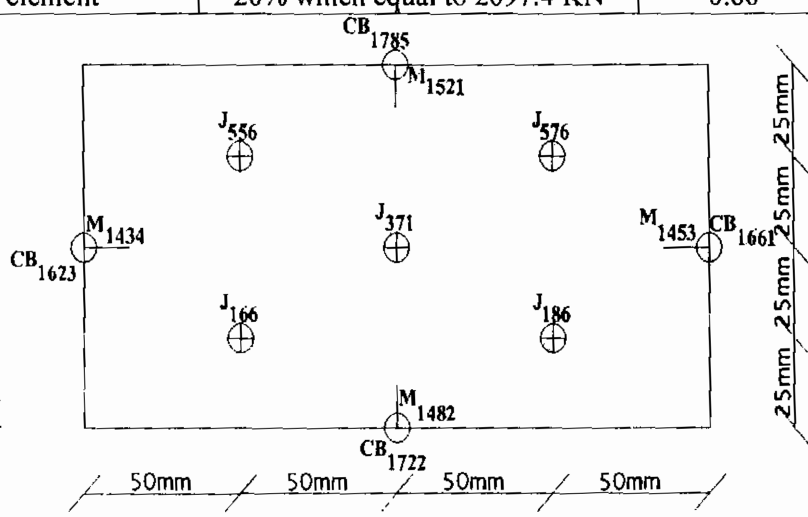


Fig.5: Location of studied joints and members with respect to group No. (1)

4.1 Static analysis

There are many investigation factors affect the response of cable in static analysis these factors are studied below:-

a) Sag/span ratio (τ) against deflections (δ) Fig. (6)

Increasing of sag/span ratio for same steel area and initial tension in cables causes a decreasing net deflections and final cable tensions.

b) Initial tension (T_{OF}) against deflection (δ) Fig. (7)

Increasing of initial tension in cables for same sag /span ratio and steel area causes a decreasing of deflection for net joints. The net having diagonal elements had a deflection lower than that without diagonals.

c) Initial tension(T_{OF}) against final tension (Ft) Figs.(8,and 9)

Increasing of initial tension increases final tension for all groups of members. For group No.(1) members the value of final tension is bigger than the value of initial tension on the contrary group No.(2) members such as M_{2974} which lie above M_{1482}.Final tensions in the net with diagonals are bigger than the net without diagonals for group No.(1) Fig. (8), on the contrary group No. (2) members Fig. (9).

d) An inclination (θ_1) against (N.F) , (B.M) in columns, and (δ) in cable net

Increasing inclination of stayed cable elements with horizontal (θ_1) decreasing normal force in columns and deflection in net Figs. (10,,and11). Bending moment in columns is also decreased but for columns which exposed to wind pressure as CB_{1722} but columns, which exposed to wind suction as CB_{1785} the bending is increased Fig.(12)

e) Area of steel of cable against deflection (δ) Fig. (13)

Changing area steel of cable is studied and it concluded that increasing area steel of cable for same pretension, rise and sag /span ratios decreasing deflection at net joints.

f) An inclination (θ_2) against deflection (δ) and final tensions in cables (Ft)

Increasing inclination angle of columns with vertical (θ_2) decreasing deflection in the net Fig. (14) and increased final tension in groups No. (1, 2) Fig. (15) for same initial tension , area steel and sag/span ratio.

g) An inclination of (θ_2) against (N.F) and (B.M) in columns Figs.(16,17)

Increasing inclination angle of columns with vertical (θ_2) decreased normal force and bending moment in columns.

4.2 Dynamic analysis

4.2.1 Frequency domain analysis

For natural frequency domain analysis many natural frequencies and mode shapes are calculated .These natural frequencies are recalculated for different values of sag/span ratios, initial tension, and spacing between cable elements. To study the influence of previous factors with frequency other factors are kept constant. Fig. (18) shows some mode shapes of the cable net.

a) Sag/span (τ) against natural frequency (f) Fig.(19)

Fig (19) indicates the first mode frequency for cable and flexural respectively and it was noted that increasing of sag/span ratio decreases the natural frequencies for both cable and flexural mode.

b) Initial tension (T_{OF}) against natural frequency (f) Fig.(20)

Increasing the initial tension (T_{OF}) increases the natural frequencies [10]

c) Spacing between cable elements (a) against natural frequency (f) Fig. (21)

Increasing the spacing between cable elements decreases the natural frequencies.

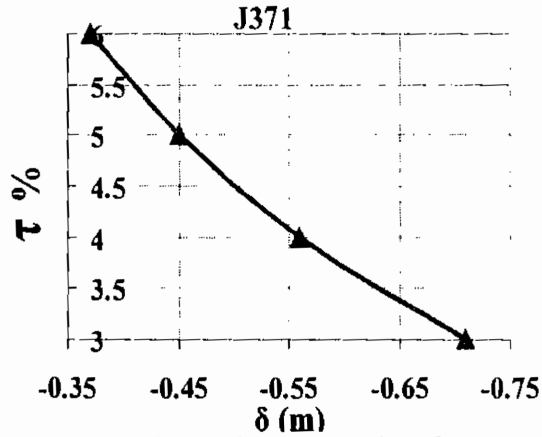


Fig.6: Variation of (τ) with (δ)

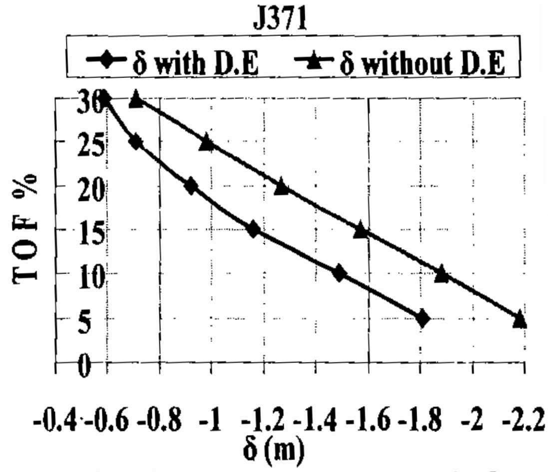


Fig.7: Variation of (T_{OF}) with (δ)

