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Seismic Time History Analysis for Cable-Stayed Bridge Considering Different Geometrical Configuration For Near Field Earthquakes

Atul K. Desai

Abstract**—**To increase the maximum span of cable-stayed bridges, Uwe Starossek has developed a modified statical system. The basic idea of this new concept is the use of pairs of inclined pylon legs that spread out longitudinally from the foundation base or from the girder level.

Spread-pylon cable-stayed bridge has distinct advantage like reduction of sag of cables and oscillation of cable during earthquake over traditional cable-stayed bridges. Spread-pylon also improves seismic performance of deck during strong ground motion.

Keywords**—**Different geometry of cable stayed bridge, seismic time history analysis, earthquake displacement ratio, response mode shape.

I. INTRODUCTION

THE evolution of the modern cable-staye1d bridges took place almost exclusively in postwar Germany in the early fifties. Since then, it has become increasingly popular in many countries because of its remarkable structural efficiency as well as its aesthetically pleasing appearance. As opposed to the classical suspension bridge, the cable-stays are directly connected to the bridge deck resulting in a much stiffer structure. A large number of closely spaced cable-stays support the bridge deck throughout its length, reducing the required depth and bending stiffness of the longitudinal girder to a minimum, thereby allowing the construction of relatively longer spans. The structural action is simple in concept: the cables carry the deck loads to the towers and from there to the foundation. The primary forces in the structure are tension in the cable-stays and axial compression in the towers and deck; the effect of bending and shear is considered to be secondary. The early designs of modern cable-stayed bridges essentiality consisted of a stiff girder supported by a few cables. The stay-forces were rather large and consequently the anchorage design was excessively complex.

Further development indicated that these problems could be eliminated by increasing the number of stays. The multi-cable arrangement has following advantages:

1. The deck can be erected using a cantilever erection sequence in conjunction with suspension by successive cable-stays.
2. The use of large number of small cables reduces the concentrated forces at the anchorage points in the tower and deck. Moreover, the deck bending moments between the suspension points are reduced
3. A damaged or corroded cable-stay can easily be replaced without over-stressing the bridge structure
4. Excellent seismic stability is obtained as the damping of the system is increased by adding a large number of cables of different lengths with different natural frequencies.

The seismic stability of the pylon is another important consideration. Very few researchers have worked on this yet many of the cable-stayed bridges are in active seismic regions. When the slender deck of relatively flexible long span structure is subjected to seismic excitation, depending upon mass distribution of deck, cable and pylon tend to induce both torsion and flexural oscillations in the bridge deck. Another problem associated with earthquake is that two earthquakes have not similar finger prints. All earthquakes have different peak ground acceleration, different duration and direction. Use of different shapes of pylon creates different length, inclination and plane of the cables, this result into complex behaviour during seismic excitation.

Ali H. M [2], Cai C. S [4] and Soneji B. B [7] have tried damper and isolation mechanism for absorbing seismic excitation, but still the problem of controlling deck oscillation during seismic excitation prevails for long span cable-stayed bridges. In additions to these, cable-stayed bridges exhibit a nonlinear structural response, principally because of geometric nonlinearity of stay-cables and combined bending moment and axial force effect in the deck and towers. As mentioned by Wei X. R [9] for long span, these considerations require relatively sophisticated analysis procedures.

Muller [10] has compared the deformational behavior of bi-stayed bridge and suspension bridge with a span of 1220m. Gimsing [11] has studied the variation of normal force in deck for the self anchored, partially and fully earth-anchored systems. However, the feasibility and behavioral aspects of partially earth-anchored (bi-stayed) system and self-anchored system for long span under seismic excitation is yet to be studied.

Looking to the increased popularity of cable-stayed bridges, it is obvious that there is a need for more comprehensive investigations of analysis and design of these contemporary bridges. The present general trends are two: one towards increasing center span length of cable-stayed bridge and second towards implementation of different aesthetical and functional shapes of pylons. Moreover, in view of the

Atul K. Desai is with the Sardar Vallabhbhai National Institute of Technology, Surat, Gujarat, India (phone: 0919327433390; e-mail: atuldesai61@gmail.com).

literature survey, the lack of research is found particularly in 3-D earthquake analysis of alternate bridge systems considering different shapes of pylon, under different duration, peak ground acceleration and pulse shape of seismic time histories. Brownjohn J. M.W [3] proposed curved cable stayed bridge, Uwe S. [8] proposed Y- shaped pylon, Karbhari V. M [6] FRP encased concrete bridge and Chang C. C. [5] Ambient vibration for long span are recent innovations.

