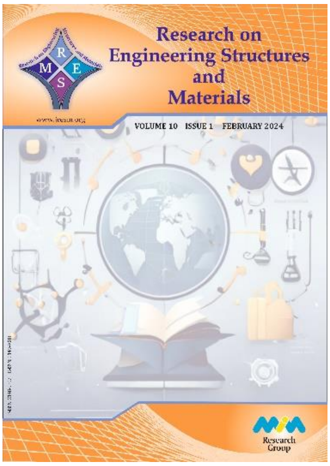
Research on Engineering Structures & Materials
www.jresm.org
Research Group



Numerical analysis of the primary and secondary structural dynamic interaction effects on elastic floor response spectra

Madhavi Latha Annamdasu, Surya Prakash Challagulla, Vyshnavi Pesaralanka, Ismail Hossain , Daniel Cruze

Online Publication Date: 20 November 2023
URL: http://www.jresm.org/archive/resm2023.25me0915rs.html
DOI: http://dx.doi.org/10.17515/resm2023.25me0915rs

Journal Abbreviation: *Res. Eng. Struct. Mater.*

To cite this article
Annamdasu ML, Challagulla SP, Pesaralanka V, Hossain I, Cruze D. Numerical analysis of the primary and secondary structural dynamic interaction effects on elastic floor response spectra. *Res. Eng. Struct. Mater.*, 2024; 10(2): 637-649.

Research on Engineering Structures & Materials

www.jresm.org

MIM Research Group

Research Article

Numerical analysis of the primary and secondary structural dynamic interaction effects on elastic floor response spectra

Madhavi Latha Annamdasu[*1,a], Surya Prakash Challagulla[1,b], Vyshnavi Pesaralanka[1,c], Ismail Hossain[2,d], Daniel Cruze[3,e]

[1]*Dept. of Civil Eng., Koneru Lakshmaiah Education Foundation (Deemed to be University), Vaddeswaram, Guntur, 522302, India*
[2]*School of Natural Sciences and Mathematics, Ural Federal University, Yekaterinburg, 620 000, Russia*
[3]*Dept. of Civil Eng., Hindustan Institute of Technology and Science, India*

Article Info

Article history:

Received 15 Sep 2023
Accepted 17 Nov 2023

Keywords:

Primary structure; Secondary structure; Tuning ratio; Dynamic interaction; Floor response spectrum; Component dynamic amplification factor

Abstract

In modern seismic design, the assessment of seismic behavior in secondary structures relies on the evaluation of the primary structure's acceleration at the support of the secondary structure. To enable effective secondary structure design, a thorough understanding of the interaction between the primary and secondary structures is essential. This article conducts an analysis based on parametric data, delving into the dynamic interaction between these structures. In this study, both the elastic primary and secondary structures are represented as single-degree-of-freedom systems. The governing equations of motion for both the coupled and uncoupled systems are derived and solved using the numerical method. Subsequently, the floor response spectrum (FRS) is computed for both coupled and uncoupled configurations. This investigation focuses on the impact of three crucial parameters: the tuning ratio (T_r), the mass ratio (μ), and the damping ratio (ξ_s) on the FRS. The analytical findings reveal that dynamic interaction does not significantly affect the FRS when the mass ratio is very low, at 0.1%. However, for a range of $0.8 \leq T_r \leq 1.2$, dynamic interaction has a substantial influence on the FRS. Additionally, this study underscores that lower damping ratios in the secondary structure result in a more pronounced coupling effect on the FRS.

1. Introduction

A building structure comprises elements that do not resist any loads. Such building elements generally are called Secondary structures (SSs). These structures are broadly categorized into three groups: architectural components, mechanical and electrical components, and building contents. Secondary structures can be divided into displacement-sensitive and acceleration-sensitive depending on the kind of failure they experience. An earthquake's ground motion can be amplified by a structure, causing floor accelerations to be greater than the peak ground acceleration (PGA). If secondary structures (SSs) are not taken into account during the design phase, they will be severely damaged by these amplified accelerations. The survivability of SSs after an earthquake is critical for ensuring the continuation of emergency services, ensuring public safety, and minimizing the financial burden of the subsequent damage. Despite their name, secondary structures are far from insignificant. Furthermore, sometimes secondary structures may be costlier than the primary structure (PS) [1], [2]. Secondary structures have been shown to be vulnerable to earthquakes in recent decades [3]–[6]. Several large hospitals were

[*]Corresponding author: chsuryaprakash@kluniversity.in
[a] orcid.org/0009-0000-6062-6847; [b]orcid.org/0000-0003-0125-1488; [c] orcid.org/0000-0003-1284-3139; [d] orcid.org/0000-0002-7256-8135; [e] orcid.org/0000-0002-4024-4742
DOI: http://dx.doi.org/10.17515/resm2023.25me0915rs

forced to evacuate during the 1994 Northridge earthquake in Los Angeles due to the failure of critical secondary structures such as emergency power systems, medical equipment control systems, and water supply pipe systems[7] Given the importance of ensuring SS integrity during seismic events, further study is needed to create credible performance-based design criteria for SSs.