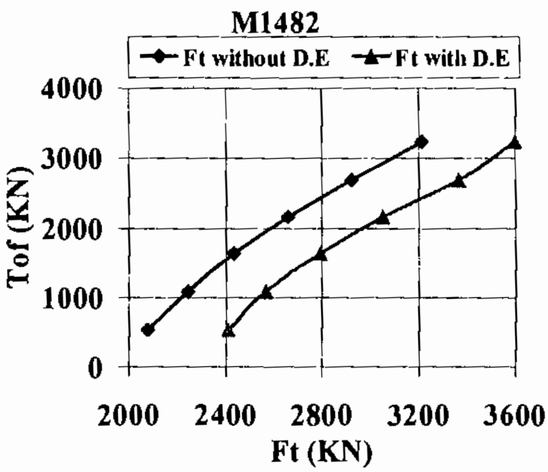


Fig.8: Variation of (T_{OF}) with (Ft)

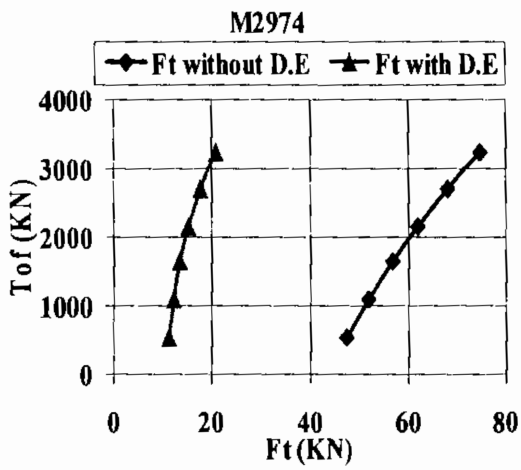


Fig.9: Variation of (T_{OF}) with (Ft)

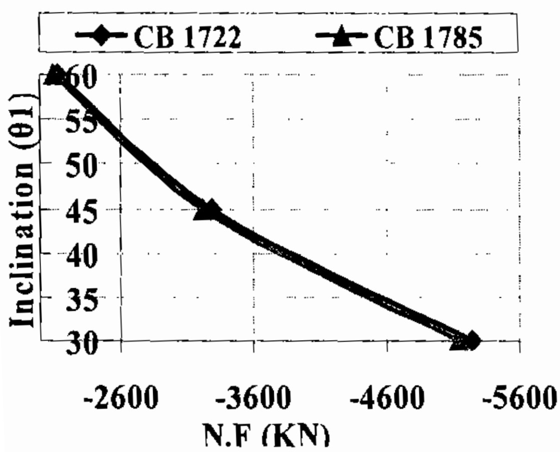


Fig.10: Variation of (N.F) with (θ_1)

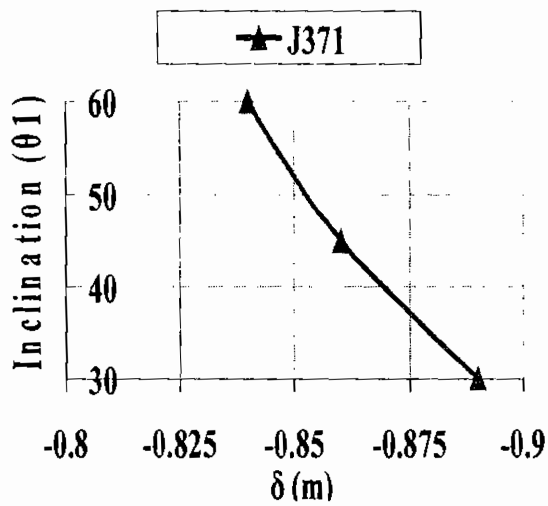


Fig.11: Variation of (δ) with (θ_1)

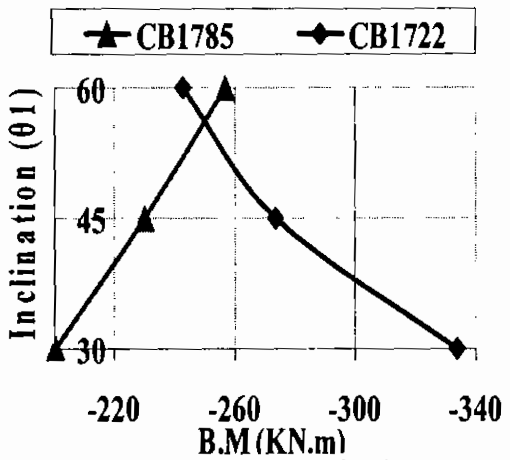


Fig.12: Variation of (B.M) with (θ_1)

