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NUMERICAL EVALUATION OF THE DYNAMIC CHARACTERISTICS OF SUSPENSION BRIDGE WITH MR DAMPER

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Abstract – Suspension bridge is a bridge in which the deck slab of the bridge is hung below the suspension cables on vertical suspenders. Usually, the bridge is designed to connect the communities which are separated by a great distance by topographical barriers such as river, mountains, etc. In a suspended deck bridge, cables suspended via towers hold up the road deck and the weight are transferred by the cables to the towers, which in turn transfer the weight to the ground. Bridge failure, which is generally associated with serious economic and life losses, is defined as the incapacity of a constructed bridge or its components to perform as specified in the design and construction requirements. Principal causes can be divided into internal causes and external causes or natural factors and human factors. Design error, construction mistakes, hydraulic, collision, and overload are the top 5 leading causes of bridge failures, resulting in more than 70% of the bridge failures. Causes of bridge failures are closely related to regional economy, structural type, type of use, material type, and service age. Recently the suspension bridge in Morbi, Gujarat about 230m long connects Darbargarh palace and Lakhdhirji Engineering College separated by Machchu river is collapsed, causing death of at least 135 people and injuries to more than 180 others. This is due to overloading, loss of strength and the occurrence of resonance.

In this paper, a suspension bridge is modelled and analyses using ANSYS. Static &Modal analysis of the structure have various configurations were done. MRF is a type of smart fluid in a carrier fluid, usually a type of oil and it can be used as a damper because its force transmission capacity can be controlled by an electro-magnet.

***Key Words*:** *Suspension Bridge, Bridge Failure, Suspension Bridge in Morbi, Modelling and Analysis by ANSYS, Magnetorheological Fluid*

1.INTRODUCTION

A suspension bridge is a type of bridge in which the deck is hung by suspension cables on vertical suspenders. The basic structural components of a suspension bridge system include stiffening girders/ trusses, the main suspension cables, main towers, and the anchorages for the cables at each end of the bridge. The main cables are suspended between the towers and are finally connected to the anchorage or bridge itself, and vertical suspenders carry the weight of the deck and the traffic load on it. Like other cable supported bridges, the superstructure of suspension bridges is constructed without false work as the cable erection method is used. The main load carrying member is the main cables, which are tension members made of high strength steel. The whole cross-section of the main cable is highly efficient in carrying the loads and buckling is not problem. Therefore, the deadweight of the bridge structure can be greatly reduced and longer span becomes possible. In addition, the aesthetic appearance of suspension bridges is another advantage in comparison with other types of bridges.

The structural components of a modern suspension bridge include the stiffening girder, the main cable, the main tower, the anchorage, and hanger ropes, etc. The stiffening girder is a deck structure together with a longitudinal stiffening system, which is the longitudinal member that supports and distributes vertical live load. The stiffening girder can be either a separate truss or plate stiffening girders combined with lateral bracing systems, or alternatively be integrated with the deck structure in the form of a shallow box girder with a low drag shape to minimize wind loading. The main cable made of high-strength steel wires supports traffic-carrying stiffening girder by hanger ropes and transfer loads by direct tension forces to towers and anchorages. A main tower is the intermediate vertical structures, which supports main cables at a level determined considering the cable sag and required clearance and transfers the external loads to bridge foundations. An anchorage is generally a massive concrete block, which anchor main cables and act as end supports of a bridge against movement in the horizontal direction. The suspension cables must be anchored at each end of the bridge or sometimes to the bridge itself because all loads applied to the bridge are transformed into a tension in these main cables.

Bridge failure, which is generally associated with serious economic and life losses, is defined as the incapacity of a constructed bridge or its components to perform as specified in the design and construction requirements. Bridge failure causes can be classified into principal causes and specific causes. Principal causes can be divided into internal causes and external causes or natural factors and human factors. Internal causes, which include design error, construction mistake, lack of maintenance, material defect, etc. External causes include natural disasters such as earthquake, flood, fire, and wind, as well as extreme loads such as collision and overload. Natural factors are mainly natural disasters, including earthquake, flood, wind, etc., which are not easy to control and prevent. Human factors are mainly associated with human cognitive limitations, carelessness, mismanagement, etc., containing design error, construction mistake, lack of maintenance, material defect, collision, overload, etc.