In this work, the problem proposed for investigation is mainly divided into following tasks:

1. Study of mathematical model for three-dimensional dynamic analysis and verification of standard soft-ware. Commercially available software SAP: 2000, which was used by Abolhassan [1] is used for the analysis.
2. Preparation of three-dimensional geometrical computer models using longitudinally spread pylons (Y – Shaped pylons) Vs conventional A-shaped pylons for straight cable-stayed bridge.

The effects of these configurations of pylon are further studied with:

1. Different inclinations of wings of Y – Shaped pylons.
2. Different anchoring system of back-stays i.e. self-anchored and partially earth anchored (bi-stayed) systems.
3. With and without intermediate side-span supports.
4. With and without dampers at pylon supports of deck.
5. The detail dynamic analysis is to be carried out further for:
    a. Establishing relationship between Peak Ground Acceleration (P.G.A.) and Earthquake Displacement Ratio (E.D.R.).
    b. Preparation of three-dimensional geometrical computer models using transversally inclined pylons for curved cable-stayed bridge. The effects of these configurations of pylon are further studied with:
        i. Different vertical inclinations of pylons.
        ii. Different duration of past-earthquakes i.e. long, short and medium duration having different P.G.A.
        iii. With and without back-stays.

The dynamic effects are studied with the modal participation ratio.

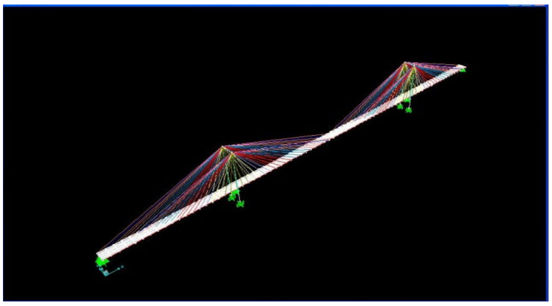

Fig. 1 Straight Cable-Stayed Bridge (A-shaped pylons) Self-Anchored Type

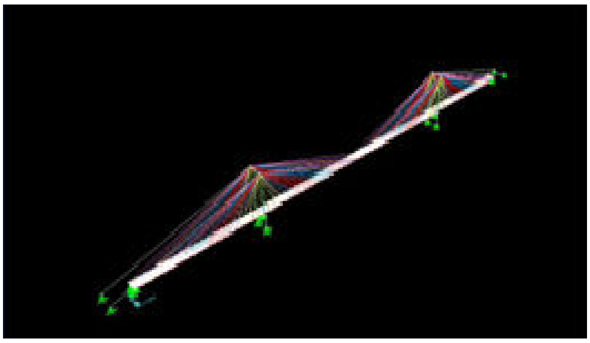

Fig. 2 Bi-Stayed Type (Partially earth-anchored)