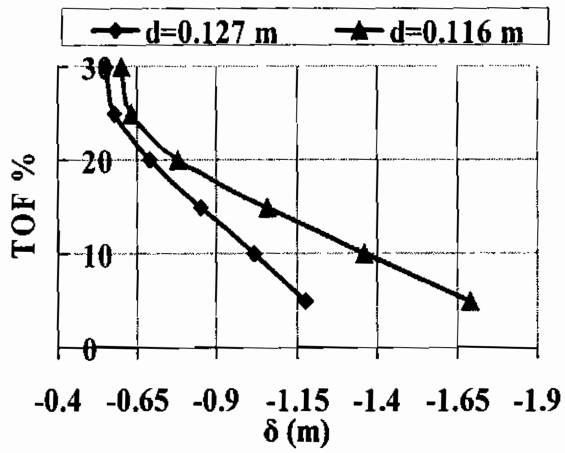


Fig.13: Variation of (δ) with (d) for J_{371}

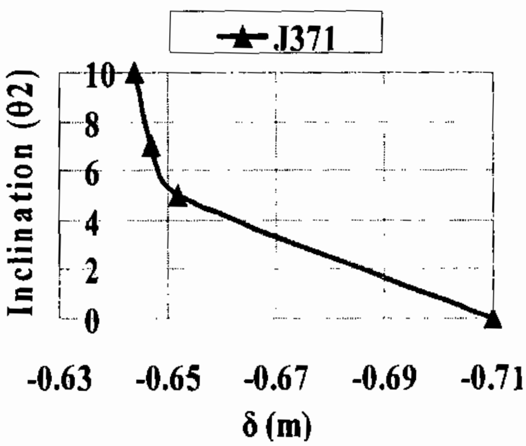


Fig.14: Variation of (δ) with (θ_2)

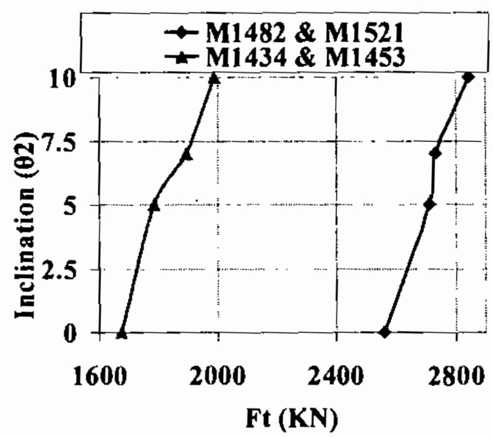


Fig.15: Variation of (Ft) with (θ_2)

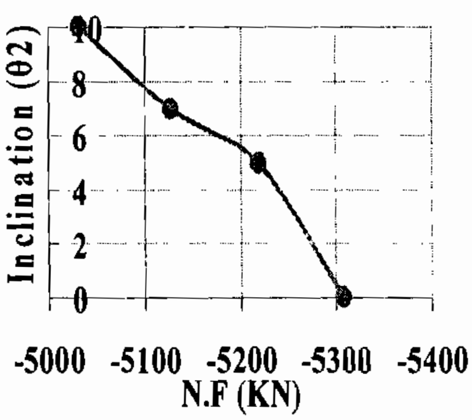


Fig.16: Variation of (B.M) with (θ_2) for CB1722

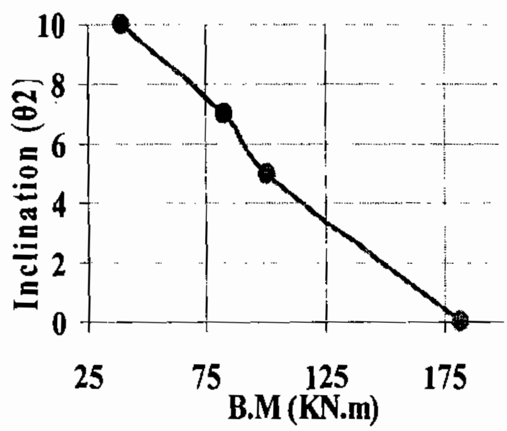
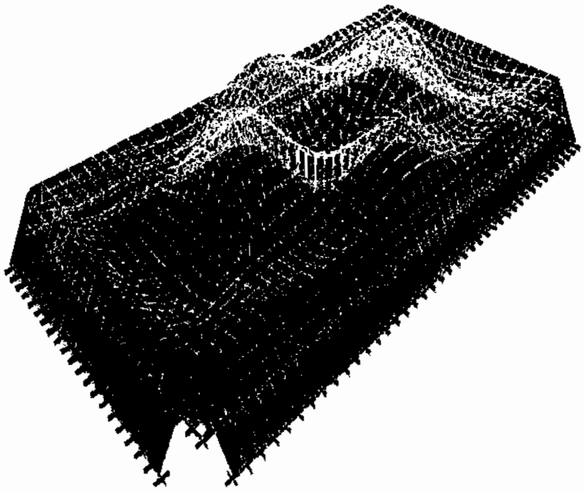
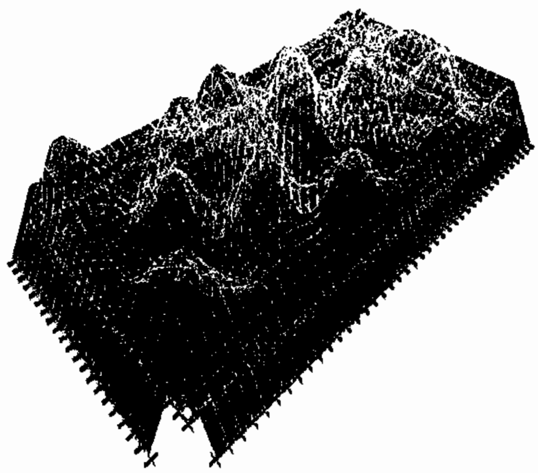


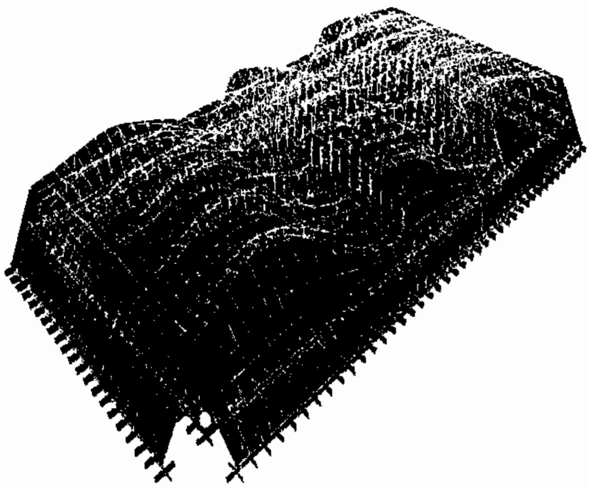
Fig.17: Variation of (N.F) with (θ_2) for CB1722