The Suspension Bridge, an engineering marvel built at the turn of the century, reflects the progressive and scientific nature of the rulers of Morbi. This was built to give a unique identity to Morbi using the latest technology available in those days, in Europe. The bridge was built in the reign of Waghjee Thakor, who ruled over it from 1879 till 1948. It is 1.25 m wide and spans 233 m on the Machchhu River connecting Darbargadh Palace and Nazarbag Palace now Lakhdhirji Engineering College, the residences of the erstwhile royal family of Morbi State. At that time, there was a limit of fifteen people on the bridge at once, as the narrow structure meant it swayed with any greater weight.

On 30 October 2022, five days after reopening, the bridge collapsed at 6:40 p.m. More than five hundred people were on the bridge at the time of the collapse, far exceeding the official capacity of 125. Security footage of the bridge showed the structure shaking violently and people holding onto cables and fencing on either side of the bridge before the walkway gave way. Images of rescue and recovery operations showed the walkway had divided at its midpoint, with some pieces still hanging from snapped cables. At least 135 people were confirmed dead, and more than 180 were rescued. Many the victims were women, the elderly, and children (39 boys and 16 girls) with the youngest fatality being an 18-month-old baby.

2. Objectives

- To find total deformation and direct stress for suspension bridge, suspension bridge with increased cross section and suspension bridge with MR damper by self-weight analysis
- To find natural frequency and deformation by modal analysis under dead load and combination of dead load & live load for various configurations
- To compare results from analysis of various configurations to adopt better configuration

3. Methodology

4. Modelling

The structure was modelled using SOLIDWORKS, a solid modelling computer-aided design (CAD) and computer –aided engineering (CAE) application published by Dassault Systems. Drafted based on the reference journal, "Challenges and strategies in structural identification of a long span suspension bridge" by Zhang *et al.* The 6th International Workshop on Advanced Smart Materials and Smart Structures Technology. The rendered model was imported onto Ansys for further analysis. The modelled structure is as given below.

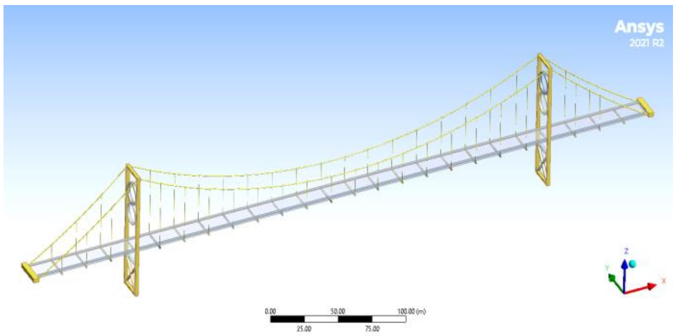

Fig – 1: Modelled structure

Table 1 (a), (b), (c) shows the dimension of the suspension bridge.

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Table -1: (a) Dimension of suspension bridge

ELEMENT	SIZE	SECTION	NUMBER OF ELEMENTS
Base sla b/ Girder	500 X 16 X 1m	Rectangular	1
Anchorage	22 X 4 X 3m	Rectangular	2
Long supporting rail	500X 2 X0.5m	Rectangular	2
Tie beam	20 X 0.6 X 1.2m	Rectangular	24
Main beam	36mm	Circular	2
Suspender cable	23mm	Circular	44

Table -1: (b) Dimension of suspension bridge

Name	Section	Web	Flange
Tower	channel	500 X 50mm	500 X 50mm
		800 X 80mm	800 X 80mm

Table -1: (c) Dimension of suspension bridge

Description	Main span	Anchorage span	Total span
Span (m)	348	80	508

Table 6.2 shows the model description including name adopted and analysis conducted.

Table -2: Description of model

MODEL NAME	DESCRIPTION	ANALYSIS DONE
C1	Normal suspension bridge	
C2	Suspension bridge with increased cross section	
C3	C1 with MR Damper	
C1D	C1 under dead load	Static & Modal
C2D	C2 under dead load	Static & Modal
C3D	C3 under dead load	Static & Modal
C1DL	C1 under combination of dead load & live load	Static & Modal
C2DL	C2 under combination of dead load & live load	Static & Modal
C3DL	C3 under combination of dead load & live load	Static & Modal

5. Analysis of Structure

Analysis of the suspension bridge model is done using ANSYS software under dead load and combination of dead load & live load. For analysis 1D finite element model is developed from the 3D model and static & dynamic analysis are done.

