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Review Article

Harmonic Response Analysis of Multi-Storey Building

Salman S. Baig[A*], Mamta Mogali[A], Dr.Mohankumar P. Hampali[B]

[A]Department of Civil Engineering, Shri Dharmasthala Manjunatheshwar College of Engineering and Technology,Dharwad-India-580002
[B]Applied Mechanics Department, Government Residence Women's Polytechnic, Tasgaon, Sangli-Maharashtra -India-416312

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Abstract

For high rise structures depending upon the precision required and limit state considered an engineer shall perform response analysis with suitable idealization for loading and geometry of the structure. The structural response for wind loads can be made more realistic by assuming wind loads as harmonic instead of quasi static approaches of equivalent static loads. Any sustained cyclic load produces a harmonic response in the building. When the natural frequency of a multi-storey building matches the frequency of forcing excitations resonance occurs causing maximum displacement. In the present context, Harmonic response technique is then adopted on ANSYS platform for a fifteen storey structure bare frame and employing mode superposition method displacements of the structure at various floor levels are evaluated. Peak displacement is then visualized from the frequency v/s displacement graph obtained from mode superposition of reduced modes at forcing frequencies.

Keywords: *Reduced mode extraction method, master's degree of freedom, mode superposition*

1. Introduction

Wind is a dynamic and random phenomenon in both time and space. The structure must have sufficient strength to resist the wind-induced forces, the structure must have adequate stiffness to satisfy occupant comfort and serviceability criteria, and the wind may produce a dynamic response in the structure.

The accuracy of analysis depends on analytical results reached in idealizations. Wind loads and machine loads can be idealized as harmonic loads to enhance the level of accuracy in predicting the displacements in the structure.

The computation of wind load on any structure or component depends on the design wind pressure which is governed by the velocity of the wind at a particular height. The velocity of wind considered depends on the basic wind speed, terrain and class of the building, risk co-efficient and topography of the region. Once the design pressure is computed at a given height the equivalent static force on the structure or component is obtained. By converting the complex wind loads into static loads the structure is analyzed for the static effects. The wind along the structures are also known to induce dynamic effects which induce increase in the amplitude of structural vibrations along with increase in wind speed. The effects are termed as galloping, flutter and ovalling. The gust factor method is used for studying these effects. In all these analytical methods loads are approximated to static loads.

Harmonic response analysis is done to predict the sustained dynamic behavior of the structure to check the displacement at resonance, fatigue and other harmful effects of forced vibrations.

2. Methodology

The approach and accuracy of the analytical results depends on the idealization of the geometry and loading of the structure. In the present context, the wind load co-efficient are computed using the codal provisions from relevant IS-875(Part-3): 1987. The symmetrical bare frame with known spacing is then performed with modal analysis using the method of reduced mode extraction which is to be preceded by mode-superposition harmonic response analysis on the lumped mass shear beam model to compute the displacements at the all sixteen nodes by considering the wind load as sinusoidal in along-wind direction. The response is then to be evaluated using the FE software package ANSYS.

3.Harmonic Response Analysis

In a structural system any sustained cyclic load will produce a sustained cyclic response or harmonic response.(ThandavaMurthy T.S, *2005*)

It is a technique used to determine the steady state response of a linear structure to loads that vary sinusoidally with time. The idea is to calculate the structure's response to several frequencies and obtain a graph of some response quantity versus frequency. Peak responses are then picked up from the graph and stresses

*Corresponding author **Salman S. Baig** is a PG Scholar, **Mamta Mogali** is working as Asst. Prof and **Dr.Mohankumar P. Hampali** as Selection Grade Lecturer.

can be reviewed at those frequencies. Peak harmonic response occurs at forcing frequencies that match the natural frequencies of the structure. Hence, natural frequencies of the structure are to be determined by performing modal analysis. A harmonic analysis cannot calculate the response of multiple forcing functions acting simultaneously with different frequencies.