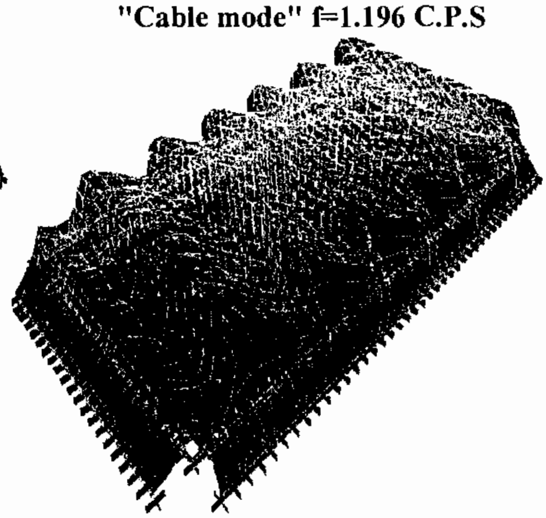
Mode No. (10)
"Cable mode" f=0.736 C.P.S



Mode No.(40)
"Cable mode" f=1.196 C.P.S

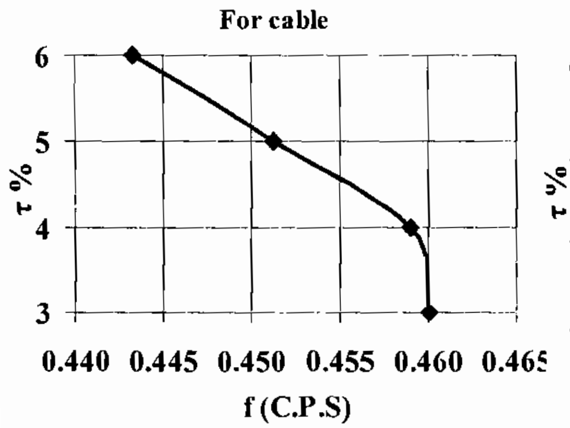


Mode No.(172)
"Flexural mode" f=2.030 C.P.S



Mode No.(225)
"Flexural mode" f=2.239 C.P.S

Fig 18:Some mode shapes



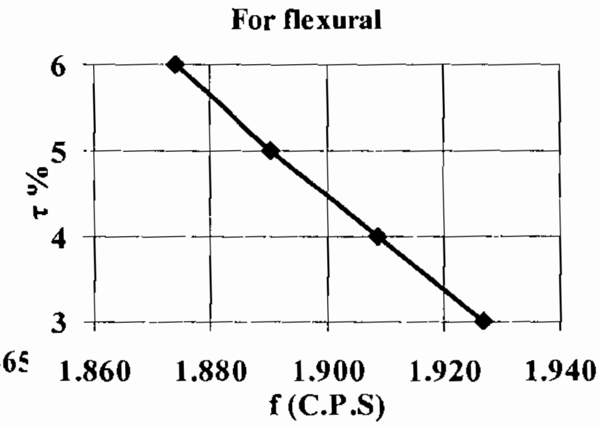


Fig.19: Variation of (τ) with (f)

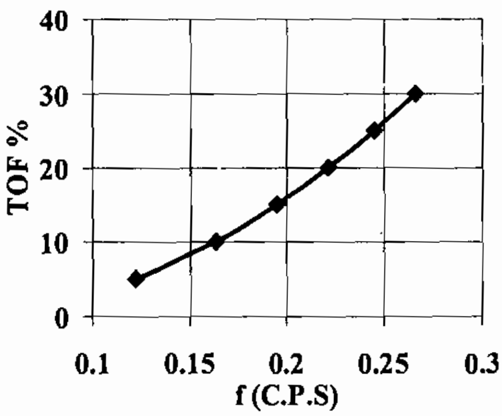


Fig.20: Variation of (T_{OF}) with (f)

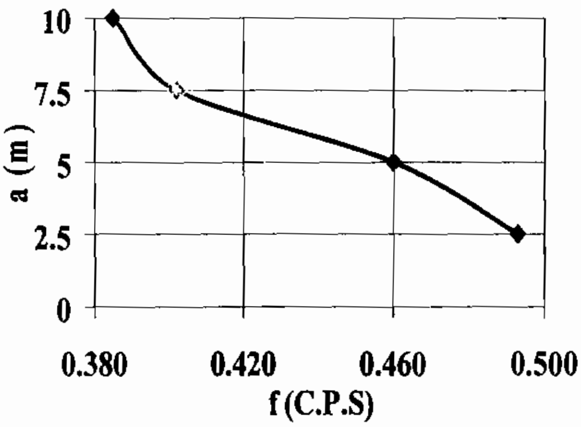


Fig.21: Variation of (a) with (f)

4.2.2 Time domain analysis

The analysis of time domain is taken place with 60 second by time interval 0.01which mean that the circles of solutions are 6000 cycles.

a)Deflection (U_z), velocity (V_z), and acceleration (a_z) for joints against time (t)

Dynamic response vibrate about an average value and the amplitude is decreased if the location of the joint far away from the center. From Fig. (22) the dynamic responses for groups No.(1,and 2) joints are very close.

Note :J_{1112} lies above J_{371}

b) Final tension in members (Ft) against time (t) Fig.(23)

Dynamic final tension vibrate up and down, the amplitude of vibration increases for the members near the roof center on the contrary of the static analysis the value of tension in members that lie on the same cable increase when going far away from the center and toward the roof edge[5] as M_{1054} Figs(24 to25).

c) Normal force (N.F), shear force (S.F),and bending moment (B.M) for column base joints against time (t) Fig.(27,and28)

Dynamic normal force, shear force, and bending moment for column base joints vibrate up and down and increase very quickly in very small time but it indicated that at the end of time analysis the dynamic response is going to be regular.

