Finite Element Analysis of Railway Bridge Piers using Mathematical and Computational Platform

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Abstract— Most of the sub-structures of new railway river bridges in INDIA are built with solid mass concrete gravity piers and abutments. These piers do not have steel reinforcement to bear the load as it does not subject to any tensile stress under regular type of loading. Safety of these piers is of major concern during high magnitude earthquake as frequent occurrence of such earthquakes is observed in India in recent times. This study aims to assess the vulnerability of the solid gravity bridge piers which forms the important component of railway bridges as the load transfer between substructure and superstructure takes through them. In the present study seven existing piers from the state of MADHYA PRADESH are evaluated using free vibration analysis and nonlinear static (pushover) analysis. Free-vibration analysis of the bridge pier shows that the mass participation of fundamental mode is always below 50%. Also, the cumulative mass participation for first six modes is found to be less than 80% for the entire selected bridge pier. This indicates the significant contribution of higher modes.
Key words: Bridges, Piers, Concrete, Mathematics, Modes of Vibration, ABAQUS

I. Introduction

Indian Railway has spent huge amount of money in last five years for doubling the railway lines in order to enhance capacity and generate returns. A number of new rail bridges have come up due to this project. Superstructure of most of these steel bridges is built using railway standard design.

Fig. 1: Typical mass concrete solid gravity bridge piers [1]

However, the sub-structure of these bridges is designed individually considering the site conditions.

A survey on these new bridges in the state of Madhya Pradesh revealed that most of the sub-structures of these bridges are built with solid mass concrete gravity piers and abutments supported by either pile foundations or well foundations. Figure 1.1 shows a typical mass concrete solid gravity bridge pier constructed by Indian railways.

A. *Types of Piers*

1) Wall type Pier
2) Capped Pile Pier
3) Tee type (Hammerhead) Pier
4) Cap and Column Pier
5) Multiple Columns (No cap)
6) Non-Redundant Piers

II. Literature Review

Fereydoon Omidinasab et.al [2] works on concrete-filled steel square columns have been simulated under the influence of blast load using ABAQUS software. These responses will be compared for scaled distances based on the distance to source and weight of explosive material.

T.P.Uma maheswari et.al [3] presents the comparison of conventional steel section and FRP (Fiber Reinforced Polymer) tow sheet wrapped steel section, which gives high strength and resists the buckling behavior. The circular hollow steel section is widely used in structural and non-structural elements, on off shower and on shower buildings.

Ammar A. Abdul Rahman et.al [4] shows the analysis of reinforced concrete bridge piers, there is now a common awareness that excessive strength of the concrete is essential and required in the analysis up to failure of the pier. A three dimensional finite element model of the complete typical pier used in Iraqi bridges was developed using the computer software ABAQUS where concrete plasticity damage was incorporated.

V Surovtsev et.al [5] the paper deals with design criteria and analysis of bridge structures in seismic region classified by a magnitude of 8-9 on the MSK-64 scale. The details of efficient structural measures controlling seismic conditions are discussed. The region is classified by a magnitude of 8-9 on the MSK-64 scale.

Olivia Mirza et.al [6] the purpose of this research is to investigate the effect of wheel loading on the interaction between sleepers and railhead in the rail component system for Minnamurra Bridge in Kiama NSW. A finite element model was analyzed for half of the existing bridge to simplify the model and analysis. The bridge was then analyzed to determine the stress distribution and vertical displacement across the sleepers and railhead.

Sumit Pahwa et.al [7] Researchers briefly explain the function of a structure during and after an earthquake usually dictates the methodology employed in the design of the structure. Lifeline structures, such as bridges, are assigned a much higher "importance" factor in the design process since these structures are "essential facilities" necessary for emergency operations subsequent to an earthquake.

Zaman Abbas Kazmi et.al [8] This study demonstrates the structural analysis and design of RCC box type minor bridge using manual approach (i.e. MDM method) and by computational approach (Staad-pro) using IRS - CBC codes. The structural elements (top slab, bottom slab, side wall) were designed to withstand Ultimate Load criteria (maximum bending moment and shear force) due to various loads (Dead Load, Live Load, SIDL, LL surcharge, DL surcharge) and serviceability criteria (Crack width) and a comparative study of the results obtained from the above two approach has been carried out to validate the correctness of the results.