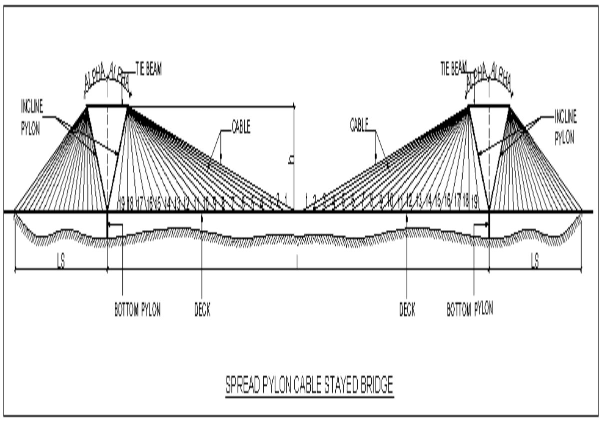

Fig. 3 Y-Shaped pylons for Cable-stayed Bridge (Spread Pylon

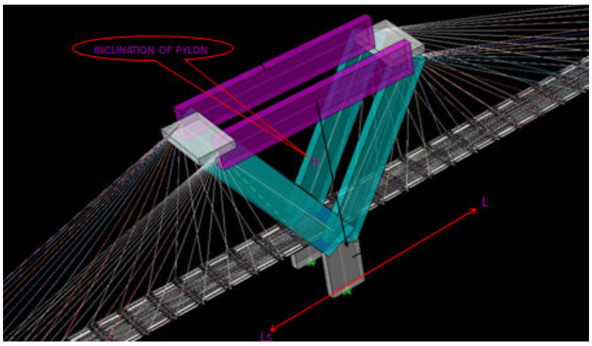

Fig. 4 Y-Shaped pylons for Cable-stayed Bridge (Spread Pylon)

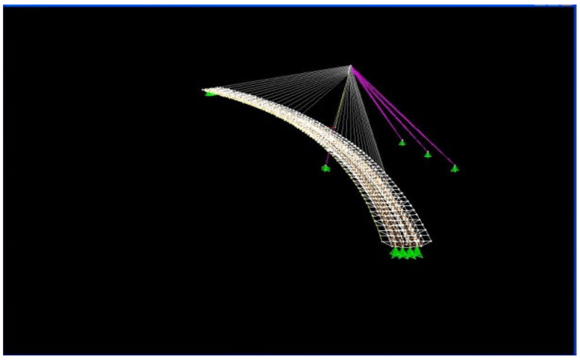

Fig. 5 Curved cable stayed Bridge with Back-Stays

II. CURVED CABLE STAYED BRIDGE WITH INCLINED PYLON 3D FEM MODEL

The provision of dampers for reducing the dynamic oscillations is also made at the pylon support to deck. The review of literature in brief is presented here under the following two topics, in addition to usual development of Cable-stayed Bridges and Static Analysis topics:

Dynamic Analysis of Cable-stayed Bridges.
Seismic Analysis of Cable-stayed Bridges.