4.3 Statistic analysis

In order to judgment on the dynamic responses some of the statistic functions as mean, variance, and standard deviation are recorded for J_{371} tables (4,to 6) and CB_{1722} table (7) .

5. CONCLUSIONS

The results showed that the following conclusions are:

1. Increasing sag/span ratio decreases the net deflections, required steel area and the natural frequencies.
2. Increasing the initial tension increase the final tension in cables, natural frequencies and decreases the deflection . For group No.(1) members the value of final tension is bigger than the value of initial tension on the contrary group No.(2) members .From comparison between with and without diagonal element it concluded that for group No. (1) members final tensions in the net with diagonals are bigger than the net without diagonals ,on the contrary group No. (2) members. And it concluded also that the net which included diagonal elements has a displacement less than the net which hasn't. Initial tension has a negligible effect comparing with increasing the steel area upon the relative final forces

in cables. This means that the steel area is the decisive in carrying the applying loads but increasing the pretension of the suspension cables is economic and efficient way for decreasing the deflection comparing with the cost of increasing steel area of cable.

3. Increasing the steel area decreases the deflection.
4. Increasing inclination of stayed cable elements with horizontal (θ_1) decreasing normal force in columns and deflection in cable net joints. Bending moments in columns are also decreased but for columns, which exposed to wind pressure but columns which exposed to wind suction the bending is increased.
5. Increasing inclination angle of columns with vertical (θ_2) decreasing deflection in cable net joints, normal force and bending moment in columns and increased final tension in cables ,for same initial tension, area steel and sag/sp:ı ratio.
6. Increasing the applying uniformly distributed loads decreases the natural frequencies.
7. Increasing the spacing between cable elements decreases the natural frequencies.
8. For time domain analysis it seems that at the beginning of time analysis the dynamic U_t ,V_t , a_i, Ft , N.F , S.F , and B.M vibrate up and down and increase very quickly in very small time but it indicated that at the end of time analysis the dynamic response is going to be regular.

