A COMPARATIVE STUDY OF PROGRESSIVE COLLAPSE OF CABLE-STAYED BRIDGE USING SAP 2000

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Abstract
Progressive collapse is a major threat causes the more demolitions of structure and leads to the loss and damage of lives. The main causes of the progressive collapse are earthquake and severe wind which results in gradual and successive failure of number of elements of the structure. The present paper includes linear static analytical procedures. For linear static analysis loading is considered as per the Post Tensioning Institute (2001) recommendations and GSA (2003) progressive collapse guidelines. Alternate path (AP) method is used for progressive collapse analysis of the cable-stayed bridge. The cable-stayed bridges are modeled in SAP 2000 with various cable arrangements and studied the deflection of girder under static loading condition. also studied the axial forces developed in the cables under the cable loss. The results are taken with respect to the various cable arrangement and number of cable lost.
Index terms: Progressive failure, Structural failures, Collapse, Linear analysis, Cable-stayed bridges

1. INTRODUCTION

Cable-stayed and suspension bridges are the largest structure designed as a platform for carrying people and vehicles. Both the bridges are held up by the cables, their modes of operations are very different. Cable-stayed bridges are less expensive quicker to build and has grater stiffness. These bridges are subjected to static and dynamic loads causes progressive failure. Progressive collapse is a major threat in such bridges. It is dynamic event caused by localised structural injuries, disturbing the initial load equilibrium causes vibrations in the structure so it either gets new equilibrium or collapses.

R. Das and A. D. Pandey [1] have demonstrated modelling and analysis of a typical cable-stayed bridges through a nonlinear dynamic procedure response of the structural model for multiple types of critical cables loss is discussed. It concludes that the possibility of progressive failure is decreased when the failed cables were closer to pylon. Uwe starossek has proposed the typology and progression collapse of structures different types of collapse are pancake type, zipper type, Domino type, section type, instability type, mixed type [2]. Amir fatollahzadeh has analysed the progressive collapse of cable-stayed bridges due to cable failure during the earthquakes i.e. Tabas, Loma Prieta and Bam. The research reveals that only two elements are capable of causing consequent damage. To avoid the destruction six base isolations are used below the structure[3]. Jian-Gua CAI and Yi-Xiang Xu have done the comparison of the linear static, nonlinear static, linear dynamic and non-linear dynamic procedure for progression collapse analysis of cable-stayed bridge. It concludes that the dynamic amplification factor of 2 is good for the static analysis procedure [4].
The cable-stayed bridges have three types according to the cable arrangement system i.e. Harp, Fan and Radial. In this paper, the analysis of these three bridges with various type of pylons against the progressive collapse is done.

2. OBJECTIVE OF STUDY

- To study the effect of linear static loading on cable-stayed bridge with various cable arrangement.

- To compare the axial cable forces and the deflection of girders under the progressive collapse mechanism.
- To find out the most stable cable arrangement against the progressive collapse.