It is a linear analysis as a result of this any non linearities such as plasticity are not accounted even though they are defined. Harmonic response analysis calculates only the structure's steady-state forced vibrations response varying with time and hence, transient vibration's which occur at the initial stage of the excitation are not considered in this analysis.(ANSYS*V 13.0*)

3.1 Harmonic response of a Damped system

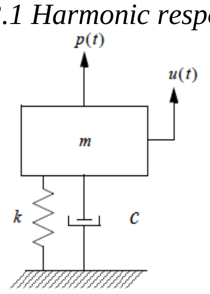

Fig.1 Damped SDOF system subjected to harmonic load

A harmonic force is represented as $P(t) = P_0\, sin\omega(t)$ where, P_0 is the amplitude or maximum value of the force and its frequency ω is termed as exciting frequency and $T = \frac{2\pi}{\omega}$ is the time period of excitation. (A. K. Chopra, *2004*) for forced harmonic vibration of the damped system the governing differential equation is,

$$m\ddot{u}+c\dot{u}+ku = P_0 \sin\omega(t) \quad (1)$$

Solving the equation for initial conditions,U=U(0)and$\dot{U} = \dot{U}(0)$,

The complimentary solution is the free vibration response given as,

$$U_C=e^{-\xi\omega_n t}(A\cos\omega_D t+B\sin\omega_D t) \quad (2)$$

$$A = U_0,\ B= \frac{\dot{U}_0}{\omega_n} - \frac{\left(\left(\frac{P_0}{k}\right)\left(\frac{\omega}{\omega_n}\right)\right)}{\left[\left(1-\left(\frac{\omega}{\omega_n}\right)^2\right)\right]} \quad (3)$$

where,$\omega_D = \omega_n\sqrt{1-2\xi}$,

The particular solution for this equation is,

$$U_p(t) = C\sin\omega t + D\cos\omega t \quad (4)$$

Where,

$$C=\left(\frac{P_0}{K}\right)\left[\frac{(1-\xi^2)}{(1-\xi^2)^2+2\xi(r)^2}\right]$$

$$D= \frac{-P_0}{K}\left[\frac{2\xi r}{\left(1-\xi^2\right)^2+(2\xi r)^2}\right]$$

The total response is given by,

$$U_t= e^{-\xi\omega_n t}(A\cos\omega_D t+B\sin\omega_D t)+ C\sin\omega t + D\cos\omega t \quad (5)$$

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Transient Steady state

4. Shear Beam Model

The framed structures are idealized as planar models with beams and slabs rigidly connected and acting as a diaphragm supporting floor loads and resting on columns. To evaluate the behavior of the structure for lateral loads, a shear beam model is an appropriate way for idealization with the shear force acting on any mass which depends on the relative displacements of adjacent masses. The model assumes that beams are infinitely stiff and axial deformations of columns are ignored. The columns behaves just like shear springs with its stiffness as $12EI/h^3$, where, EI is the flexural rigidity and h is the storey height. Therefore, building can be represented as a lumped mass system connected by shear springs. The masses are lumped at each floor level and the inter storey spring stiffness is equal to the sum of the columns in that storey.(Pankaj Agarwal *et al*,*2006*)

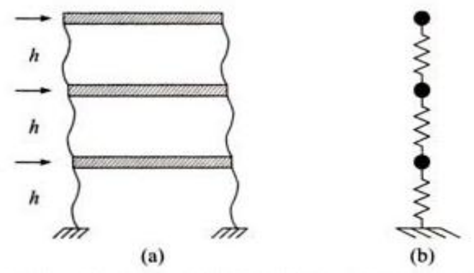

Fig .2 a) Deflection of a frame under lateral load b) shear beam model

5. Problem Statement

An exterior transverse building frame of a 15 storey regular building is considered for carrying out harmonic response analysis for an equivalent static load idealized as sinusoidal in form. The building is having following parameters:-

- Geometric data

Length = 24.0m
Width = 24.0m
Height of building = 51.2m
Height of typical storey = 51.2m

- Wind Data

Wind zone = 5
Basic wind speed =50 m/s
Location = Madras
Terrain category = 2
Class of structure = B
Mean design life =50 years

