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Evaluation of the Vibrational Properties of Three-Span Continuous Concrete Bridge by Dynamic Finite Element Method

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ABSTRACT: This study follows two objectives: first, determining the effect of defining master dynamic degrees of freedom on vibrational properties and increase structure analysis running speed, and second, estimation of response accuracy and vibrational properties of simplified dynamic finite element model of the bridge by one-dimensional elements and lump masses. After designing simplified model of bridge with nine lump masses, the estimation error rate in dominated period of the structure is examined in both accurate model and lump mass. The mass and stiffness matrices derived from analysis of ANSYS software are also shown. The responses of accurate and simplified models are studied, and it was observed that the simplified finite element model has reasonable estimation of vibrational properties of the bridge.

Keywords: Concrete Bridge, Dynamic Finite Elements, Mass Matrix, Stiffness Matrix, Master Dynamic Degree of Freedom, ANSYS

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INTRODUCTION

Matrix reduction by dynamic finite element method is a process to reduce the size of stiffness matrix, mass and damping of a numerical model and to accelerate structural analysis, resulting in lower costs of analysis. In general, this method is used in substructure and dynamic analysis such as free vibration, regular dynamic loading, and time history. Applying substructures means concentration of different elements on one element (by calculating compound stiffness matrix for all sets of elements). The matrix reduction makes it possible for an accurate model, such as static stress analysis, to use only parts with considerable dynamic contribution in dynamic analysis. These parts are specified with master dynamic degrees of freedom and reflect the dynamic behavior of the model. ANSYS program is able to use this method; the greatest advantage of this method is saving processing time for lump matrix, particularly in dynamic analysis and analysis of models with large number of dynamic degrees of freedom (ANSYS INC., 2009). The situations of master dynamic degrees of freedom are selected in the nodes with relatively large mass, relatively high rotational inertia and relatively low stiffness. For instance, in choosing master dynamic degrees of freedom of figure 1, relative rotation is bigger and relative stiffness is efficient. However, in selecting situation and type of degree of freedom, both rotational and orbital, modal forms of structure can be used (ANSYS INC., 2009). In this study, to compare dynamic behavior of bridge, an accurate finite element model is designed by the cubic eight-node elements, and also a finite element model is designed as linear structure and lump mass. ANSYS 14 software, with special abilities in discretization methods, is used in numerical modelling (Wrobel, 1990). ANSYS analytical principles of matrix reduction, makes lump stiffness matrix more accurate, and offers approximate mass matrix (ANSYS INC., 2009). In 2008, a program was written that is able to explore mass, stiffness and damping matrices from ANSYS software. He also studied the effect of type, number and form of element in mass and stiffness matrices (Acton, 2008). Mellal et al. (2007) seismically analyzed the area of multi-span bridge using finite element method. In modelling deck of this simple bridge, some structures have been used, the bridge deck was modelled using one-dimensional elements and the column height is raised to the center of deck section (Mellal et al., 2007).

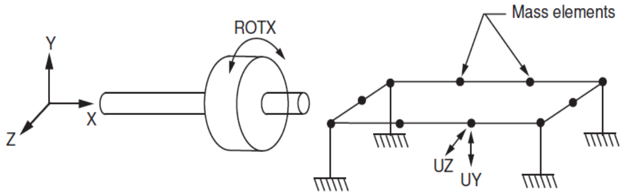

Figure 1. The situation of master degrees of freedom of transform mass (right) and large rotational inertia (left)

Finite element model with distributed mass

Geometrical and mechanical properties of under study concrete bridge include three continuous spans with 20 meters long considered with two circular profile columns with diameter of 2 meters, net height of 10meters, special weight of 2,500 kilograms per cubic meter for reinforced concrete, Young's modulus of 205*10 Pascal, Poisson's ratio of 0.2 and damping ratio of 0.05. Numerical model, direction of coordination axes, and geometric properties of deck section are indicated in figure 2. Figure 3 indicates modal forms of structure for recognition and selection of situation and type of degree of freedom, including rotational and orbital. The maximum mass contribution belongs to the stimulation of