L. Di Sarno et.al [9] the present analytical work, the earthquake response analysis of typical existing bridges for high speed railway was carried out through linear and nonlinear dynamic analyses using refined finite element three-dimensional lumped-plasticity models and multiple component ground motions. The seismic vulnerability of such bridges was assessed through local and global response quantities.

Rupen Goswami et.al [10] the paper presents a review of seismic strength design provisions for reinforced concrete (RC) bridge piers given in Indian codes. In the earlier IRC codes, the seismic design force for bridges was low and the flexibility of the structure was not accounted for in the design force estimate. These deficiencies have been overcome in the Interim IRC: 6-2002 provisions. However, the current Indian codes treat RC piers as gravity load carrying compression members, and no provisions are available for their shear design.

III. ANALYSIS METHODOLOGY

Free vibration response of structures is very important to assess their behavior when subjected to dynamic loading like earthquake and wind. Also, when the structures are subjected to strong earthquake or wind storm, they exhibit inelastic behavior, which cannot be assessed by elastic analysis. A non-linear analysis evaluates the performance of the structures taking into account the post-elastic behavior and predicts the vulnerability of the structure. The present study conducts free vibration analyses and pushover analysis using finite element software ABAQUS.

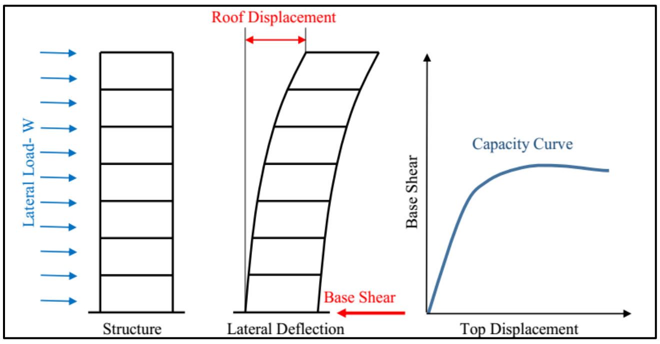

Fig. 2: Schematic representation of Push Over based Analysis [11]

A. *Finite Element Analysis [12]*

The general procedure to solve a problem in FEM is

1) Model the structure with suitable geometry and material properties.
2) Discrete the model into elements by suitably selecting the type of element.
3) Apply the boundary conditions and force vectors.
4) Stiffness matrix for the element will be developed by the software and combined to form global stiffness matrix and force and displacement matrix will be developed.
5) Finally solutions to the problem are obtained.

In Abaqus modeling and analysis includes following three steps: [13]

1) Pre-processing
2) Simulation
3) Post processing

This Chapter presents the analysis methods used in this study i.e., free vibration analysis, pushover analysis and finite element analysis. This chapter also presents about the analysis steps involved in abaqus software.

IV. STRUCTURAL MODELING

S. No.	H (m)	Base Dimension (m)		Top dimensions (m)		Slope (in both dim.)
		Rectangular Portion (L×B)	Diameter of semi-circular portion, (D)	Rectangular Portion (L×B)	Diameter of Semi-circular portion, (D)	
1	7.5	4×2.50	2.50	4×1.5	1.5	1 in 15
2	10.5	4×2.90	2.90	4×1.5	1.5	1 in 15
3	8.4	4×2.62	2.62	4×1.5	1.5	1 in 15
4	11.2	4×3.75	3.75	4×1.5	1.5	1 in 10
5	16.8	4×4.75	4.75	4×2.5	2.5	1 in 15
6	12.	4×3.90	3.90	4×1.5	1.5	1 in 10
7	12.3	4×4.15	4.15	4×2.5	2.5	1 in 15

Table 1 Details of the selected piers [14], [15]

All the railway bridges considered in this study are multi-span bridges and therefore have multiple piers. The piers of one bridge are identical in shapes and sizes except for the length. Length of the piers is varying according to the river profile. One representative pier from each of the seven bridges is considered for analysis. Table 1 presents the dimensions of selected seven piers. Mass concrete of M-25 grade was used to build these piers.