6. Wind loads on 15 storey bare frame

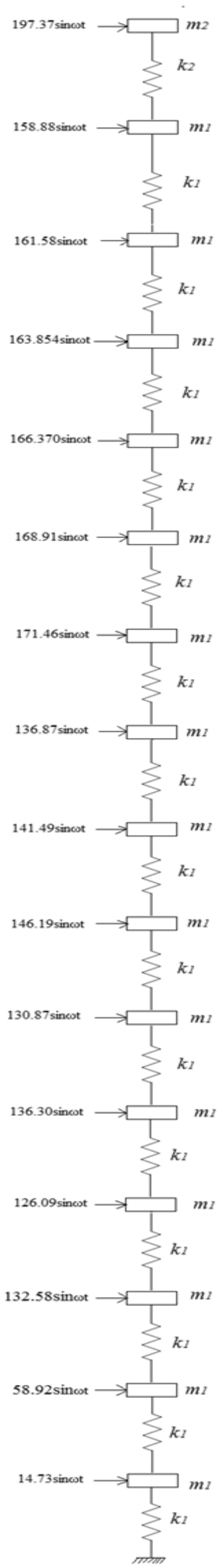

Fig.3 Wind loads on lumped mass model

The wind loads computed for the considered numerical case as per the codal provisions of IS 875 (part-3) 1987 at each storey level are assumed to be sinusoidal and applied at the joints The maximum amplitude is identified by the static load intensities. All loads are assumed to have same frequency. In the present approach the dynamic effects of wind loads are expressed in terms of an equivalent static load idealized in a sinusoidal form (Thambirajah Balendra *et al,1989*) to enhance the accuracy level. The fig.3 shows the wind loads idealized as harmonic loads at each of the nodal point.

7. The FEA Model and Mode superposition Harmonic Response Analysis

The finite element model adopted for the harmonic response analysis consists of two nodded spring mass damper with only one degree of freedom at each node for the lumped mass(D. Boggs *et al,1989*).The real constant inputs are the mass at j^{th} node, stiffness and damping ratio. Damping is to be provided for avoiding the infinite results, in the current analysis damping ratio of 5% is adopted as the reinforced concrete framed structure is considered. The FEA element consisting of spring-mass-damper used for performing the analysis is as shown in Fig.4

Harmonic response analysis is performed using the mode superposition method. Prior, to the mode superposition harmonic analysis; modal analysis is to be done which is the prerequisite as the mode shapes are to be used in harmonic analysis. Modal analysis is performed using reduced method for mode extraction. The reduced method is comparatively fast as it uses master's degree of freedom. In the present analysis the master's degree of freedom are selected strictly in x direction only, at each of the node except the initial node where, all degrees of freedom are restrained as the base is assumed to be fixed. As a result of which in the initial solution only the nodal displacements are calculated at the master's degree of freedom.

Now, the harmonic analysis is done using mode superposition method. The mode superposition method sumps up the factored mode shapes that are extracted from the modal analysis which is performed in the first phase finally to compute the structure's response.

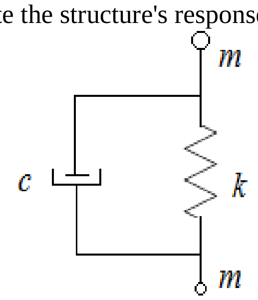

Fig.4 2-nodded spring-mass-damper element

As the mode shapes are used from the reduced modal solution, the forces are assigned at the master's degree of freedom. The frequency range to be used in performing harmonic response analysis is taken from the modal solution. The number of solution on the either side of natural frequency is kept 4 and the total is restricted to 60. This results in more accurate matching of natural frequency of structure with the forcing frequency which causes resonance and maximum amplitude. The displacement response is given in meters for the frequency range taken. The Fig.5 illustrates the FEA model evaluated for perform analysis.