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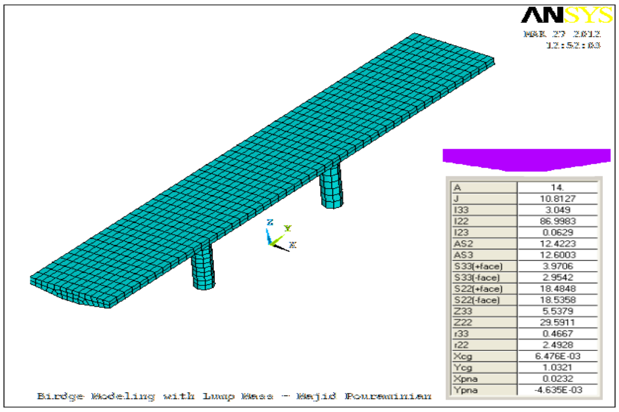
first mode (horizontal movement of deck along the longitudinal direction of the bridge) (Togan and Daloglu, 2006; Peng and Chen, 2009; Rezaiguia and Laefer, 2009; Karimi Moridani et al, 2013). In this study, six master dynamic degrees of freedom are selected. Obviously, as the number of master dynamic degree of freedom is considered high, dimensions of stiffness, mass and damping is more and numerical number is real representative of structure. For a structure with n degree of freedom, the matrices of stiffness, mass and damping are n*n. Obviously, after determination of the mass and stiffness matrices, frequencies and modes of vibration of the structure can be easily set and then using the modal analysis method the dynamic or quasi-dynamic analysis will be done in structures. For numerical model of distributed mass, the master degree of freedom is introduced in two modes, and their mass and stiffness matrices are derived, as indicated in figures 4 and 5. Position of degree of freedom is different in first and second modes. Both modes lead to the formation of unique mass and stiffness matrices of structure. Considering the fact that frequencies and vibrational modes of a structure is independent from position of degrees of freedom of structure, however, in both modes the vibrational periods should be equal and the final form of vibrational modes be similar.



A	14.
J	10.8127
I33	3.049
I22	86.9983
I23	0.0629
AS2	12.4223
AS3	12.6003
S33(+face)	3.9706
S33(-face)	2.9542
S22(+face)	18.4848
S22(-face)	18.5358
Z33	5.5379
Z22	29.5911
r33	0.4667
r22	2.4928
Xcg	6.476E-03
Ycg	1.0321
Xpna	0.0232
Ypna	-4.635E-03

Figure 2.finite element model of bridge and geometric properties of deck section (ANSYS14 software)

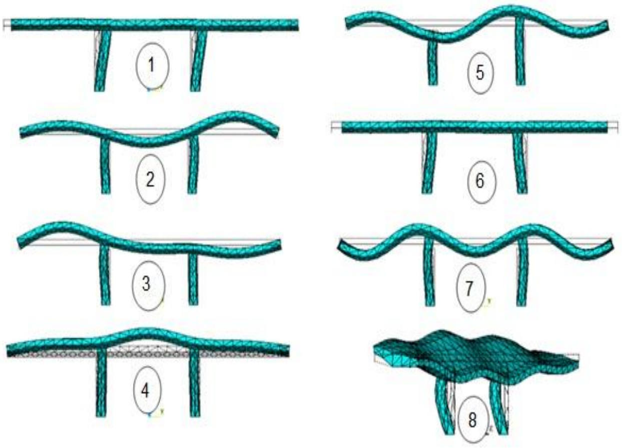
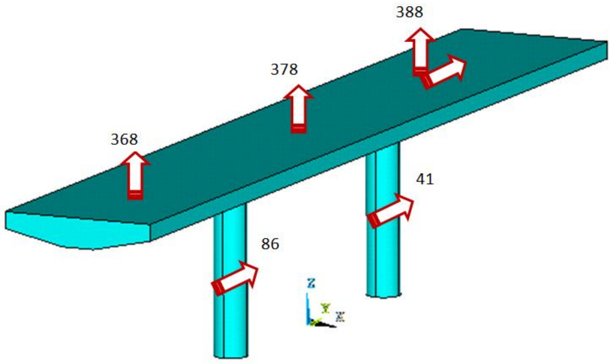


Figure 3. Vibrational modes of the bridge

Distributed mass models with 6 master degrees of freedom (first mode)