3. GEOMETRY OF CABLE-STAYED BRIDGE

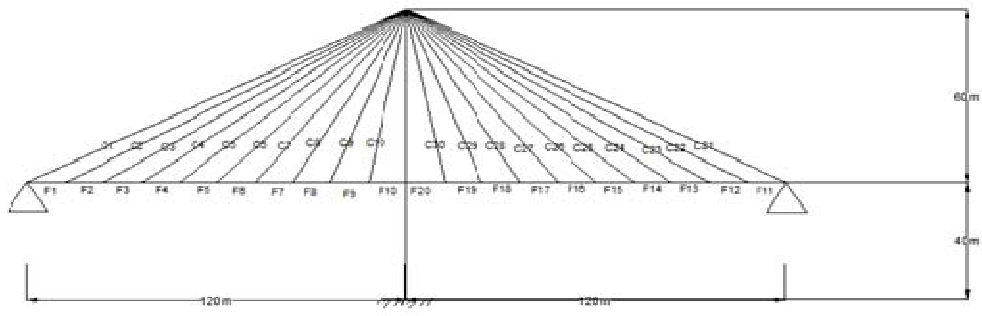


Fig.3.1 Typical Geometry of Cable-stayed Bridge

As the bridge with two pylons, three spans i.e. two end spans and one middle span is quite difficult to analyse. So here bridge with two end spans with single pylon is finalized. The schematic diagram of the cable-stayed bridge is as shown in Fig.3.1. The bridge has one single tower of 100 m high and two equal end spans of 120 m. The girder is assumed to be hinged with the tower at the height of 40 m above from base and simply supported at both ends. It is also supported by 40 stay cables, 20 on each side. Cables have the spacing of 12m. The cross section of the tower is 5m x 5m. The pylon is an H-type pylon, having the angle of 26.6^0. The box girder is considered with a thickness of 0.5 m, side thickness is 0.3m. The width of the girder is 26.5m which consists of 6 lanes of 3.75m each and two pedestrian tracks of 2m each. The depth of the girder is 3m.

4. MATERIAL PROPERTIES

Following tables shows the materials properties used for the bridge.

Table.I reinforced pylon and box girder properties

Grade of the concrete	M40
Modulus of Elasticity	3.16×10^7 N/mm^2
Possion's ratio	0.2
Weight density	24.99KN/m^3

Table. II Cable and Tendons properties

Ultimate Strength	1860 KN/m^2
Modulus of Elasticity	2.0×10^8 N/mm^2
Possion's ratio	0.3
Weight density	76.98 N/m^3

5. MODELING BY USING SAP2000

SAP2000 is the easiest most productive solution for structural analysis and design needs. It can analyse simple 2D frames as well as the complex 3D structures. It is the most suitable finite element tool for modelling and progressive collapse analysis of cable-stayed bridges.

The three types of cable arrangements i.e. Harp, Fan and Radial has modelled by using SAP2000 as shown in following figures.

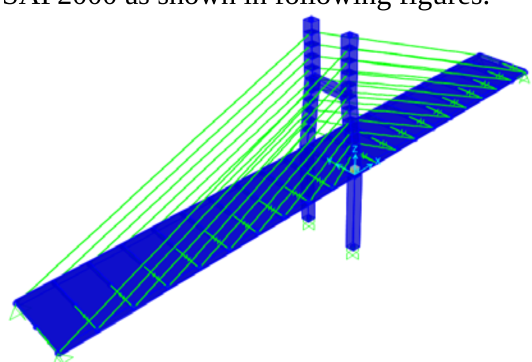


Fig. 5.1 Harp Cable arrangement

Fig.5.1.shows the FE model of harp cable arrangement. In harp cable arrangement system the cables are connected to two tower at different heights and parallel to each other. Though it seems more pleasing aesthetically, it

can cause bending moments in the tower and the whole pattern tends to less stable.

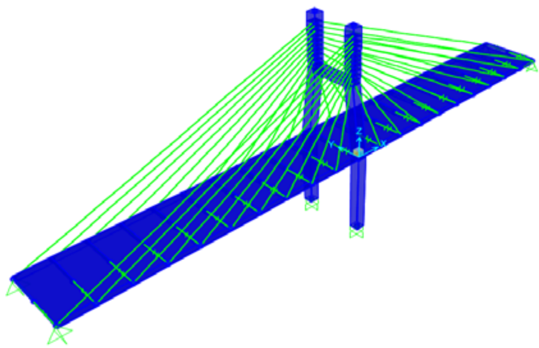


Fig. 5.2 Fan Cable arrangement

Fig.5.2. shows the FE model of the fan cable arrangement. In fan type cable arrangement, the cables are connected with a steeper slope. This system gives most effective support of vertical deke force and leads to smallest cable diameter.