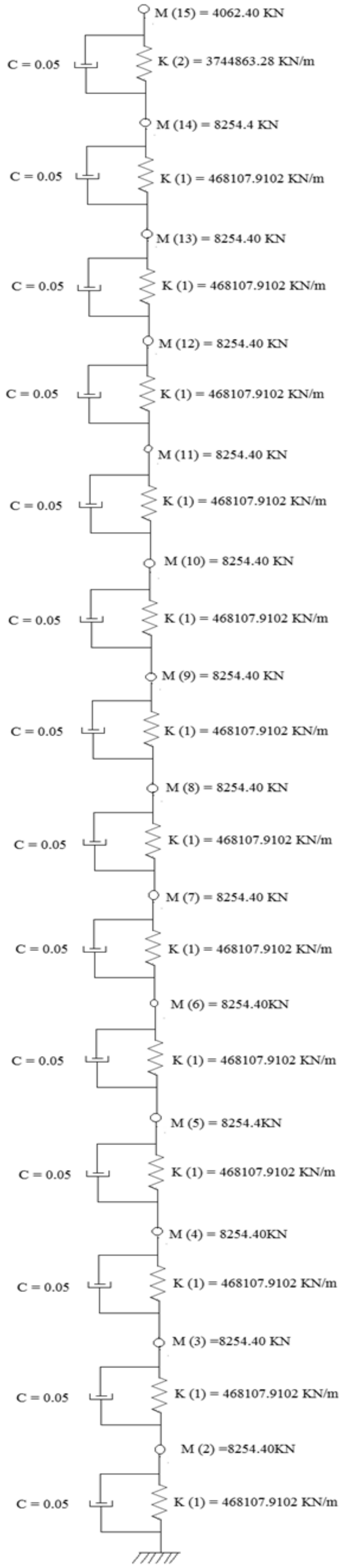

Fig.5 FEA Model consisting of spring-mass-damper element used in analysis.

8. Results and Discussions

Harmonic response analysis is performed which is preceded by modal analysis using reduced mode extraction method on ANSYS. The results obtained are natural frequencies, time period, mode shapes and summed up nodal displacements at each node.

8.1 Modal Analysis

Modal analysis is performed and the natural frequencies and modal periods are evaluated. Fifteen mode shapes are extracted from the analysis. The frequencies and modal periods are presented in table 1.

Table.1 Mode Shapes, frequency and time period

Mode shapes	Frequency (Hz)	Time period (secs)
Mode 1	0.22552	4.4404
Mode 2	0.37518	2.6653
Mode 3	0.62073	1.611
Mode 4	0.85948	1.1634
Mode 5	1.0888	0.9184
Mode 6	1.3062	0.7655
Mode 7	1.5093	0.6625
Mode 8	1.6959	0.5896
Mode 9	1.8638	0.5365
Mode 10	2.0114	0.4971
Mode 11	2.1369	0.4679
Mode 12	2.239	0.4466
Mode 13	2.3166	0.4316
Mode 14	2.3688	0.4221
Mode 15	2.3952	0.4175

8.2 Harmonic Response Analysis

Harmonic response analysis is carried out using mode superposition method by using all 15 mode shapes from the modal analysis.

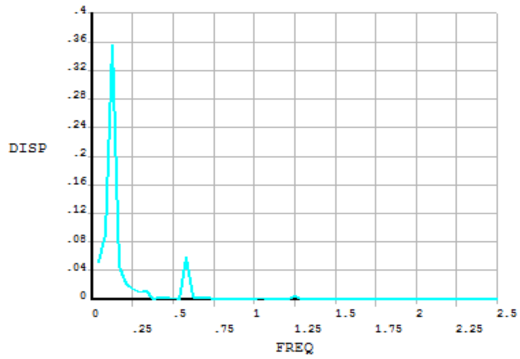

Fig.6 Typical response curve for Node no.17 having maximum displacement of 0.910924E-01m at frequency 0.83333E-01Hz

This analysis has given the summed up response for each node corresponding to forcing frequency. The displacement response is represented in Table 2. The typical graph for peak response is shown in Fig.6

Table.2 Forcing frequency and peak displacements at nodes

Node no.	Frequency (Hz)	Nodal Displacement UX (m)
01	0	0
02	0.58333	0.311711E-01
03	0.58333	0.549268E-01
04	0.58333	0.655455 E-01
05	0.58333	0.603544 E-01
06	0.83333E-01	0.440244 E-01
07	0.83333E-01	0.516203 E-01
08	0.83333E-01	0.586871 E-01
09	0.83333E-01	0.651579 E-01
10	0.83333E-01	0.710114 E-01
11	0.83333E-01	0.762292 E-01
12	0.83333E-01	0.807123 E-01
13	0.83333E-01	0.844443 E-01
14	0.83333E-01	0.896081 E-01
15	0.83333E-01	0.874127 E-01
16	0.83333E-01	0.910333E-01
17	0.83333E-01	0.910924E-01

Conclusions

In harmonic analysis all lateral loads are assumed to be having same frequencies with different amplitudes. The Mode superposition harmonic solution with reduced modal shapes gives the quick prediction of structure's response for the sinusoidal excitation. The modal analysis has predicted 15 interested mode shapes out of which first four modes are having maximum time period and are significantly vulnerable. The mode superposition harmonic analysis done for all 15 mode shapes within the frequency range provided gives the summed up response at each node, peak displacement visualized in the frequency v/s response curve is found to be highest for node 17.

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