In this mode, the master degrees of freedom are considered according to figure 4. High relative mass, low relative stiffness, vibration form of the dominant mode, and dimensions of structure elements are efficient parameters of this selection. Stiffness and mass matrices derived from the software are indicated below with respect to the defined degree of freedom. To determine the mass, stiffness and damping matrices in ANSYS software, the master dynamic degrees of freedom should be outlined after substructure analysis. Then, the model should be analyzed to derive required matrices. Comparison of the values of the mass matrix elements (Figure 4), it is observed that fifth element in the main diagonal have great contribution in responses, which according to definition, represents the generalized force required for U388-Y degree of freedom to create a single corresponding acceleration in U388-Y degree of freedom, that has the most mass contribution in structural response (Chopra, 1995; Clough and Penzien, 1975). As can be seen the mass and stiffness matrices are symmetric.



$$M = \begin{array}{c} \begin{array}{cccccc} \text{41-Uy} & \text{86-Uy} & \text{368-Uz} & \text{378-Uz} & \text{388-Uy} & \text{388-Uz} \end{array} \\ \begin{bmatrix} \mathbf{91450} & 59153 & 53579 & 34790 & 140781 & 28829 \\ 59153 & \mathbf{115821} & 23161 & 27441 & 275050 & 2162 \\ 53579 & 23161 & \mathbf{377959} & 60149 & 15682 & 21985 \\ 34790 & 27441 & 60149 & \mathbf{418441} & -54207 & 40068 \\ 140781 & 275050 & 15682 & -54207 & \mathbf{1705814} & -60242 \\ 28829 & 2162 & 21985 & 40068 & -60242 & \mathbf{363799} \end{bmatrix} \end{array}$$

$$K = \begin{bmatrix} 0.42e9 & -29578116 & -8858209 & 45740033 & -0.24e9 & -41879040 \\ -29578116 & 0.41e9 & 38860972 & -46883117 & -0.21e9 & 5490602 \\ -8858209 & 38860972 & 0.19e9 & 7649017 & -28252204 & -4848494 \\ 45740033 & -46883117 & 7649017 & 0.23e9 & -499006 & 12055593 \\ -0.24e9 & -0.21e9 & -28252204 & -499006 & 0.34e9 & 35839764 \\ -41879040 & 5490602 & -4848494 & 12055593 & 35839764 & 0.196e9 \end{bmatrix}$$

Figure 4. Finite element model of first mode

One of the advantages of dynamic element model with finite master degree of freedom is that the time required for modal analysis of bridge,considering all degrees of freedom of structure, is twice the time required for analysis of the model with six master dynamic degrees of freedom.

Distributed Mass model with 6 master degrees of freedom (second mode)

Since the frequencies and vibrational modes of a structure are independent from the situation of degrees of freedom of structures, the second mode is presented to show change in the values of mass and stiffness matrices due to the effect of changing the situation of the degrees of freedom and no perceptible change in response to seismic loading. In this mode, the master degrees of freedom are considered as figure 5. Mass and stiffness matrices derived from the software according to the defined degree of freedom are indicated in the follow.

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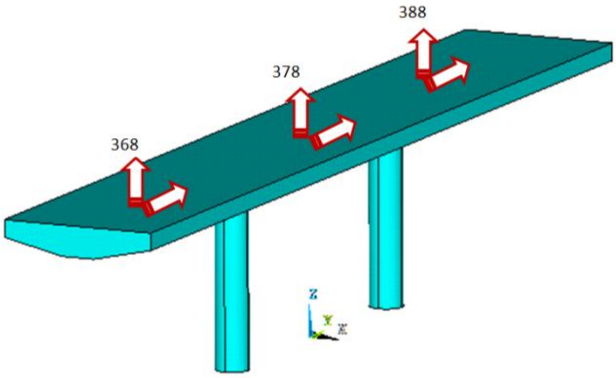
Comparing the values of elements of mass matrix of figure 6, it is shown that the most contribution in response in the direction of degrees of freedom is based on the dominant mode. Therefore, first, third and fifth element of main diagonal of mass matrix has greater values, but due to the increase of the number of master degrees along the deck of bridge, all values are less than the value of fifth element in the main diagonal.