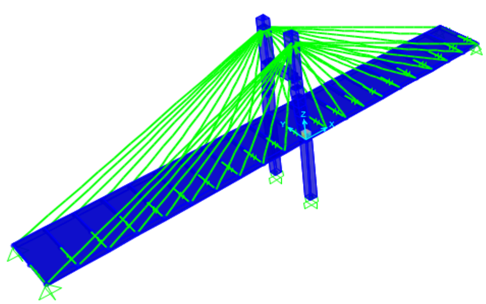


Fig. 5.3 Radial Cable arrangement

Fig.5.3 shows the FE model of radial cable arrangement. In radial cable arrangement, all the cables are anchored at the common point at the tower. In this good detail are difficult to be achieved. The concentration of anchorages can cause structural difficulties**.**

Similarly the models for the various cable arrangements with A- type pylon and Y- type pylon are done in SAP2000**.**

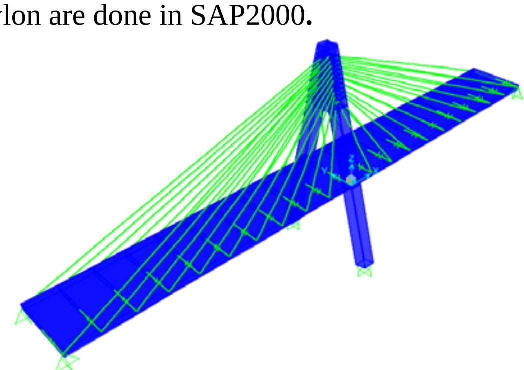


Fig 5.4 Fan Cable arrangement with A-type pylon

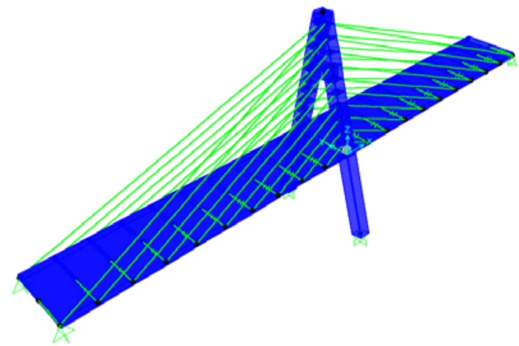


Fig 5.6 Harp Cable arrangement with A-type pylon

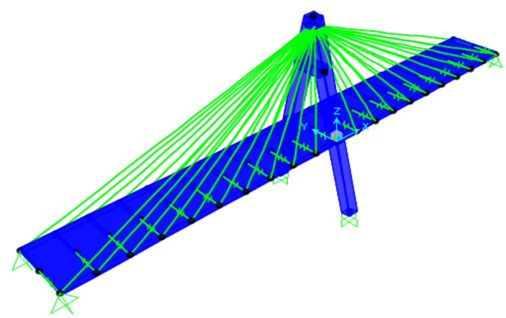


Fig 5.7 Radial Cable arrangement with A-type pylon

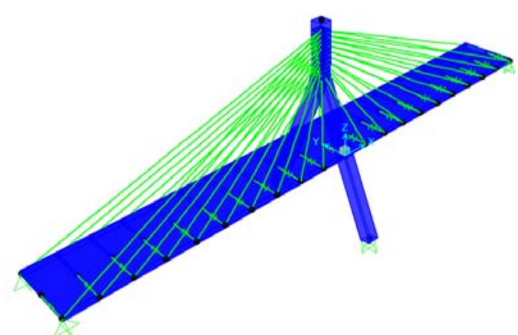


Fig 5.8 Harp Cable arrangement with Y-type pylon

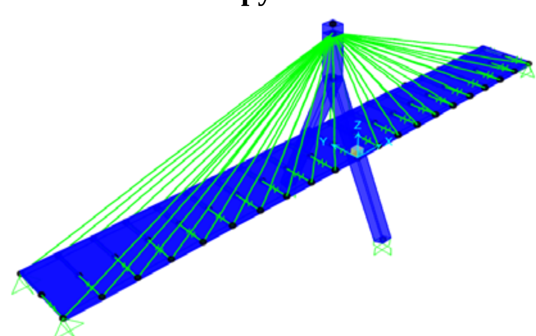


Fig 5.9 Radial Cable arrangement with Y-type pylon

6. LOADING CONDITION

According to the Post-Tensioning Institute (2001) recommendations and GSA (2003) progressive collapse guidelines, following loading combination is used while evaluating the progressive collapse