- Analysis on C1 under dead load (C1D)

Static & Dynamic analysis for C1D is performed to find total deformation, direct stress, and natural frequencies. Figure 2 & Figure 3 shows the geometry and loading condition for C1D.

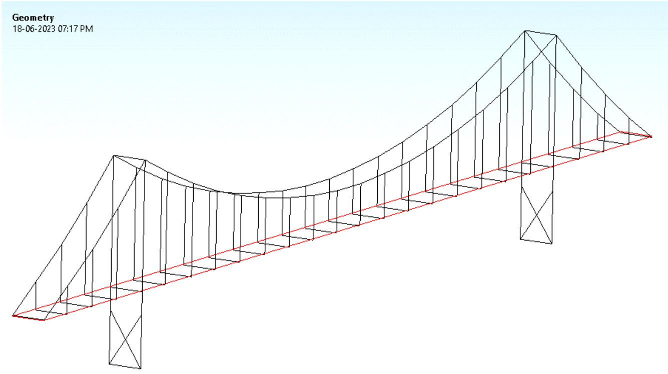

Fig – 2 Geometry for C1D

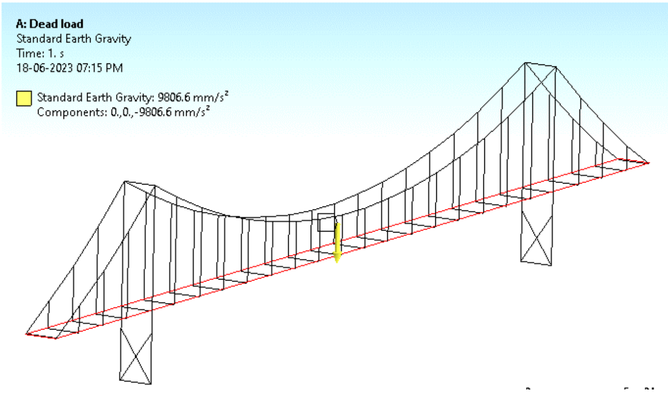

Fig – 3 Loading condition for C1D

Total deformation for C1D is 3.3791mm obtained as maximum and it is shown in figure 4.

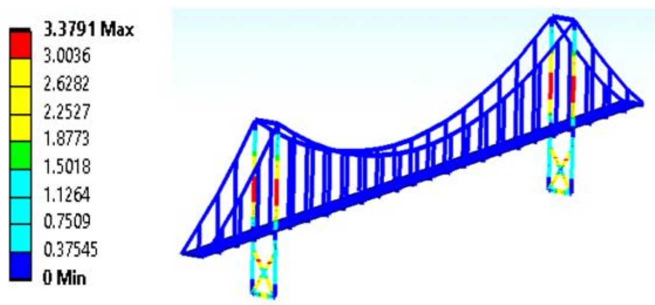

Fig – 4 Total deformation for C1D

Figure 5 shows the direct stress developed under dead load at the joint locations. The maximum compressive direct stress is obtained as 2.0957 MPa and that of maximum tensile stress is obtained as 1.7938 MPa.

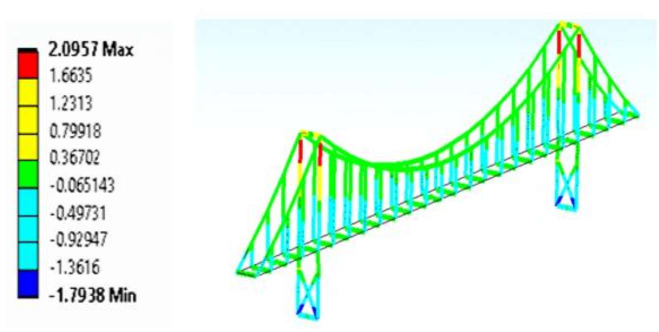

Fig – 5 Direct stresses for C1D

Modal analysis done for C1D to find the natural frequencies of C1 and corresponding deformations of each mode. The frequency range obtained is given in the table 3. The fundamental frequency for C1D is as 0.89189 Hz

Table 3 Natural frequencies for C1D

MODES	FREQUENCY (Hz)
1	0.89189
2	0.89189
3	0.89654
4	0.89654
5	1.07390
6	1.07390

Mode shapes obtained are as follows.