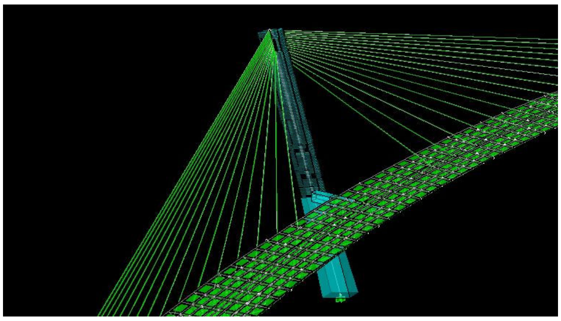

Fig. 6 3D FEM model of curved cable-stayed bridge

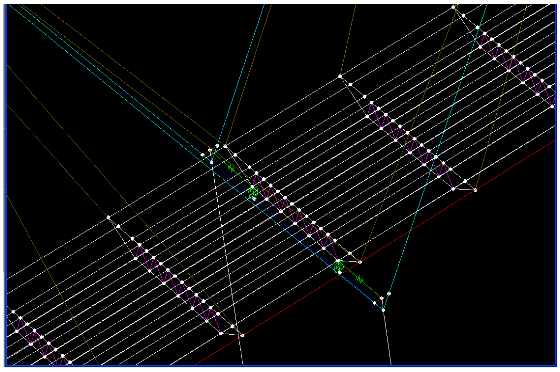

Fig. 7 Dampers and link elements

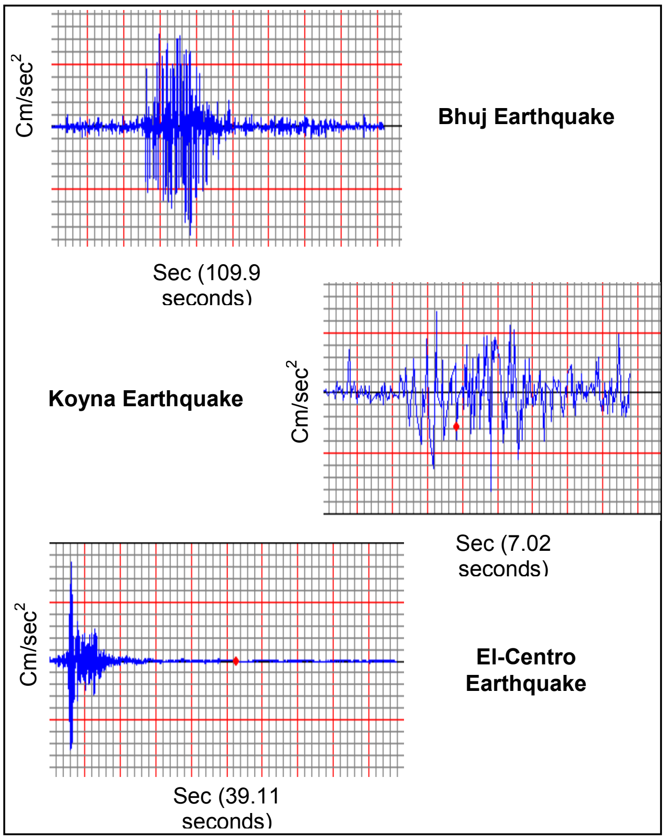

Fig. 8 Time history of earthquake used

TABLE I
TIME HISTORY & DURATION OF EARTHQUAKE USED

Name	Magnitude	Duration of Earthquake (sec)	PGA Value (cm/sec^2)	Time for PGA (sec)
Bhuj Earthquake (2001, Gujarat, INDIA)	7.7	109.995	104	46.005
Koyna Earthquake (1967,Maharashtra,INDIA)	6.5	7.02	54.1	2.606
El-Centro Earthquake (1940, California, USA)	6.7	39.11	678.55	3.16

III. LONGITUDINALLY SPREAD VS. CONVENTIONAL A-SHAPED PYLONS FOR STRAIGHT CABLE- STAYED BRIDGES

A. Effect on Natural Period

There is no significant effect of spread pylon angle for modes higher than eight. Higher the spread angle higher is the natural period for lesser modes.

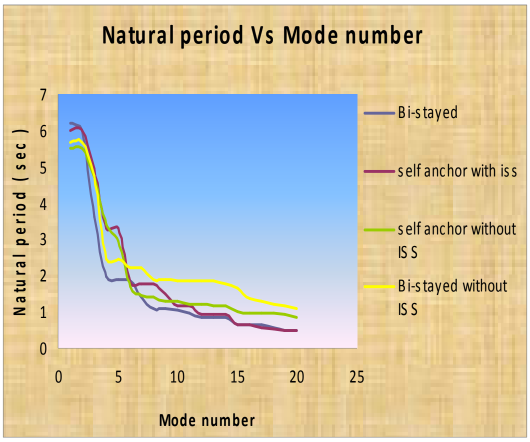

Fig. 9 Effect on Natural period for various configurations

The Intermediate side span supports plays important role in bi-stayed bridge for higher modes than self-anchored bridge. The behavior of bi-stayed & self-anchored bridge with intermediate supports is similar for modes higher than ten.

There is no significant effect of spread pylon angle for modes higher than eight. Higher the spread angle higher is the natural period for lesser modes.

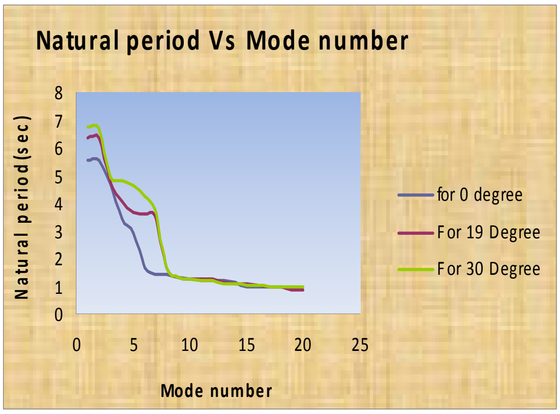

Fig. 10 Effect on Natural period for various angles

B. Effect on Mode Shapes

Twisting of pylon is self-anchored Bridge is observed having intermediate Side Span Supports. Severe vertical bending of deck is observed in self-anchored (without ISSS) and 00 spread pylon bridges. Thus the total behavior can be changed at higher modes due to provision of intermediate side Span Supports.