Load=1.0*DL+0.75*LL+1.0*PS+1.0*CL… (1)

Where DL - Dead load
LL - Live load
PS - Prestressing Force
CL- Equivalent Force due to cable failure

6.1 Prestress Force Calculations for Box Girder

By considering the weight density of concrete 25kN/m^3

DL= Self Weight of Box Girder
=304 KN/m

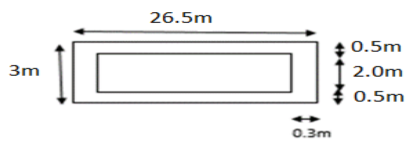


Fig.6.1.1 Box Girder

Moment of inertia of Box Girder,

I= $(BD^3/12) – (bd^3/12)$…………………..(2)
=21.69 m^4

Where:
B- Outer width of box girder
D- Outer depth of box girder
b- Inner width of box girder
d- Inner depth of box girder
Section of modulus

Z= (I/y) ………………………………….(3)
=14.46 m^3

Where:
y- Distance of Extreme fibre from the neutral axis

For Presetting Forces,
(P/A) ± (P.e/z) = M/z……………………..(4)
Where:
P- Prestressing force
A - Cross section area of Box Girder
M - Maximum bending moment
e - Eccentricity of prestressing force
Considering the parabolic prestressing and eccentricity is taken as 10%

e = 10% of 3m= 0.3m

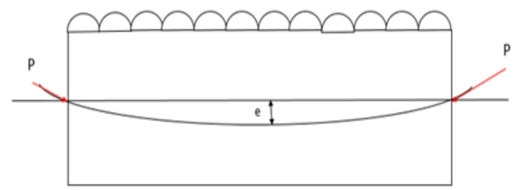


Fig.6.1.2 Typical Diagram of Prestress Force

Maximum Bending Moment,

M = $(wl^2)/8$…………………………..(5)

Where:
W-Dead load+ pedestrian load
l- Length of segment of Box Girder

For Live Load,
Pedestrian Live Load
For effective span > 30m

p = [(13.3) + (400/L)] * [(17-b) / (142.6)] KPa……..…(6)

Where,
b = Width of footpath
L = Length of effective span

p = 1.3625 KN/m^2
= 1.3625 * 26.5
p = 36.1065 KN/m

As per IRC specifications,
For Heavy Loading, a load of 1.93 tons/m
Length of each traffic lane is considered.
1.93 * 9.81 = 18.933 KN/m^2
Total Heavy Loading for 6 Lanes
= 6 * 18.933
= 113.599 KN/m

Total Live Load = Pedestrian Load + Traffic Load
= 149.706 KN/m
Total Load, w = 453.706 KN/m

Max. Bending Moment,
= (wl^2) / 8………………From Eq. 5
= 8166.708 KN-m

Prestressing force P,
(P/A) ± (P.e/z) = M/z………………(7)
i) (P/A) + (P.e/z) = M/z,
P = 5467.37 KN.

ii) (P/A) - (P.e/z) = M/z

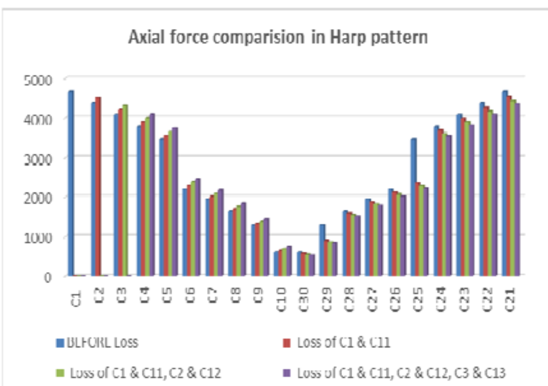
P = 9231.62 KN.