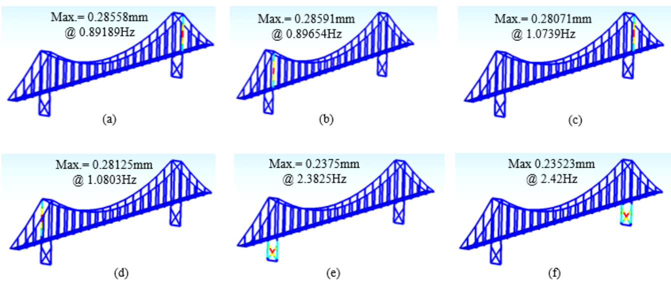

Fig – 6 Total deformation under C1D

- Analysis on c1 under combined dead load & live load (C1DL)

Static & Dynamic analysis for C1DL is done to find total deformation, direct stress, and natural frequencies of the structure. The geometry and boundary conditions are same, but loading condition is not same. Total deformation and direct stress for C1DL is same as that of C1D.

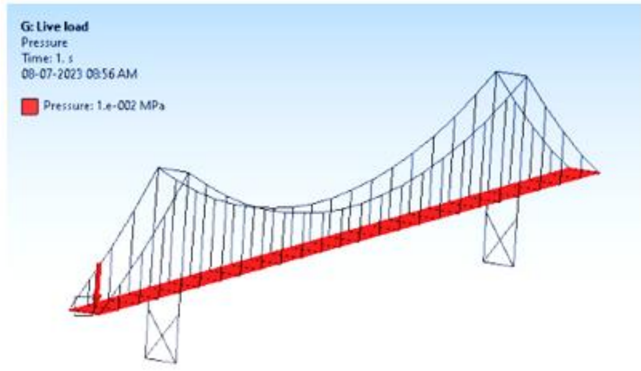

Fig – 7 Live loading condition for C1DL

Modal analysis for C1DL is done to find the natural frequencies of C1 under combined action of dead load & live load and there by the corresponding mode shapes of the structure.

Table 4 Natural frequencies for C1DL

MODES	FREQUENCY (Hz)
1	0.89640
2	0.89640
3	0.90101
4	0.90101
5	1.07840
6	1.07840

The mode shapes obtained are as follows.

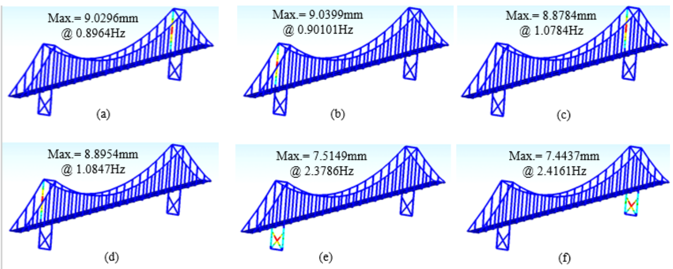

Fig – 7 Total deformation under C1DL

- Analysis on C2 under dead load (C2D)

Static & dynamic analysis for C2D done to find the total deformation, direct stress, and natural frequencies of the structure. The loading and boundary conditions are same as that of C1, geometry is not same (increased cross-section).

Total deformation for C2D is 2.6038mm obtained as maximum. The maximum compressive direct stress is obtained as 1.9326 MPa and that of maximum tensile stress is obtained as 1.7735 MPa.