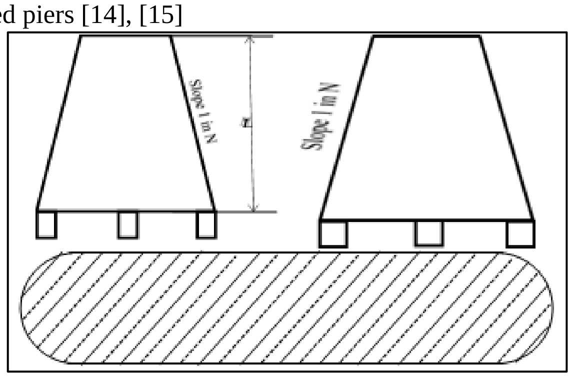

Fig. 3: Plan and Elevations of typical Solid Gravity Pier used in this study [16]

Abaqus element library provides a large variety of elements in modeling different geometries and structures like beam elements, brick elements, truss elements, membrane elements, shell elements, quadrilateral elements. Figure shows the elements available in the abaqus element library.

V. GEOMETRIC MODELLING

First, in the part module, the base section of the pier is drawn and extruded to the height, H of the selected pier with slope 1 in N. [17]. In the property module, then material properties i.e., concrete damaged plasticity model parameters are given and assigned to the section. In the step module, step is created for the type of analysis. In the present study static procedure is selected and geometric non-linearity is taken into account by selecting the Nlgeom-on. In the load module, boundary conditions are created. Figure 4 shows the boundary conditions applied to the structure. The bottom end of the pier is assumed fixed and top is displaced to certain displacement. The displacement is applied in incremental manner.

In the mesh module, the structure is discredited into finite number of elements. The structure is discredited using C3D8R element. It is 3D element with 8 nodes with six degrees of freedom with three translations at each node translations in the nodal x, y, z directions and rotational along nodal x, y, z directions. At other nodes the displacements, stress, strain values are calculated by interpolating with the nodal values.

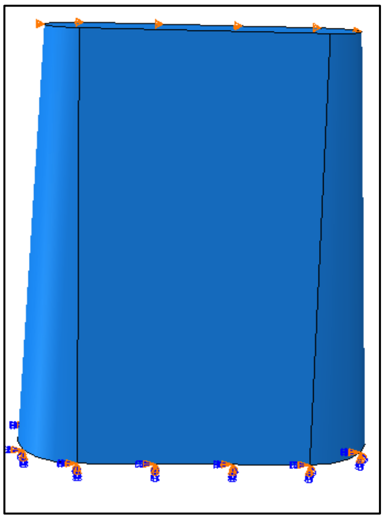

Fig. 4: Pier model in abaqus

K_C	Dilatency angle (ψ)	σ_{bo}/σ_{co}	ϵ	μ
0.67	38^0	1.16	0.1	0.0001

Table 2: CPDM parameters used in this study [18]

This chapter presents details of selected railway bridge piers and describes about the Concrete Damaged Plasticity model which is used for nonlinear material modeling. It describes about the Abaqus simulation process and different types of elements available in the element library and finally about the modeling of the piers selected for the present study.

Material	M25	Young's Modulus = 25×10³MPa Poisons ratio = 0.2	
Concrete Compression		Concrete Compression damage	
Stress (MPa)	Inelastic strain	Damage	Inelastic strain
12.50	0	0	0
16.44	0.00025	0.1024	0.00025
20.00	0.00050	0.1578	0.00050
25.00	0.00150	0.3103	0.00150
23.08	0.00250	0.4482	0.00250
20.00	0.00350	0.5676	0.00350
17.24	0.00450	0.6619	0.00450
15.00	0.00550	0.7333	0.00550
12.82	0.00675	0.7979	0.00675
11.15	0.00800	0.8433	0.00800
Concrete Tension Stiffening		Concrete Tension damage	
Stress (MPa)	Inelastic strain	Damage	Inelastic strain
2.58	0	0	0
2.30	1.21E-05	0.11	1.21E-05
1.99	2.58E-05	0.23	2.58E-05
1.50	0.0002	0.74	0.000193
1.16	0.0003	0.86	0.0003
0.60	0.0006	0.96	0.0006
0.26	0.0008	0.98	0.0008

Table 3: Compression and Tension Stress Strain Values of M25 Concrete

VI. RESULT & ANALYSIS

Modal properties of the selected railway bridge piers were obtained from the linear dynamic modal analysis. Table 4 shows the details of the important modes of the bridge in X direction. The table shows that the percentage of mass participation in the first mode is zero and the cumulative mass participating percentage in the first six modes is between 65%-85%. Hence, the higher mode participation in the response of railway bridge pier is significant unlike in regular buildings where only fundamental mode contribution is vital. Table 5 shows the cumulative mass participation in X and Y directions for first six modes.