7.RESULTS AND DISCUSSION

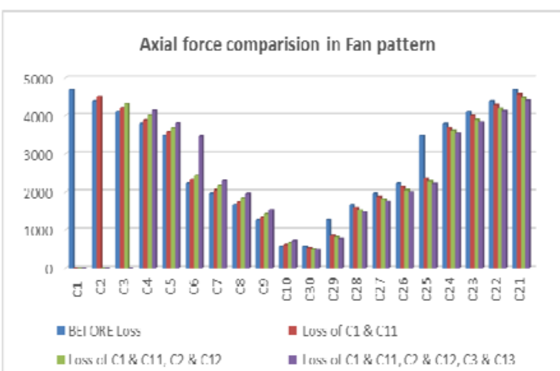
The various models of cable-stayed bridge has drawn by using SAP2000. These models then analysed by using the above mentioned loading condition. The progressive collapse analysis is done by using Alternate Path method i.e. by removing the critical cables. The analysis is done by removing the cables successively and checking their effects on the axial cable forces and the deflections of the girder.

7.1 Axial Cable Force Comparison

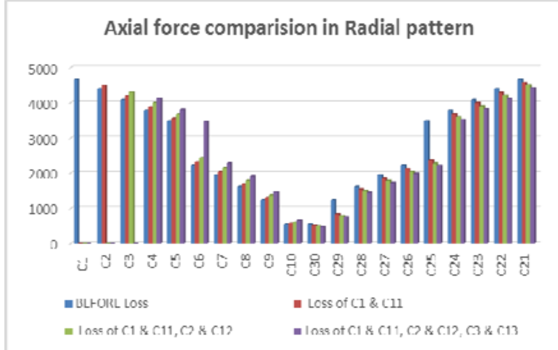
The harp, fan and radial models are analyzed by removing cables C1 &C11, also successively the by removing C2 & C12, C3 & C13. Then the axial forces are compared after the cable losses. The comparison is shown in graph 7.1.1, graph 7.1.2, graph 7.1.3.



GRAPH 7.1.1 Axial Force Comparision In Harp Pattern with H-type pylon

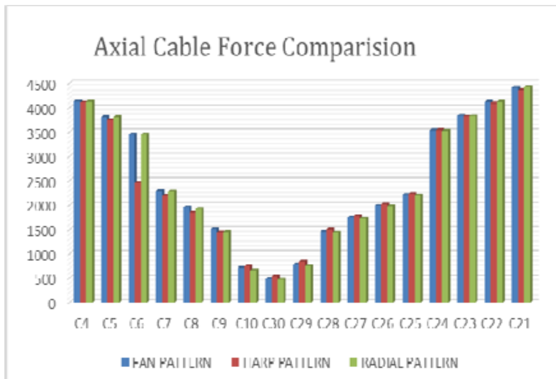


GRAPH 7.1.2 Axial Force Comparision In Fan Pattern with H-type pylon



GRAPH 7.1.3 Axial Force Comparision In Radial Pattern with H-type pylon

The graph 7.1.4 shows the axial cable force comparison of the Harp, Fan and Radial pattern bridges after the loss of 6 cables.



GRAPH 7.1.4 Axial Force Comparision In Various Cable Patterns with H-type pylon

The tables III, IV and V shows the percentage increase in the axial cable forces in FAN, HARP AND RADIAL cable arrangements with H-type pylon, A-type of pylon and Y- type pylon respectively. Maximum percentage increase occurred in FAN pattern with H- type pylon.