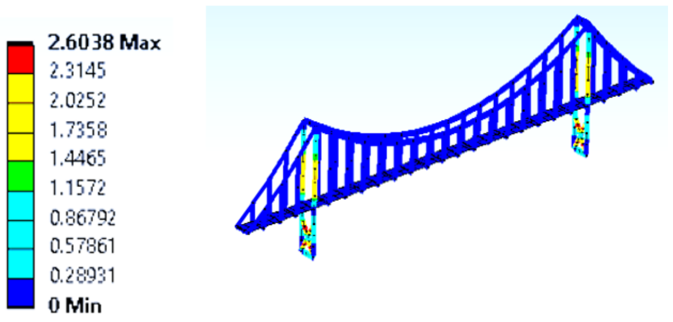

Fig – 8 Total deformation for C2D

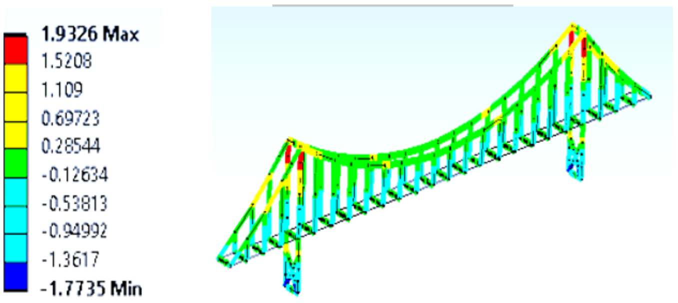

Fig – 9 Direct stresses for C2D

Modal analysis done for C2D to find the natural frequencies of C2 and corresponding deformations of each mode. The fundamental frequency for C2D is as 1.4176 Hz.

Table 5 Natural frequencies for C2D

MODES	FREQUENCY (Hz)
1	1.4176
2	1.4176
3	1.4255
4	1.4255
5	1.4377
6	1.4377

The mode shapes obtained are as follows.

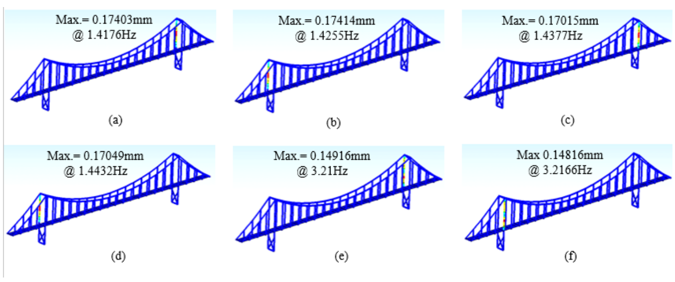

Fig – 10 Total deformation under C2D

- Analysis on C2 under combined dead load & live load (C2DL)

Static & Dynamic analysis for C2DL is done to find total deformation, direct stress, and natural frequencies of the structure. The geometry and boundary conditions are same, but loading condition is not same. Total deformation and direct stress for C2DL is same as that of C2D.

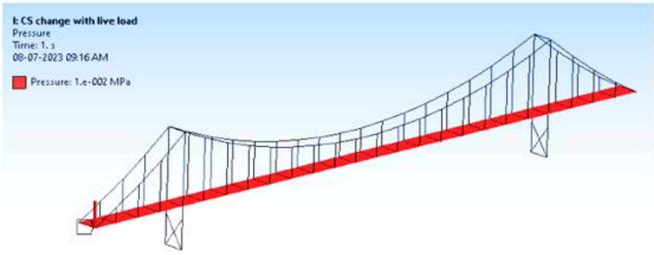

Fig – 11 Live loading for C2DL

Modal analysis for C2DL is done to find the natural frequencies of C2 under combined action of dead load & live load and there by the corresponding mode shapes of the structure.

Table 6 Natural frequencies for C2DL

MODE	FREQUENCY
1	1.4176
2	1.4176
3	1.4255
4	1.4255
5	1.4377
6	1.4377

The mode shapes obtained are as follows.

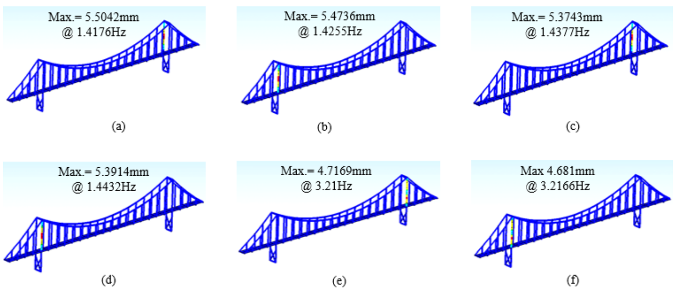

Fig -12 Total deformation under C2DL

- Analysis on C3 under dead load (C3D)

Static & dynamic analysis for C3D done to find the total deformation, direct stress, and natural frequencies of the structure.