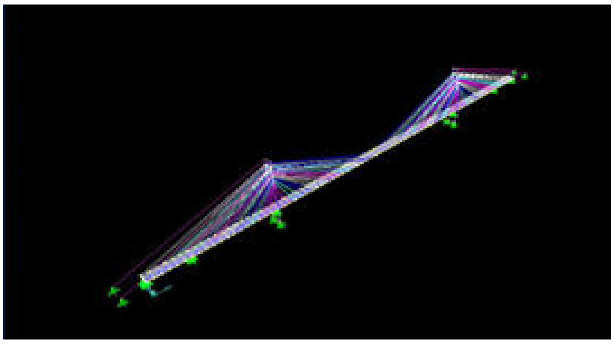

Fig. 11 Straight cable –stayed bridge

C. Stress Condition of Cables for Different Seismic Time Histories

Very large variation of cable stress is observed during different earthquake time histories. For maximum cable forces, axial stress was workout. HYSD wires are used having permissible tensile stress of 1800N/mm^2. According to IS: 1893, permissible stress can be increased by 33% for seismic design.

TABLE II
CABLE STRESS FOR DIFFERENT SEISMIC TIME HISTORIES

Sr. No.	Types of Cable-stayed Bridge	Maximum Axial Stress in Cable due to Earthquake			Permissible stress of cable with 33% higher yield stress (N/mm^2)
		Koyna (N/mm^2)	El-Centro (N/mm^2)	Bhuj (N/mm^2)	
1	Self Anchored with ISSS	7.33	27.95	6.99	2394.00
2	Self Anchored without ISSS	185.65	1364.00	475.00	2394.00
3	Bi-stayed bridge with ISSS	1.88	0.53	5.97	2394.00
4	Bi-stayed bridge without ISSS	95.28	944.04	322.92	2394.00
5	00 Spread angle Pylon	185.65	1364.00	475.00	2394.00
6	190 Spread angle Pylon	518.42	2221.8	2129.20	2394.00
7	300 Spread angle Pylon	592.48	2218.09	462.87	2394.00

Table shows maximum axial stress for different types of bridge systems during long, medium and short duration time histories. All values are well below the maximum permissible stress. Bi-stayed bridge with intermediate side span support shows very less cable stress due to all the three time histories as compared to other pylon configurations.

IV. EARTHQUAKE-DISPLACEMENT RATIO (EDR) FOR VARIOUS CABLE-STAYED BRIDGES

The "Earthquake Displacement Ratio" is proposed here which is a ratio of maximum dynamic (seismic) vertical or lateral displacement to the maximum static displacement at the centre of the main span of the bridges. These both displacements must be measured at the same point. Earthquake displacement ratio can be evaluated as a seismic damage index.

TABLE III
E.D.R. FOR DIFFERENT CABLE-STAYED BRIDGES A-SHAPED PYLON

E.D.R. FOR DIFFERENT BRIDGE

A-Shaped Pylon Bridge (Vertical Direction)

Type of Bridge	Static Deck Displacement (cm)	Bhuj Earthquake (Long Duration)		Koyna Earthquake (Short Duration)		El-Centro (Medium Duration)	
		Seismic Deck Displacement (cm)	E.D.R.	Seismic Deck Displacement (cm)	E.D.R.	Seismic Deck Displacement (cm)	E.D.R.
Self anchored with ISSS	66.247	52.93	0.798	15.613	0.235	182.82	2.75
Self anchored without ISSS	80.41	111.21	1.383	30.55	0.3799	250.94	3.12
Bi-stayed With ISSS	120.38	68.33	0.567	17.72	0.147	523.00	4.34
Bi-stayed without ISSS	62.419	100.46	1.609	24.49	0.392	244.98	3.92

TABLE IV
E.D.R. FOR DIFFERENT CABLE-STAYED BRIDGES SPREAD PYLON

Spread Pylon Bridge (Vertical Direction)

Type of Bridge	Static Deck Displacement (cm)	Bhuj Earthquake (Long Duration)		Koyna Earthquake (Short Duration)		El-Centro (Medium Duration)	
		Seismic Deck Displacement (cm)	E.D.R.	Seismic Deck Displacement (cm)	E.D.R.	Seismic Deck Displacement (cm)	E.D.R.
00 Spread Angle	80.41	111.21	1.383	30.55	0.3799	250.94	3.12
190 Spread Angle	70.04	97.89	1.397	30.099	0.4297	243.02	3.469
300 Spread Angle	68.07	94.45	1.387	26.33	0.3868	245.16	3.601