$$M = \begin{array}{cccccc} \text{368-Uy} & \text{368-Uz} & \text{378-Uy} & \text{378-Uz} & \text{388-Uy} & \text{388-Uz} \\ \hline \mathbf{1276668} & 161180 & -11376 & 189086 & -496916 & 120624 \\ 161180 & \mathbf{366321} & -25517 & 48067 & -135275 & 24409 \\ -11376 & -25517 & \mathbf{572132} & -35422 & 312003 & -42969 \\ 189086 & 48067 & -35422 & \mathbf{414982} & -146564 & 39058 \\ -496916 & -135275 & 312003 & -146564 & \mathbf{1006940} & -85045 \\ 120624 & 24409 & -42966 & 39059 & -85045 & \mathbf{369730} \end{array}$$

$$K = \begin{bmatrix} 0.1e10 & -13163393 & -0.82e9 & -11317009 & -0.17e9 & -6549330 \\ -13163393 & 0.19e9 & -10303764 & 12787236 & 9900842 & -6079252 \\ -0.82e9 & -10303764 & 0.17e10 & 13732648 & -0.85e9 & 14915817 \\ -11317009 & 12787236 & 13732648 & 0.23e9 & -413211 & 170117112 \\ -0.17e9 & 9900842 & -0.85e9 & -413210 & 0.105e10 & 4901021 \\ -6549330 & -6079252 & 14915817 & 17011712 & 4901021 & 0.19e9 \end{bmatrix}$$

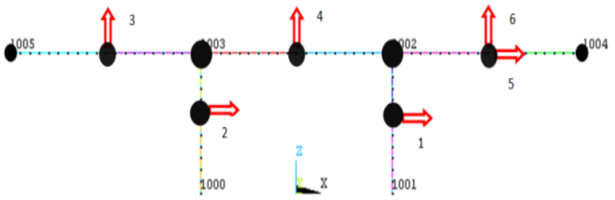
Figure 5. Finite element model of second mode

Finite element model with lump mass

To compare vibrational properties of bridge in both accurate and lump matrix model, columns and deck of bridge were modelled by linear elements and the total mass of structure were loaded as lump mass in 9 situation (figure 6). Beam height modelled instead of deck is at the balance center of deck section (1.06 m from the seat), that increases the net height of bridge columns to 11.06 meters from the ground. Increase of column height has no effect on lump mass entering to columns. This model has also reviewed two different modes of degrees of freedom situation, as shown in figures 6 and 7.

Lump mass model with 6 master degrees of freedom (first mode)

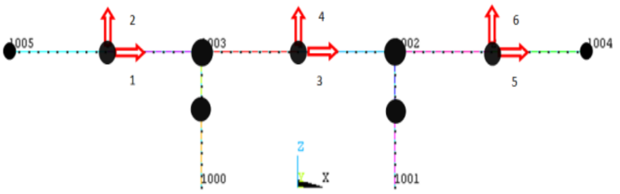
Columns and deck of bridge are modelled by linear elements with geometric characteristics of section and has low mass. However, total mass of structure is distributed in 9 points as lump mass, as shown in Figure 6. To stimulate the effect of lump mass, Mass21 element and for linear members, Beam4 element is used. This element is used to define spot mass in two- and three-dimensional spaces. Stiffness and mass matrices of first mode are indicated in the follow (ANSYS INC., 2009). In mass matrix of Figure 6, it is shown that the maximum mass contribution is in elements of second column of main diagonal. Obtained results are different from contribution of maximum mass along deck of bridge. After contribution of mass along the second master degree of freedom, the maximum mass belong to directions 1, and 5 (along deck of bridge), respectively. Hence, it is expected this model encounter error in estimation of vibrational features and structure responses. Since two volume of mass contribution belongs to lump mass on bridge piers, it seems that increasing the number of master degrees of freedom in dynamic finite element model reduces this error.