Mode No.	Frequency (Hz)	Time period (s)	Cumulative Mass Participation (UX)	Cumulative Mass Participation (UY)
1	15.66	0.0638	0	0.44
2	28.77	0.0347	0.48	0.44
3	46.78	0.0214	0.48	0.44
4	56.56	0.0177	0.48	0.67
5	84.80	0.0118	0.48	0.67
6	85.05	0.0118	0.73	0.67

Table 4: Elastic Modal Properties for Bridge pier

Pier No.	UX	UY
1.	0.73	0.66
2.	0.75	0.71
3.	0.61	0.55
4.	0.80	0.75
5.	0.78	0.71
6.	0.79	0.74
7.	0.78	0.75

Table 5: Cumulative Mass Participation of selected piers in first six modes

Figure 5 to Figure 10 shows the mode shapes of pier# 6 for first six modes. From this figure (also from the Table 4) it can be seen that first two fundamental period reflects the translator motion of the pier in two orthogonal horizontal directions (X- and Y- directions) with significant mass participation although the participating mass ratio in these two modes are below 50% in this case. It can be observed from this figure that torsional mode (Mode# 3) and the rocking mode (Mode# 5) do not contribute anything in the mass participation. Two bending modes (Mode# 4 and Mode# 6) contributes significant amount of mass participation.