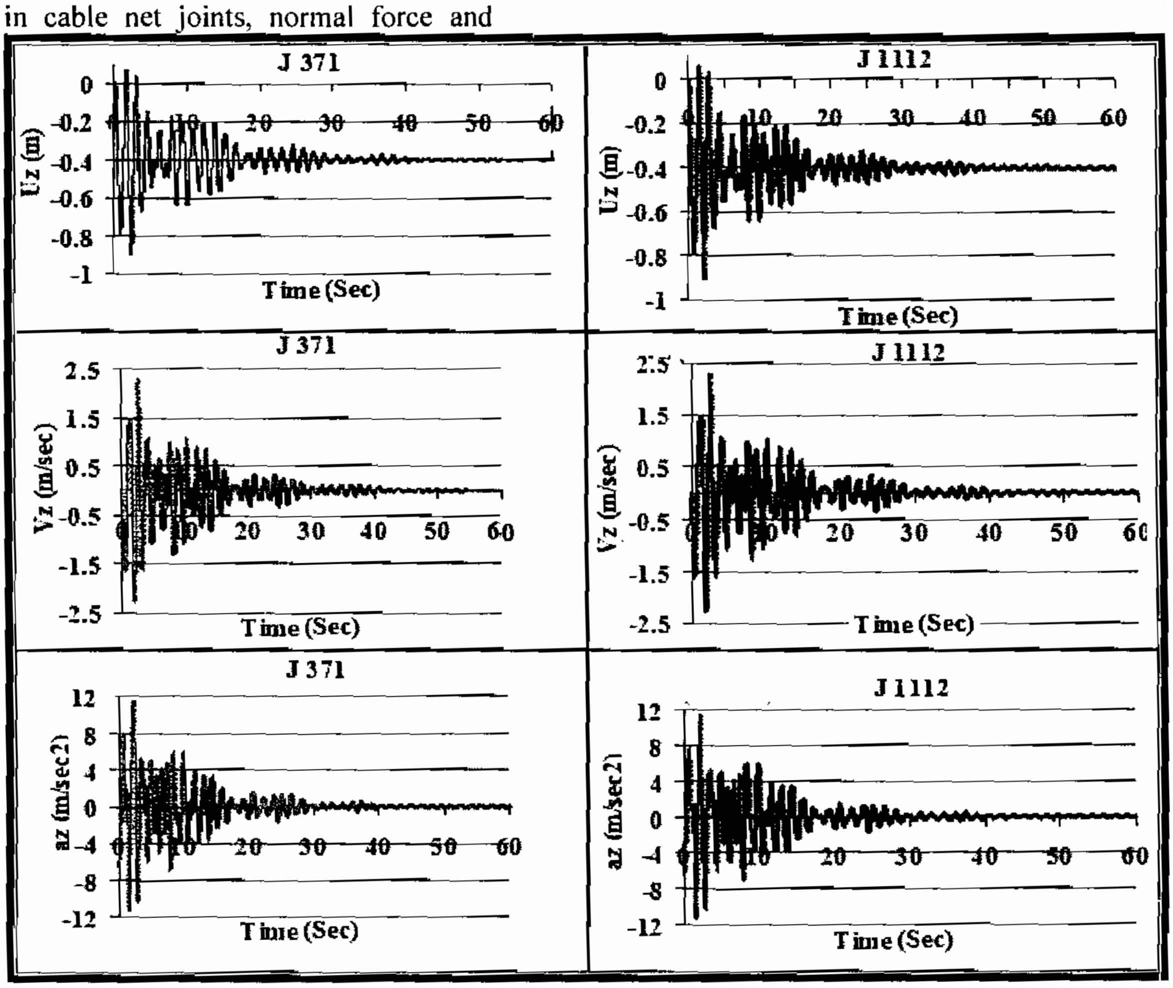


Fig.22: Variation of dynamic response for J_{371} ,and $_{1112}$

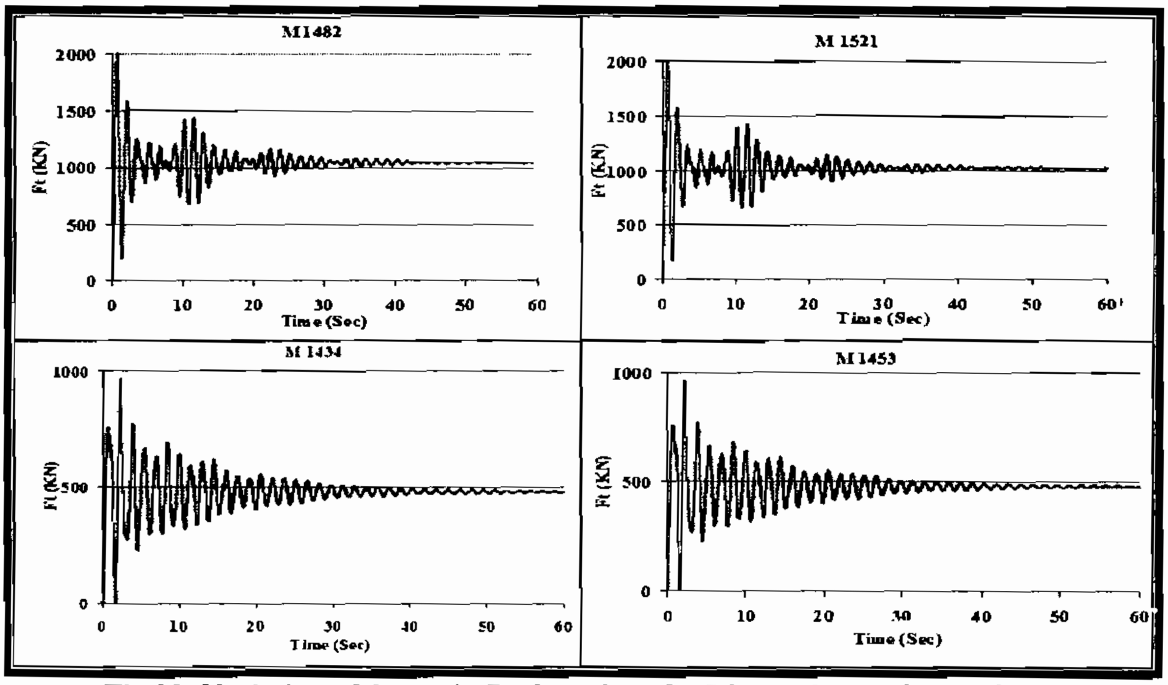


Fig.23: Variation of dynamic final tensions for M_{1482}, M_{1521} , M_{1434} , M_{1453}