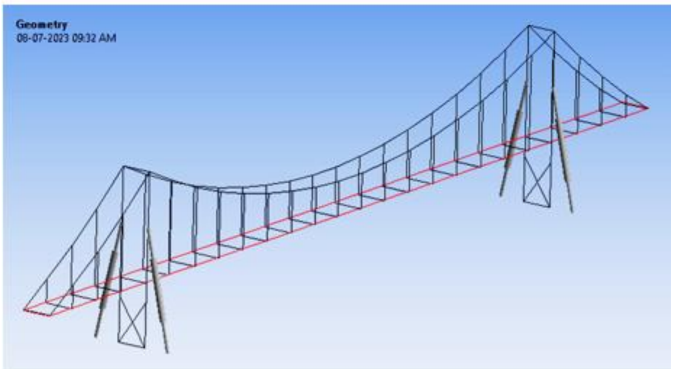

Fig – 13 Geometry for C3D

Loading and boundary conditions are same as that of previous models. The total deformation for C3D is obtained as 2.6038mm. Maximum compressive stress is 0.57228 MPa and that of maximum tensile stress is obtained as 1.7738 MPa.

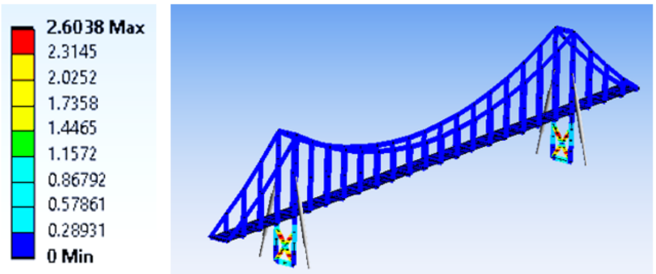

Fig – 14 Total deformation for C3D

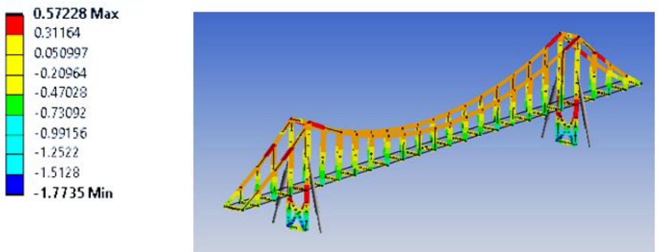

Fig – 15 Direct stress for C3D

Table 7 Natural frequencies for C3D

MODE	FREQUENCY
1	3.3921
2	3.4371
3	3.4562
4	3.5083
5	4.048
6	4.1352

The mode shapes obtained are as follows.

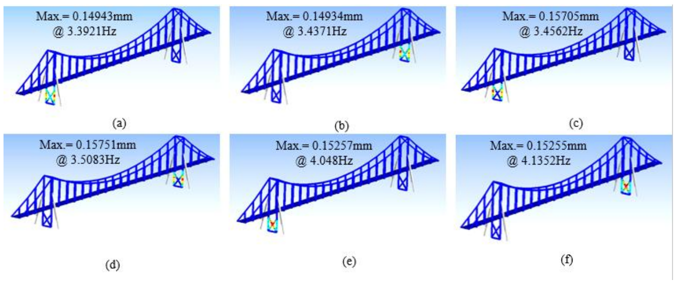

Fig – 16 Total deformation under C3D

- Analysis on C3 under combined dead load & live load (C3DL)

Static & Dynamic analysis for C3DL is done to find total deformation, direct stress, and natural frequencies of the structure. The boundary and loading condition are same as that of previous combined analysis. Total deformation and direct stress for C3DL is same as that of C3D. Modal analysis for C3DL is done to find the natural frequencies of C3 under combined action of dead load & live load and there by the corresponding mode shapes of the structure.

Table 8 Natural frequencies for C3DL

MODE	FREQUENCY
1	3.3921
2	3.4371
3	3.4562
4	3.5083
5	4.048
6	4.1352

The mode shapes obtained are as follows.