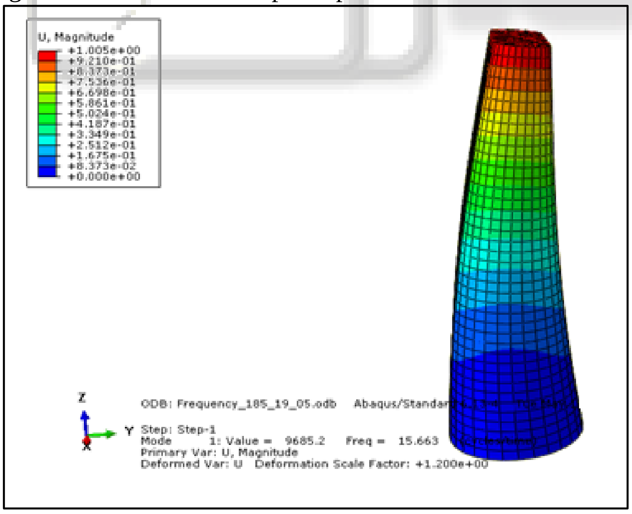

Fig. 5: Mode Shapes 1

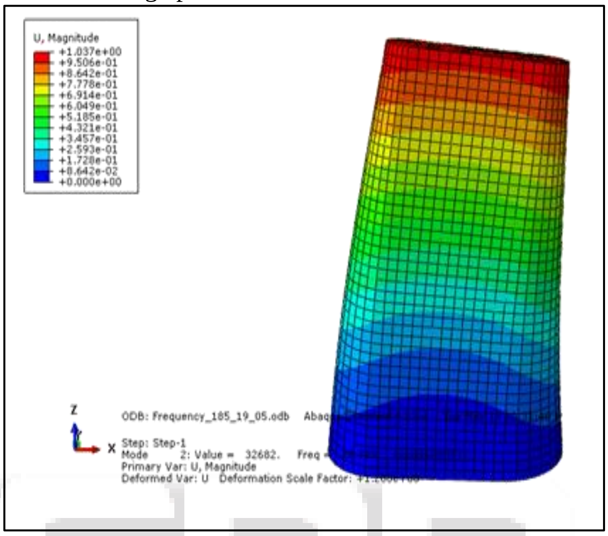

Fig. 6: Mode Shapes 2

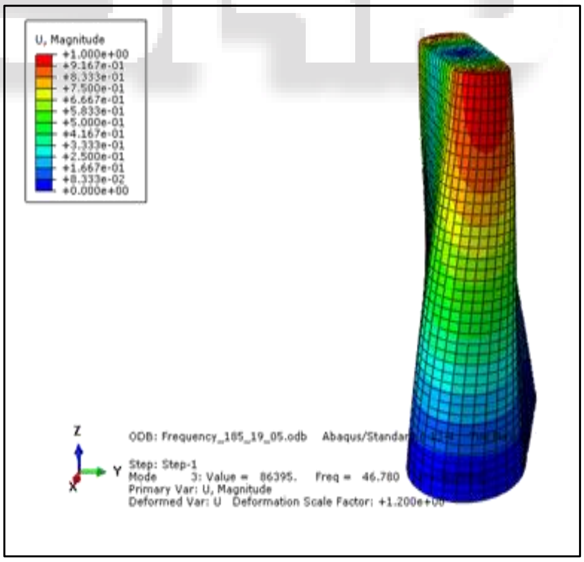

Fig. 7: Mode Shapes 3

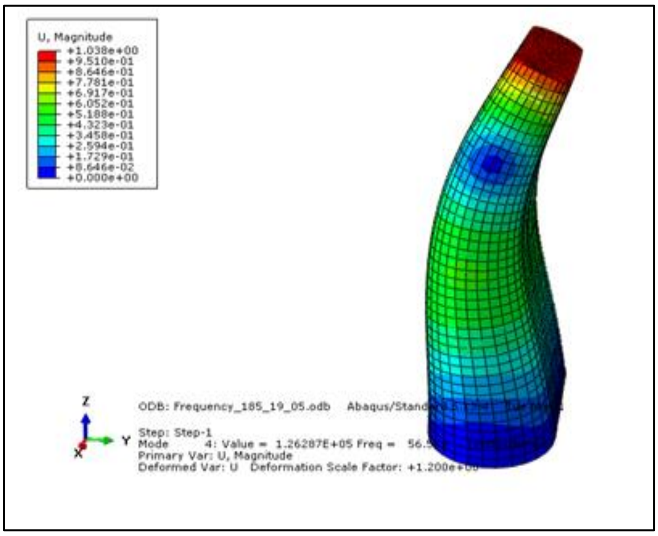

Fig. 8: Mode Shapes 4

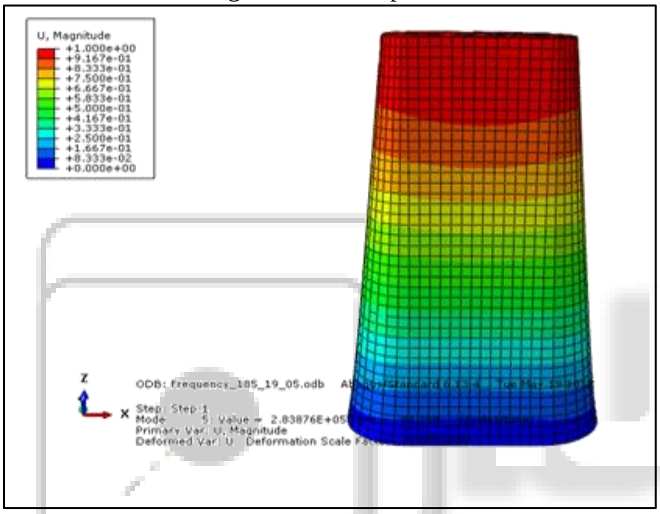

Fig. 9: Mode Shapes 5

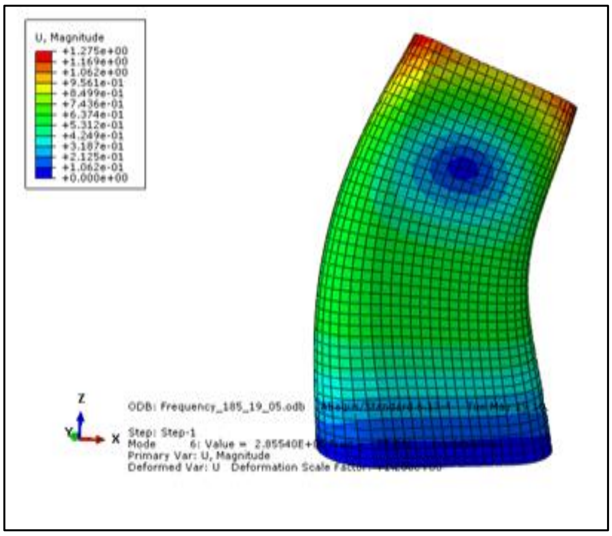

Fig. 10: Mode Shapes 6

A. *Results from Pushover Analysis*

Nonlinear static analysis (Pushover) is performed and nonlinear deformations considered that are selected in the steps of loading and boundary conditions of the analyzing. Simulation of the frame elements is modeled with first-order 3D prescribed material elements (AL), in which the nonlinear static deformation is allowed.

The characteristics elastic stiffness, yield strength and yield displacement of the pushover curve depend on the lateral force distribution. The uniform distribution generally leads to pushover curve with higher elastic stiffness, higher yield strength, and lower yield displacement compared to all other distributions Pushover analysis is carried out on the selected railway bridge piers using displacement controlled method and the capacity curves of the piers are plotted.

Piers	Weight, W (KN)	Area (m^2)	Height, h (m)	Top Disp δ (mm)	Base Shear, V_B (KN)	$\frac{V_B}{W}$	Drift Ratio, $\frac{\delta}{h}$ ($\times 10^{-3}$)
1	2040	14.91	7.500	1.23	462	0.226	0.164
2	3272	18.21	10.500	1.97	426	0.131	0.188
3	2383	15.87	8.402	1.42	448	0.188	0.169
4	4564	26.04	11.250	2.27	615	0.135	0.202
5	10454	36.72	16.875	3.93	675	0.065	0.233
6	5085	27.55	12.000	2.50	624	0.123	0.208
7	6687	30.13	12.375	2.40	712	0.107	0.194

Table 6: Summary of the pushover analysis results