$$M1 = \begin{array}{cccccc} 1 & 2 & 3 & 4 & 5 & 6 \\ \hline 735313 & 551496 & 64537 & 7975 & 192664 & -63188 \\ 551496 & 2332393 & 248939 & -190012 & 193142 & -52697 \\ 64537 & 248939 & 432348 & 26769 & 18550 & -13366 \\ 7975 & -190012 & 26769 & 477091 & -2148 & 46581 \\ 192664 & 193142 & 18550 & -2148 & 591055 & -20470 \\ -63188 & -52697 & -13366 & 46581 & -20470 & 410822 \end{array}$$

$$K1 = \begin{bmatrix} 0.11e11 & -0.23e10 & -0.29e9 & 0.71e9 & -0.34e10 & -0.45e9 \\ -0.23e10 & 0.94e10 & -87945881 & -0.17e9 & -0.77e9 & 0.27e9 \\ -.29e9 & -87945881 & .16e10 & -73860903 & -73133733 & 53877441 \\ 0.71e9 & -0.17e9 & -73860903 & 0.21e10 & -0.31e9 & -0.13e9 \\ -0.34e10 & -0.77e9 & -73133733 & -0.31e9 & 0.24e10 & 0.39e9 \\ -0.45e9 & 0.27e9 & 53877441 & -0.13e9 & 0.39e9 & 0.17e10 \end{bmatrix}$$

Figure 6. Finite element model with linear element and lump mass (first mode)



$$M1 = \begin{array}{cccccc} 1 & 2 & 3 & 4 & 5 & 6 \\ \hline 605758 & 9676 & 79631 & -8388 & 357 & 2022 \\ 9676 & 405866 & 7653 & 46339 & -2022 & 7705 \\ 79631 & 7653 & 510263 & 0 & 79631 & -7653 \\ -8388 & 46339 & 0 & 458519 & 8388 & 46339 \\ 375 & -2022 & 79631 & 8388 & 605758 & -9676 \\ 2022 & -7705 & -7653 & 46339 & -9676 & 405866 \end{array}$$

$$K1 = \begin{bmatrix} 0.2e10 & -0.21e9 & -0.14e10 & 0.217e9 & -4093417 & -9993393 \\ -0.21e9 & 0.17e10 & -0.21e9 & -0.101e9 & 9993393 & 24698886 \\ -0.146e10 & -0.21e9 & 0.41e10 & 0 & -0.14e10 & 0.21e9 \\ 0.217e9 & -0.101e9 & 0 & 0.21e10 & -0.217e9 & -0.101e9 \\ -4043417 & 9993393 & -0.145e10 & -0.217e9 & 0.204e10 & 0.216e9 \\ -9993393 & 24698886 & 0.21e9 & -.101e9 & 0.216e9 & 0.171e10 \end{bmatrix}$$

Figure 7. Finite element model with linear element and lump mass (second mode)

Lump mass model with 6 master degrees of freedom (second mode)

The total mass of structure was also lumped in 9 points, such as lump mass for second mode, except that the location of the degrees of freedom is different from the first mode, as shown in figure 7; mass and stiffness matrices of second mode are also indicated in the follow.

The estimated time period of 9 first modes of finite element model for both the distributed mass of the first mode (Figure 4), and lump mass of first mode (Figure 6) are shown in Table 1. According to Table 1, error of simplified model with lump mass for the dominant mode is 18% and the greater errors belong to modes with less

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contribution in structure response. Comparison of period of modes shows that lump mass model has greater main alteration than accurate model.

Table 1. Comparison of period of finite element model

Mode no.	Accurate model (seconds)	Lump mass model (seconds)	Error in response (%)
1	1.08	1.28	18
2	0.72	0.62	14
3	0.27	0.38	40
4	0.26	0.29	15
5	0.25	0.23	8
6	0.24	0.20	16
7	0.24	0.12	50
8	0.15	0.11	27
9	0.12	0.10	17

CONCLUSION

- The running time required for modal analysis of bridge, considering all degrees of freedom of structure, is twice the time required for the analysis of model with only 6 master dynamic degrees of freedom, that for models with very high element and degrees of freedom this time saving increases.
- However, matrix reduction of ANSYS program offers accurate lump stiffness matrix and approximated mass matrix, which is true for this study.
- Simplified model of dynamic finite element with lump mass has period greater that accurate model.
- Comparison of vibrational features of accurate numerical model and lump mass indicated that estimation error of dominant period of structure by lump mass method is only 10% (period greater than accurate model) and the larger error value belongs to modes with less mass contribution that seems response error reduces by definition of more lump mass.

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