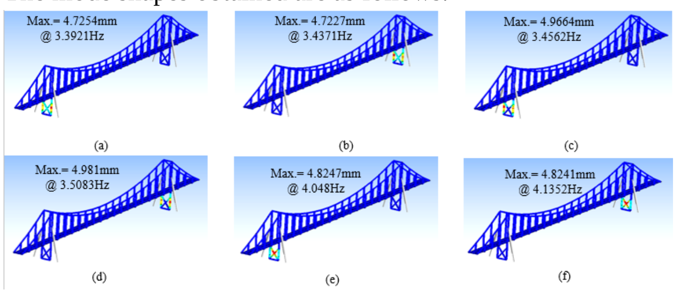

Fig – 17 Total deformation under C3DL

6. Results and Discussion

Table 9 Total deformation & direct stress

MODEL	TOTAL DEFORMATION (mm)	DIRECT STRESS (MPa)
C1	3.3791	2.0957
C2	2.6038	1.9326
C3		0.57228

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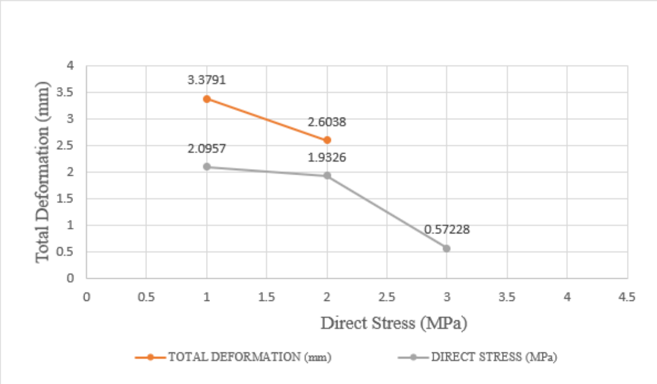

Fig – 18 Plot for total deformation and direct stress for all configurations

Table 10 Comparison of natural frequencies under dead load

MODE	C1D	C2D		C3D	
	Frequency	Frequency	% increase	Frequency	% increase
1	0.89189	1.4176	37.08	3.3921	73.71
2	0.89189	1.4176	37.08	3.4371	74.05
3	0.89654	1.4255	37.10	3.4562	74.05
4	0.89654	1.4255	37.10	3.5083	74.45
5	1.07390	1.4377	25.30	4.048	73.47
6	1.07390	1.4377	25.30	4.1352	74.03
7	1.08030	1.4432	25.14	6.2299	82.65
8	1.08030	1.4432	25.14	6.2552	82.72
9	2.38250	3.2100	25.77	6.3068	62.22
10	2.42000	3.2100	24.61	6.3068	61.62

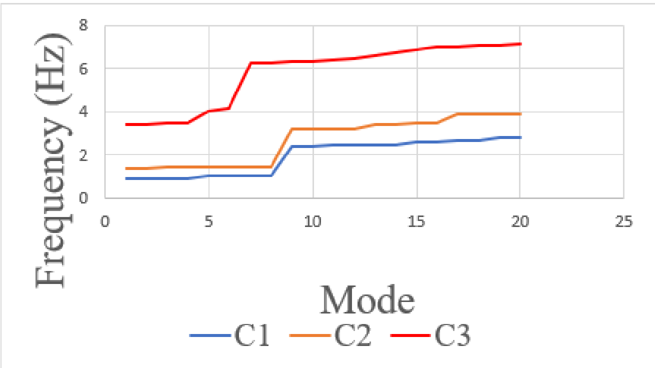

Fig – 19 Plot of frequency with respect to each mode for all configurations under dead load

Table 11 Comparison of natural frequencies under combination of dead load & live load

MODE	C1DL	C2DL		C3DL	
	Frequency	Frequency	% increase	Frequency	% increase
1	0.89640	1.4176	36.76	3.3921	73.57
2	0.89640	1.4176	36.76	3.4371	73.91
3	0.90101	1.4255	36.79	3.4562	73.93
4	0.90101	1.4255	36.79	3.5083	74.31
5	1.07840	1.4377	24.99	4.048	73.35
6	1.07840	1.4377	24.99	4.1352	73.91
7	1.08470	1.4432	24.84	6.2299	73.76
8	1.08470	1.4432	24.84	6.2552	82.65
9	2.37860	3.2100	25.90	6.3068	62.28
10	2.41610	3.2100	24.73	6.3068	61.69