Table 6 shows that the displacement limit state of collapse occurs at a base shear range of 6.5- 22.6% of the total weight and a drift ratio of 0.0164% to 0.0233%. This table shows that the base shear capacity of the bridge pier (V_B/W) is inversely proportional to the pier height. Figure 11 presents a scatter of (V_B/W) versus pier height.

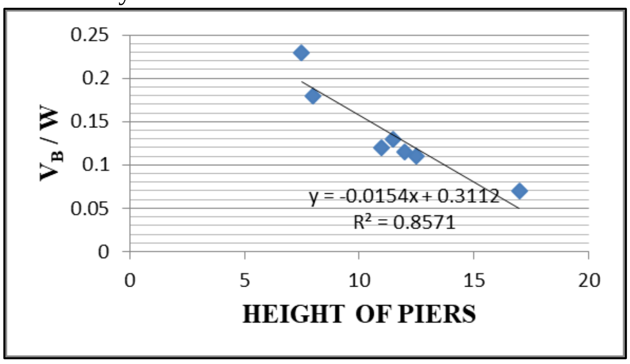

Fig. 11: (V_B/W) versus pier height scatter

VII. Summary & Conclusion

Most of the sub-structures of new railway river bridges in the state of Madhya Pradesh are built with solid mass concrete gravity piers and abutments. These piers do not have steel reinforcement to bear the load as it does not subject to any tensile stress under regular type of loading. Safety of these piers is of major concern during high magnitude earthquake.

This study aims to assess the vulnerability of the solid gravity bridge piers which forms the important component of railway bridges as the load transfer between substructure and superstructure takes through them. In the present study seven existing piers from the state of Madhya Pradesh are evaluated using free vibration analysis and nonlinear static (pushover) analysis.

The significant conclusion drawn from the present study is as follows:

1) Free-vibration analysis of the bridge pier shows that the first two fundamental modes reflect the translator motion of the pier in two orthogonal horizontal directions (X- and Y- directions) with mass participation below 50% for both of the twomodes.
2) The participating mass ratio for torsion mode (Mode# 3) and the rocking mode (Mode# 5) found to bezero.
3) The cumulative mass participation for first six modes is found to be less than 80% for the entire selected bridge pier. This indicates the significant contribution of higher modes.

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