TABLE V
E.D.R. FOR DIFFERENT CABLE-STAYED BRIDGES A-SHAPED PYLON

A-Shaped Pylon Bridge (Lateral Direction)

Type of Bridge	Static Deck Displacement (cm)	Bhuj Earthquake (Long Duration)		Koyna Earthquake (Short Duration)		El-Centro (Medium Duration)	
		Seismic Deck Displacement (cm)	E.D.R.	Seismic Deck Displacement (cm)	E.D.R.	Seismic Deck Displacement (cm)	E.D.R.
Self anchored with ISSS	0.263	113.05	429.8	64.99	247.12	485.8	1847
Self anchored without ISSS	0.303	158.00	520.0	60.88	200.36	421.31	1386.61
Bi-stayed With ISSS	0.471	188.55	400.31	63.40	134.62	566.2	1202.12
Bi-stayed without ISSS	0.257	118.84	461.69	62.52	242.89	393.22	1527.66

TABLE VI
E.D.R. FOR DIFFERENT CABLE-STAYED BRIDGES SPREAD PYLON

Spread Pylon Bridge (Lateral Direction)

Type of Bridge	Static Deck Displacement (cm)	Bhuj Earthquake (Long Duration)		Koyna Earthquake (Short Duration)		El-Centro (Medium Duration)	
		Seismic Deck Displacement (cm)	E.D.R.	Seismic Deck Displacement (cm)	E.D.R.	Seismic Deck Displacement (cm)	E.D.R.
00 Spread Angle	0.303	158.00	520.00	60.88	200.36	421.31	1386.61
190 Spread Angle	0.217	171.48	790.2	60.27	277.74	383.80	1768.66
300 Spread Angle	0.2506	153.60	612.9	61.27	244.49	405.79	1619.27

The following observations are made:

1. Intermediate side span support has considerable effect on EDR. It reduces EDR up to 50%.
2. Koyna (short duration) earthquake leads to less EDR means dynamic effect is less. EI-Centro (Medium duration) earthquake leads to more EDR means dynamic effect is more.
3. Spread angle has no effect on EDR, but looking to only the displacement 300 spread angle pylon bridges has least static and dynamic displacement.
4. EDR in lateral direction is very much higher than in vertical direction.

V. VERTICALLY INCLINED PYLONS FOR CURVED CABLE-STAYED BRIDGES

A. Effect On Static Modal Load Participation Ratios

As the inclination of pylon increases the static model load participation ratio goes on decreasing. The percentage decrease is very low up to 1% only. Thus effect is very low.

B. Effect On Dynamic Modal Load Participation Ratio

The dynamic modal load participation ratio is being affected considerably in vertical direction due to increase of inclination of pylon. In longitudinal direction, the dynamic modal load participation ratio is highest for 75.250 pylon inclination.