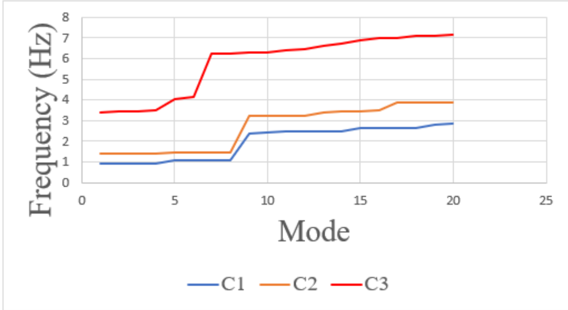

Fig – 20 Plot of frequency with respect to each mode for all configurations under combined dead load and live load

Table 12 Comparison of total deformation under modal analysis with dead load

MODE	C1D	C2D	C3D
	Total Deformation (mm)	Total Deformation (mm)	Total Deformation (mm)
1	0.28558	0.17403	0.14943
2	0.28558	0.17403	0.14934
3	0.28591	0.17414	0.15705
4	0.28591	0.17414	0.15751
5	0.28071	0.17015	0.15257
6	0.28071	0.17015	0.15255

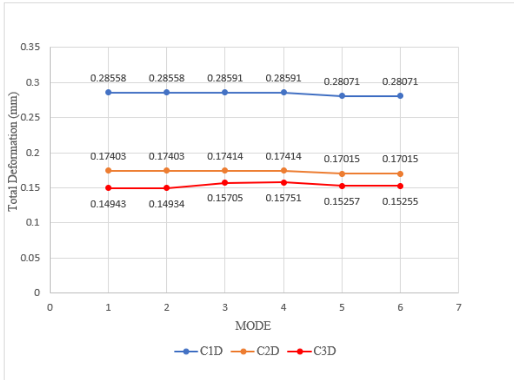

Fig – 21 Plot of deformation with respect each mode under dead load

Table 13 Comparison of total deformation under modal analysis with combination of dead load & live load

MODE	C1DL	C2DL	C3DL
	Total Deformation (mm)	Total Deformation (mm)	Total Deformation (mm)
1	9.0298	5.5042	4.7254
2	9.0298	5.5042	4.7227
3	9.0399	5.4736	4.9664
4	9.0399	5.4736	4.9810
5	8.8784	5.3743	4.8247
6	8.8784	5.3743	4.8241

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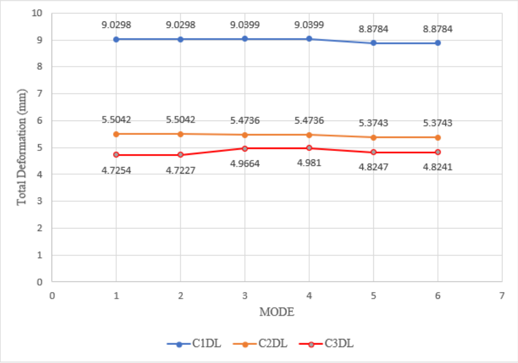

Fig – 22 Plot of deformation with respect each mode under combiined dead load & live load

3. CONCLUSIONS

Suspension bridge of span 508m is modelled in SOLIDWORKS and analysed the FE model by ANSYS software.Analysis for C1, C2, & C3 under dead load and combination of dead load & live loadis done to find efficientand economical way for mitigate the failure of the suspension bridge, for this analysis done to shift the natural frequency of the structure to an extented natural frequency. Total deformation and direct stress under static analysis are determined for all configurations. By modal analysis natural natural frequencies and total deformations of the structure subjected to dead load and combination of dead load and live load are determined.

- Total deformation of C1D is 3.3791mm, C2D and C3D is 2.6038mm
- Percentage decrease in total deformation under dead load from C1 to both C2 & C3 is about 22.94%
- The average total deformation under modal analysis of C1D is 0.2656mm, C2D is 0.1543mm, and C3D is 0.1716mm
- The percentage decrease in total deformation under modal analysis done for dead load only is 42% from C1 to C2 and 35.39% from C1 to C3
- The average total deformation under modal analysis of C1DL is 7.5029 mm, C2DL is 4.875 mm, and C3DL is 5.428 mm
- The percentage decrease in total deformation under modal analysis done for combination of dead load & live load is 35% from C1 to C2 and 28% from C1 to C3
- Average percentage increase in natural frequency from C1D to C2D is about 29.96% and 73.29% from C1D to C3D
- Average percentage increase in natural frequency from C1DL to C2DL is 29.73% and 72.336% from C1DL to C3DL
- Natural frequency of the structure can extended to a higher mode by the application of MR damper

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