For many years, it has been thoroughly studied how the SSs react to earthquakes in order to ensure public safety and lessen the financial effect of the resultant damage. A common method to obtain the seismic demand on the secondary structures is the floor response spectrum (FRS) method. For calculating the input load of a secondary structure, the floor response spectrum approach is frequently used [8]–[10]. To design secondary structures, engineers have frequently employed this technique. This method's major assumption is that the secondary structure doesn't interact with the main structure, that its presence has no impact on the primary system's dynamic response, and that it has no impact on the other way around. When the secondary structure (SS) has significant mass, the validity of this assumption may be compromised. In such cases, the potential for interaction between the primary and secondary structures necessitates the consideration of the entire system [11]–[13]. In general, disregarding the interaction leads to an overestimate of secondary structural demand and, as a result, an excessively conservative design [14]. Hence, there is a need to study the seismic behavior of secondary structures while accounting for the dynamic interaction between the primary and secondary structures. This investigation aims to develop precise and practical methods for evaluating the seismic response of secondary structures.

Numerous researchers have explored the interaction effects and dynamic characteristics of integrated systems by utilizing a combined oscillator-structure model, as indicated in references [11], [15]–[18]. Nevertheless, it's important to note that prior research has not extensively addressed the impact of the dynamic properties of both primary and secondary structures on the seismic performance of secondary structures. Therefore, this study focuses on analyzing the seismic response of the secondary structure in cases where its weight is in the same order of magnitude as that of the primary structure. In this study, we employ single-degree-of-freedom (SDOF) elastic primary (PS) and secondary structures (SS) to explore how their dynamic interaction influences the seismic response of the SS. To assess the seismic demands on secondary structures, we analyse the floor response spectra (FRS) both with and without accounting for dynamic interaction, and we calculate the component dynamic amplification factors (CDAFs). These measures are essential in our evaluation of the seismic behavior of secondary structures. In the generation of FRS, component dynamic amplification factors play an important role as they reflect the amplification of SSs. The impacts of several factors are examined on the FRS and CDAF, including the fundamental vibration period of the PS, the mass ratio, and the damping ratio of the SS. Finally, the component dynamic amplification factors are compared with those obtained from the current code-based formulations.

The paper is organized as follows: Section 2 provides a concise overview of the modelling of both the coupled and uncoupled systems. Section 3 discusses the selection of ground motions and provides specific details pertinent to this research. In Section 4, the research findings are presented, with a focus on three key response parameters: acceleration time history response, floor response spectra, and component dynamic amplification factors. The paper concludes in Section 5 with succinct summarizing remarks.

2. Modelling and Analysis

In this study, a SDOF system is used for both the elastic primary structure (PS) and the elastic secondary structure (SS). Both the PS and SS are considered to be two-dimensional

(2D) framed building systems. In this study, the analysis that incorporates the dynamic interaction is referred to as the "coupled analysis." In the coupled analysis, the entire structure, comprising both the primary and secondary structures, is treated as a two-degree-of-freedom system. Conversely, the "uncoupled analysis" is conducted without considering the dynamic interaction between the primary structure (PS) and secondary structure (SS). During the uncoupled analysis, both the primary and secondary structures are separately regarded as single-degree-of-freedom systems. A series of analysis cases were performed using the uncoupled method to illustrate the observable impact of dynamic interaction between the PS and SS on the seismic response of the SS. Fig. 1 shows the SDOF primary structure attached to an acceleration-sensitive SDOF secondary structure. This study makes the assumption that the primary structure's damping ratio (ξ_p) is 5%.

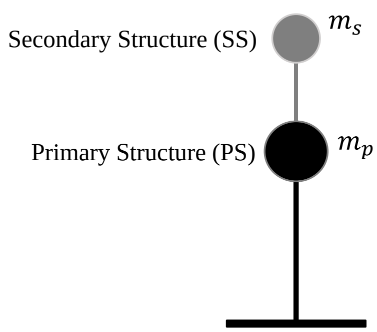


Fig. 1. Primary structure with a Secondary structure

2.1. Uncoupled Analysis

In this type of analysis, the dynamic interaction between the PS and SS (Fig. 1) is neglected. The dynamic response of the primary structure for a given earthquake loading can be computed according to Eq. (1).

$$m_p\ddot{x}_p + c_p\dot{x}_p + k_p x_p = -m_p\ddot{x}_g \quad (1)$$

where m_p, c_p, and k_p are the mass, damping, and stiffness for the primary structure: $c_p = 2m_p\xi_p\omega_p$; ω_p is the given primary structure's frequency; x_p, $\dot{x}_p$, and $\ddot{x}_p$ are the relative displacement, velocity, and acceleration of the primary structure with reference to the ground; $\ddot{x}_g$ is the acceleration of the ground motion; $\ddot{x}_p + \ddot{x}_g$ is the primary structure's absolute acceleration response. To analyze the secondary structure, the absolute acceleration response of the primary structure is given as an input to the secondary structure, and the response of the SS can be computed according to Eq. (2).