Table. III Percentage increase in cable forces after cable loss with H-type pylon

CABLE TYPE	FAN	HARP	RADIAL
C1 & C11 loss	7.6323%	5.5040%	6.2146%
C1 & C11, C2 & C12 loss	8.3883%	6.4715%	6.8910%
C1 & C11, C2 & C12, C3 & C13 loss	9.0497%	7.2696%	7.6178%

Table. IV Percentage increase in cable forces after cable loss with A-type pylon

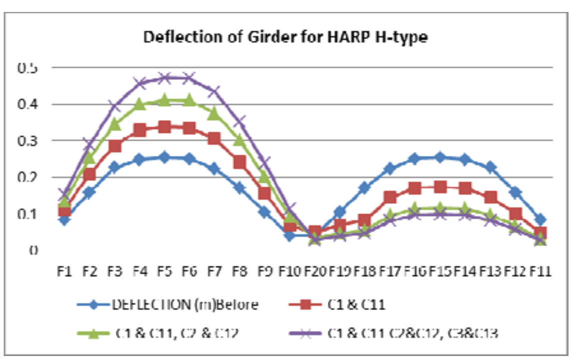
CABLE TYPE	FAN	HARP	RADIAL
C1 & C11 loss	4.0085%	2.0414%	2.9167%
C1 & C11, C2 & C12 loss	4.2693%	2.272%	3.4674%
C1 & C11, C2 & C12, C3 & C13 loss	4.5349%	2.4119%	4.0942%

Table. V Percentage increase in cable forces after cable loss with Y-type pylon

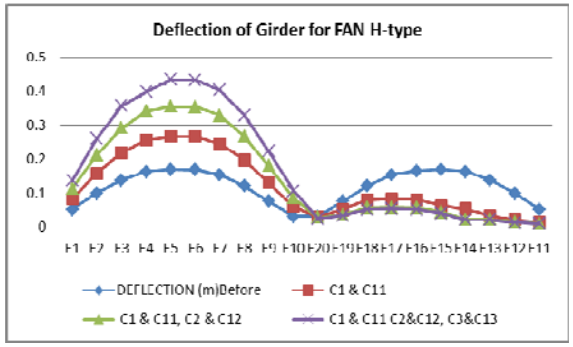
CABLE TYPE	FAN	RADIAL
C1 & C11 loss	3.5478%	3.2415%
C1 & C11, C2 & C12 loss	3.7657%	3.4767%
C1 & C11, C2 & C12, C3 & C13 loss	3.9833%	3.7456%

7.2 Comparison Of Deflection Of Girder

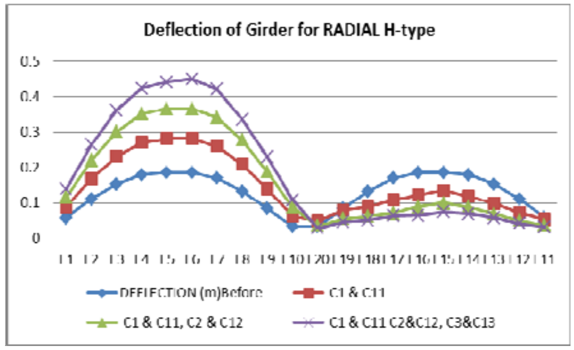
After the successive cable loss, the deflection of the girder starts increasing. The deflection is more occured in between frames F4 and F6. The deflection of girder for the Harp, Fan and Radial patterns was shown in graph 7.2.1, graph 7.2.2, graph 7.2.3 respectively. Highest vertical deflection obtained in Harp pattern with H type pylon is 0.4714m.