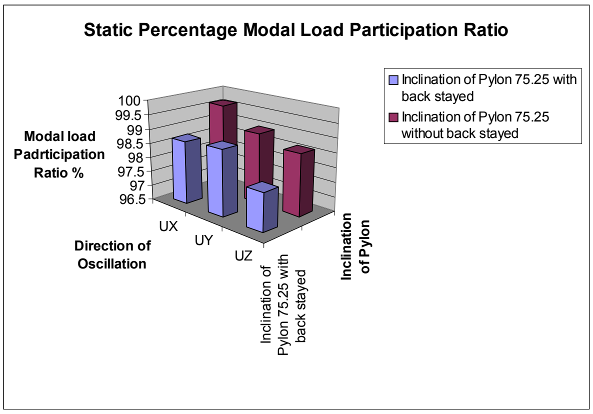

Fig. 12 Static percentage modal participation ratio

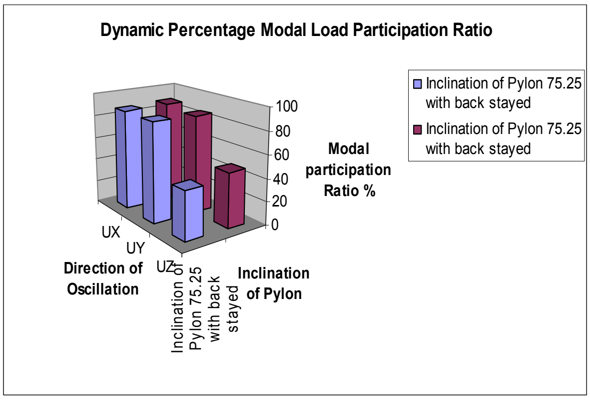

Fig. 13 Dynamic percentage modal participation ratio

C. Effect On Mode Shapes

Back-stays play important role in curved cable-stayed bridge. In initial five modes, lateral sway as well as vertical bending of deck is found due to non-provision of back-stays. It leads to torsion mode of deck during 8th mode. The deformation of deck becomes severe in all the three directions during 17th mode. Thus the deck oscillation is mainly controlled by the back-stays.

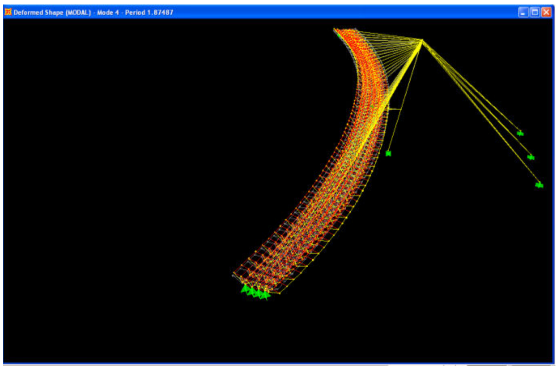

Fig. 14 Mode 4 of curved cable-stayed bridge with back-stays (inclination of pylon 72.250)

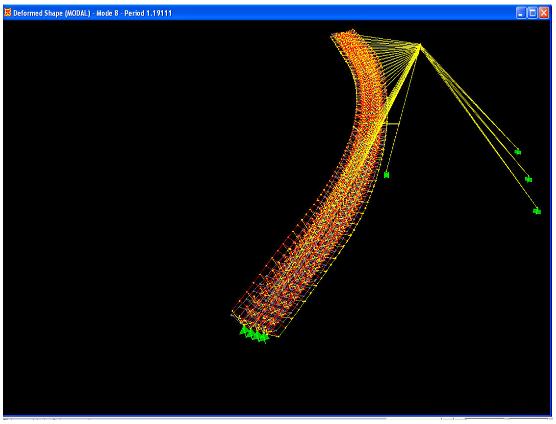

Fig. 15 Mode 5 of curved cable-stayed bridge with back-stays (inclination of pylon 72.250)

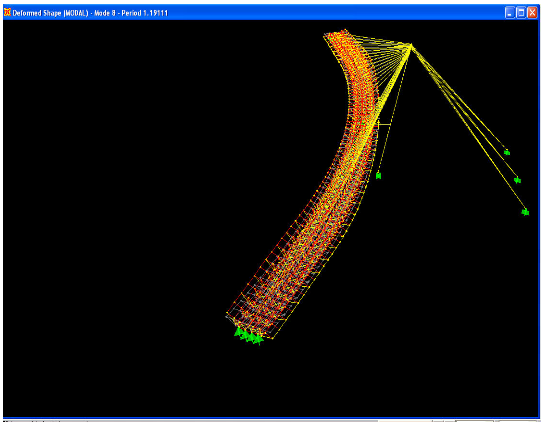

Fig. 16 Mode 8 of curved cable-stayed bridge with back-stays (inclination of pylon 72.250)

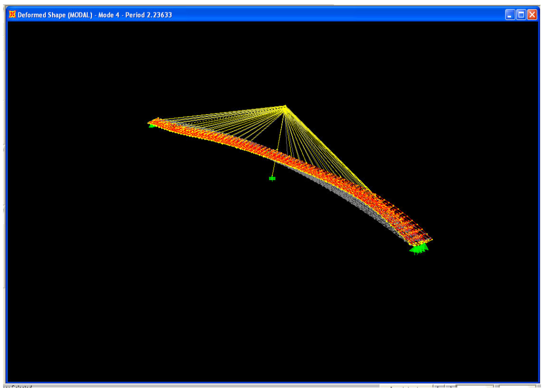

Fig. 17 Mode 4 of curved cable-stayed bridge without back-stays (inclination of pylon 72.250)