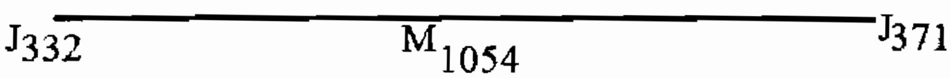


Fig. 24: Configuration of M_{1054}

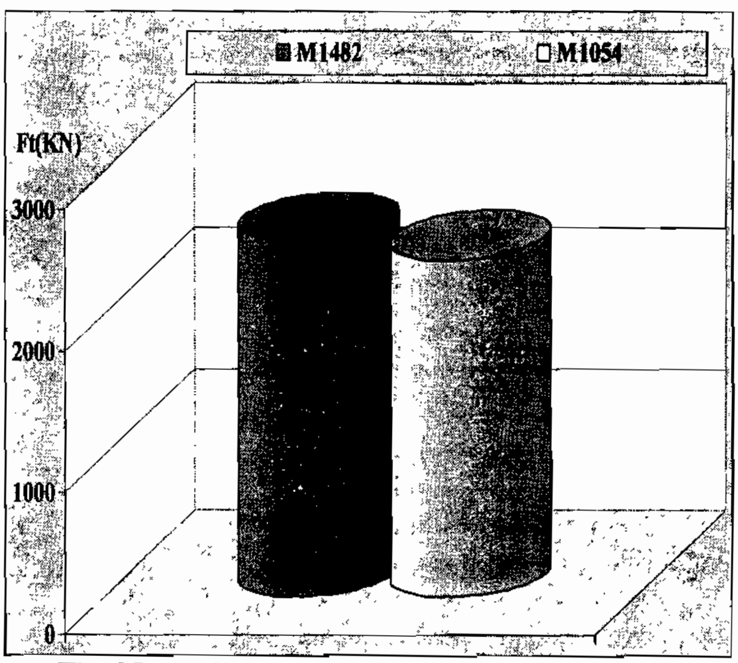


Fig. 25: Variation of static Ft of M_{1482} ,and M_{1054}

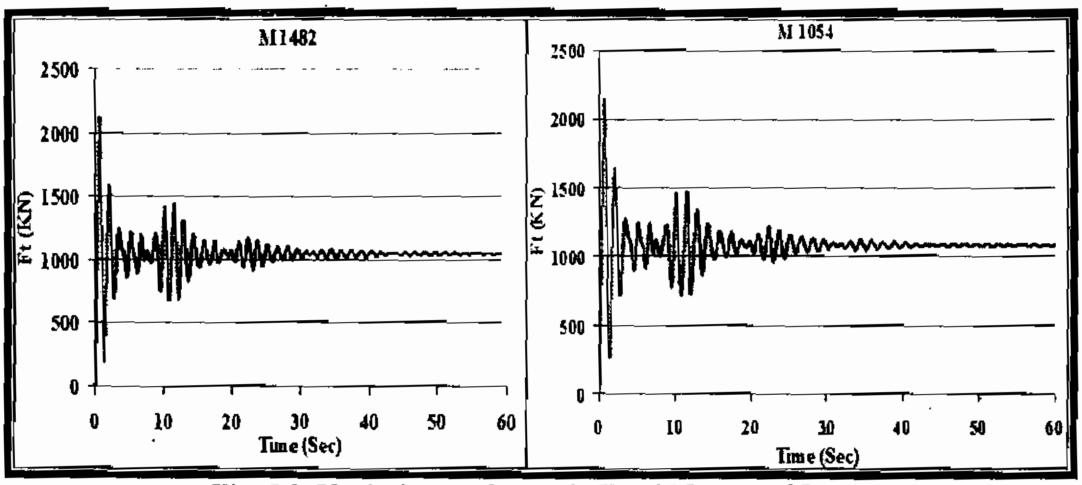


Fig. 26: Variation of dynamic Ft of M_{1482}, and M_{1054}

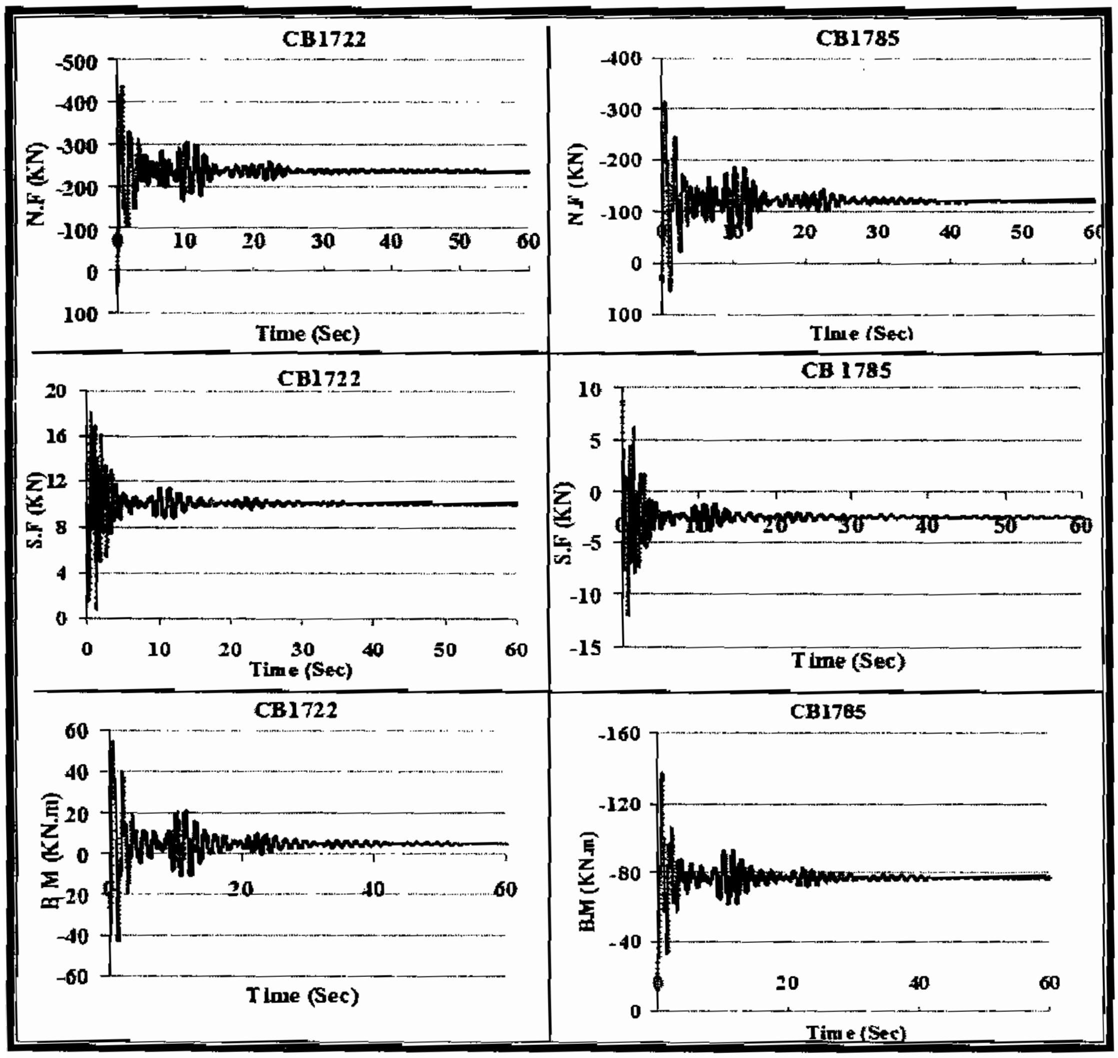


Fig.27: Variation of dynamic N.F, S.F, and B.M for CB_{1722} ,and CB_{1785}

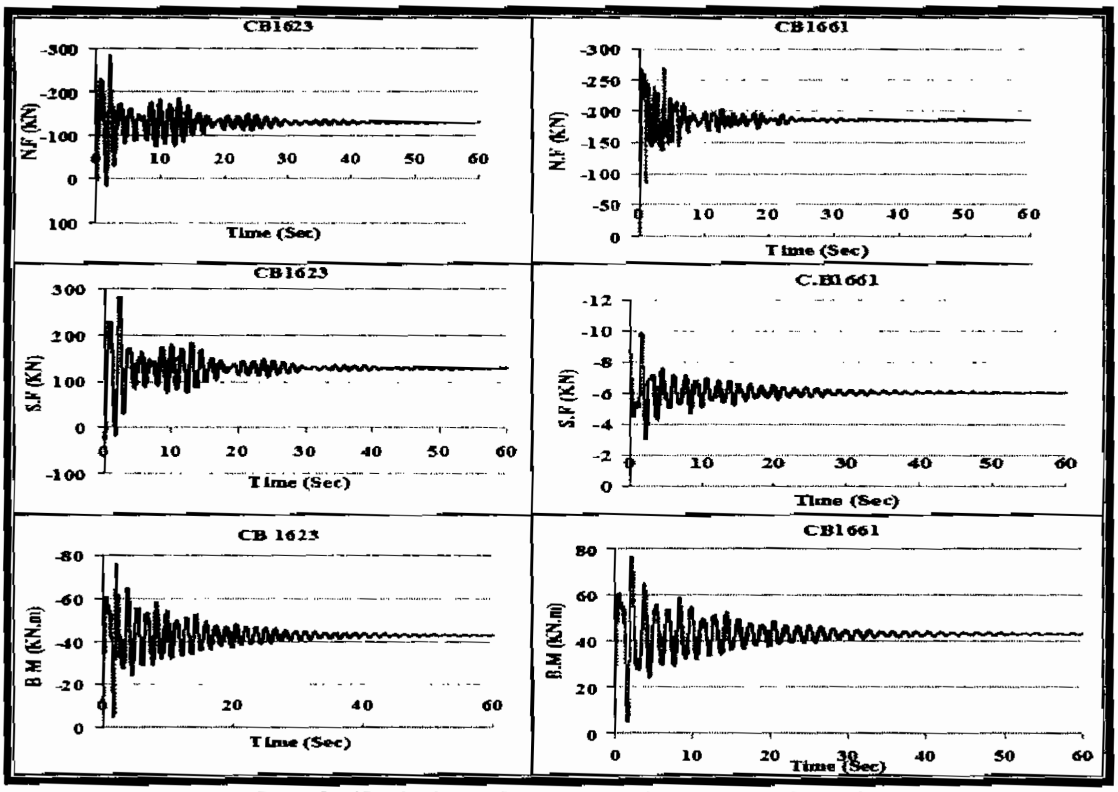


Fig.28: Variation of dynamic N.F, S.F, and B.M for CB $_{1623}$,and CB $_{1661}$

Table 4: Displacements at joint No. (371)

Joint Disp.	Ux 371	Uy 371	Uz 371
Mean	0.0403	0.00281	-0.403
Variance	9.2E-05	1.5E-07	0.0090
Standard Deviation	0.0096	0.0003	0.0953

Table 5: Velocities at joint No. (371)

Joint velocities	Vx 371	Vy 371	Vz 371
Mean	0.0007	5.52E-05	-0.8134
Variance	0.0018	1.80E-05	3.12815
Standard Deviation	0.0432	0.0042	1.76865

Table 6: Accelerations at joint No. (371)

Joint acc.	$a_{x\ 371}$	$a_{y\ 371}$	$a_{z\ 371}$
Mean	-3.2E-5	-3.8E-5	0.0003
Variance	0.04300	0.0029	4.074
Standard Deviation	0.20738	0.0545	2.0186

Table 7: Normal force, shear force, and bending moment at C.B No. (1722)

Column straining actions	N.F	S.F	B.M
Mean	-24.040	-1.029	0.495
Variance	6.941	0.0107	0.452
Standard Deviation	2.634	0.1037	0.672

6. REFERENCES

[1] Wilson E L. Static and dynamic analysis of structures. Computers and Structures, Inc., Berkeley, California, USA,2006.

[2] Buchholdt H A. An Introduction to Cable Roof Structures. London, UK: Thomas Telford, 1999.

[3] Stefanou G D. Dynamic response of tension cable structures due to wind loads. Computers ,and Structures,1992, 43(2): 365-372.