Graph 7.2.1 Deflection of Girder for HARP H-type Bridge

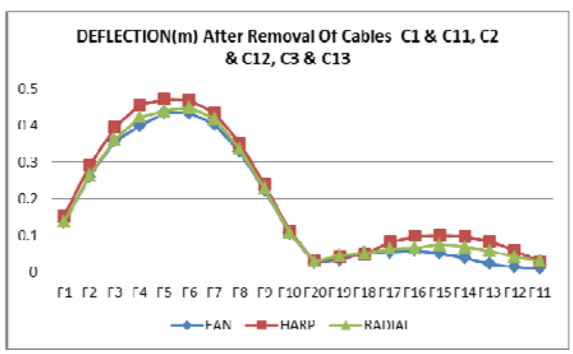


Graph 7.2.2 Deflection of Girder for FAN H-type Bridge

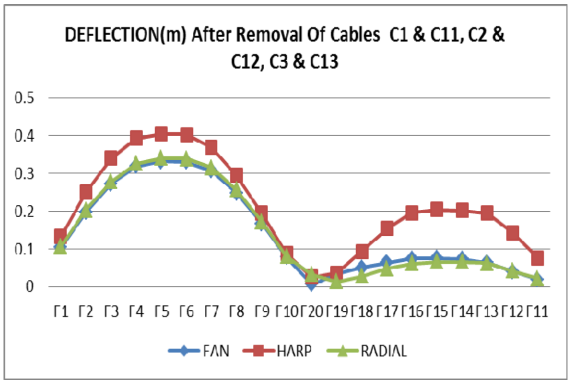


Graph 7.2.3 Deflection of Girder for RADIAL H-type Bridge

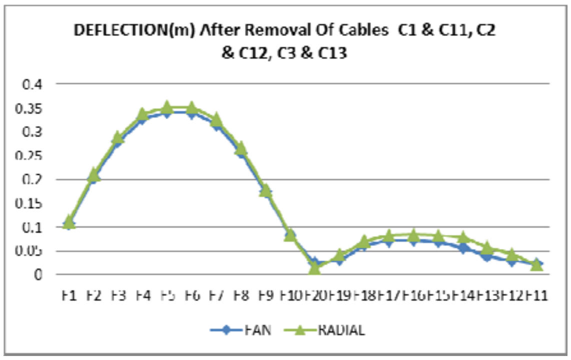
The comparison in deflection of girders in the three patterns with H-type pylon, A-type pylon and Y-type pylon were shown in graph 7.2.4, graph 7.2.5, graph 7.2.6 respectively after the loss of of C1 and C11, C2 and C12, C3 and C13 cables. It is observed that maximum deflection is 0.4714m in HARP pattern with H type pylon. Minimum deflection is 0.3317m observed in FAN pattern with A-type pylon.



Graph 7.2.4 Comparison of Deflection of girder for various cable arrangements with cable loss of C1 and C11, C2 and C12, C3 and C13 H-type pylon



Graph 7.2.5 Comparison of Deflection of girder for various cable arrangements with cable loss of C1 and C11, C2 and C12, C3 and C13 A-type pylon



Graph 7.2.6 Comparison of Deflection of girder for various cable arrangements with cable loss of C1 and C11, C2 and C12, C3 and C13 Y-type pylon

8. CONCLUSION

From the above results and discussion, it is concluded that

- The deflection of girder at the other side of the pylon cannot be considered as negligible under the loss of outside cables. The vertical deflection at the other side of the pylon decreases as the location of the lost cable approaches the pylon.
- The cables adjacent to the ruptured cable do not reach the tension yield and the maximum nodal vertical displacement decreases when the lost cables are near the pylon.
- When only Cable arrangement is considered the maximum deflection is obtained in HARP cable arrangement whereas the FAN cable arrangement gives least deflection.
- In case of cable arrangement with pylon geometry, the FAN cable arrangement with A-type pylon gives best results against progressive collapse. HARP cable arrangement with H-type pylon gives worst results progressive collapse.
- The axial forces in the cables start increasing in the adjacent of the lost cables up to the location of the pylon, after the pylon, the axial forces in cables starts decreasing.
- The cables which are in the vicinity of the pylon have very less axial forces, so they have very less possibility of cable loss.
- FAN cable arrangement with A-type Pylon can be considered as the best possible combination against the progressive collapse.

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