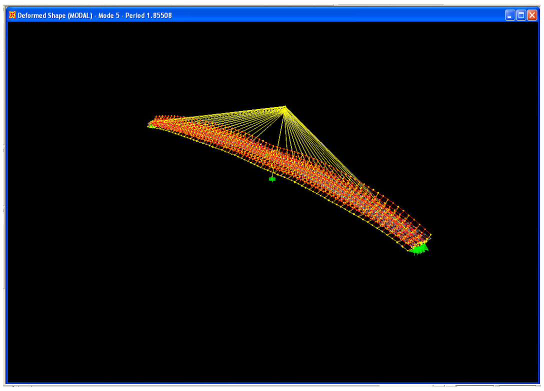

Fig. 18 Mode 5 of curved cable-stayed bridge without back-stays (inclination of pylon 72.250)

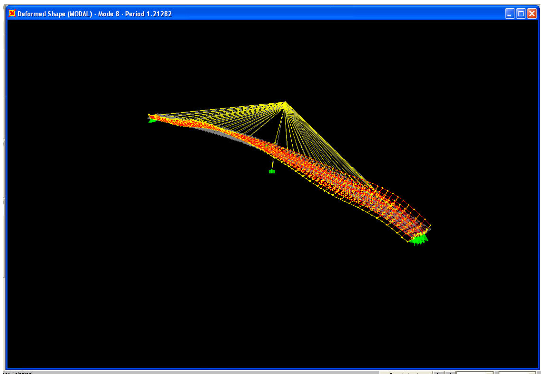

Fig. 19 Mode 8 of curved cable-stayed bridge without back-stays (inclination of pylon 72.250)

From this study following conclusions are drawn:

1. The first five modes are the major contributory modes. It is necessary to include at least five modes in the analysis in order to obtain the most fundamental movements. It might be sufficient to consider only these modes in a preliminary analysis.
2. For pylon and deck, additional responses from the higher modes could be significant. A total of twenty modes should be incorporated, if an accurate result is required.
3. For long span cable-stayed bridge, Option of Bi-stayed Bridge with intermediate side span gives lowest bending moment of pylon base, for all three seismic time histories.
4. For controlling the central deck deflection for long span cable-stayed bridge, is inclination of cables key factor for seismic performance of cable stayed bridge. Spread pylon bridge with spread angle ∝ = 300 and Bi-stayed bridge with intermediate side span supports options gives lowest central deck deflection.
5. Bi-stayed cable-stayed bridge has reduced cable forces and bending moment of pylon as compared to conventional cable-stayed bridge.
6. Back-stay in curved cable-stayed bridge reduces pylon base bending moment, deflection of deck and fundamental time period of the bridge.
7. The seismic isolation using damper in the cable-stayed bridge helps to reduce the acceleration response and the base shear response substantially in all types of cable-stayed bridges.
8. "Delay" is observed in peak occurrence time in all response quantities for all different time histories. This "Delay" mainly depends upon the bridge structural configuration i.e. shape of the pylon, cable arrangement and deck arrangement.
9. Vertical excitation which is usually ignored in the seismic analysis of buildings but drastically affect the response of cable-stayed bridge.
10. For long span straight cable-stayed bridge, there is some relationship observed between Peak Ground Acceleration (PGA) and Earthquake Displacement Ratio (EDR) for vertical and lateral directions.
    a. Spread pylon cable-stayed bridge (vertical direction). EDR = 1.180 loge (P.G.A.) – 4.196
    b. Spread pylon cable-stayed bridge (lateral direction). EDR = 542 loge (P.G.A.) – 1912
    c. Straight cable-stayed bridge (vertical direction). EDR = 1.048 loge (P.G.A.) – 3.669
    d. Straight cable-stayed bridge (lateral direction). EDR = 467.4 loge (P.G.A.) – 1659
11. This ratio helps to arrive at the dynamic displacement in comparison to static displacement for any peak ground acceleration. Spread pylon bridge has lesser EDR which shows the added stiffness than the conventional A-shaped pylon cable-stayed bridges.

    The study conducted here is useful to arrive at the best pylon shape and cable-anchoring system (self-anchored or bi-stayed) from dynamic point of view for any type of earthquake (viz- short, medium or long duration).

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