[4] M.Naguib "optimum shape of convex cable roof beams" Mansoura Engineering Journal (MEJ), Egypt, 1996.

[5] Mohie-Eldin, M. "Static and Dynamic Analysis of Circular Cable Suspended Roofs", M. Sc. Thesis, Mansoura University, Egypt, 2003.

[6] Buchholdt, H. A., "Structural Dynamics for Engineers ", Redwood Books, Great Britain, 1997.

[7] Ghafari Oskoei S A. Analysis of cable roof structure to dynamic loads due to wind and earthquake in frequency domain [Dissertation]. University of Tehran, 2006.

[8] Dynamic Analysis of Cable Roofs under Transient Wind: A Comparison between Time Domain and Frequency Domain Approaches S. Ali Ghafari Oskoei, Ghyslaine McClure, Inghua science and technology, October 2008.

[9] Ghafari Oskoei S A, McClure G, et al. Dynamic analysis of cable roofs under turbulent wind using a frequency domain approach. Journal of Wind Engineering and Industrial Aerodynamics, under review submitted 19/08/2008.

[10] M. Naguib"Natural Frequencies and Modes of Vibrations for Cable Roofs", Mansoura Engineering Journal (MEJ) Vol; .21, No 2, June 1996

7. LIST OF SYMBOLS

The following is a list of the most important symbols that appear in the paper:

L=Length of longitudinal rectangular net.

B=Width of rectangular net.

d=Diameter of cable

J_i=Joint number.

M_i=Member number.

C_{Bi}=Column base joint.

a= Spacing between cable elements

θ_1=Inclination of stayed cable elements with horizontal.

θ_2= Inclination of columns with vertical

δ= Deflection in Z direction.

τ=(sag/span) ratio.

T_{OF}=(Initial tension / Breaking load) for cables (KN).

D.E =Diagonal element.

Ft=Final tension.

N.F=Normal force.

S.F=Shear Force.