$$m_s\ddot{x}_s + c_s\dot{x}_s + k_s x_s = -m_s(\ddot{x}_p + \ddot{x}_g) \quad (2)$$

where, k_s, c_s, and m_s, are the stiffness, damping, and mass of the secondary structure: $c_s = 2m_s\xi_s\omega_s$; ξ_s, and ω_s are the damping ratio and frequency of the SS; x_s, $\dot{x}_s$, and $\ddot{x}_s$ are the relative displacement, velocity, and acceleration of the secondary structure, respectively. The procedure of generating the floor response spectrum without considering the dynamic interaction between the structures is shown in Fig. 2.

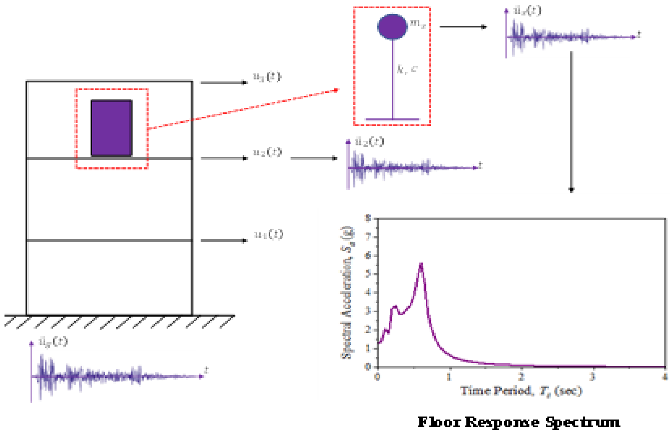


Fig. 2. Procedure for generation of floor response spectrum via uncoupled analysis

2.2. Coupled Analysis

This type of analysis takes into consideration the dynamic interaction between the PS and SS. The dynamic behavior of the PS and SS for a given earthquake loading can be computed according to Eqs. (3) &(4), respectively.

$$m_p\ddot{x}_p + c_p\dot{x}_p - c_s\dot{x}_s + k_p x_p - k_s x_s = -m_p\ddot{x}_g \tag{3}$$

$$m_s\ddot{x}_s + c_s\dot{x}_s + k_s x_s = -m_s(\ddot{x}_p + \ddot{x}_g) \tag{4}$$

Eqs. (3) & (4) can be written in matrix form as follows in eq. (5):

$$\begin{bmatrix} m_p & 0 \\ 0 & m_s \end{bmatrix}\begin{Bmatrix} \ddot{x}_p \\ \ddot{x}_s \end{Bmatrix} + \begin{bmatrix} c_p & -c_s \\ 0 & c_s \end{bmatrix}\begin{Bmatrix} \dot{x}_p \\ \dot{x}_s \end{Bmatrix} + \begin{bmatrix} k_p & -k_s \\ 0 & k_s \end{bmatrix}\begin{Bmatrix} u_p \\ u_s \end{Bmatrix} = -\begin{Bmatrix} m_p\ddot{x}_g \\ m_s(\ddot{x}_p + \ddot{x}_g) \end{Bmatrix} \tag{5}$$

The Eqs. (1)-(4) are written as a system of first-order ordinary differential equations and solved numerically using the fourth-order Runge-Kutta technique in MATLAB R2019B. The Runge-Kutta method is a numerical technique for approximating solutions to ordinary differential equations (ODEs) with known initial conditions. It subdivides the problem into smaller steps and calculates slopes at various points within each step. By updating the solution at the end of each step, it iteratively refines the approximation until reaching the desired endpoint. The accuracy can be controlled by adjusting the step size, with smaller steps providing greater precision. This method is widely used in various scientific and engineering fields to solve ODEs, especially when exact analytical solutions are unavailable.

3. Ground Motions

Actual ground-motion data provide a realistic response in the seismic response evaluation technique [19], [20]. Such data is freely available in the PEER [21] NGA-West2 Database. As a result, in the current study, 11 horizontal ground motion excitations for hard soil type were examined according to ASCE 7-16 [22] for hard soil type. To reflect hard soil, ground motions with shear wave velocities (V_{S30}) of 360-760 m/s are used [23]. Ground motion details are shown in Table 1. In this study, spectrum compatible ground motions are used since they can greatly reduce computation work compared to multiple ground motions [24]. To generate spectrum-compatible earthquake excitations, the time-domain spectral matching technique [25] is applied. Fig. 3 depicts the IS 1893:2016 spectra (5% damping) and the mean ground excitation spectra. The average spectrum shall not fall below 90% of the target spectrum for the whole-time range, according to ASCE 7-16. The Fig.3 shows that the mean spectra are over 90% of the target spectra.

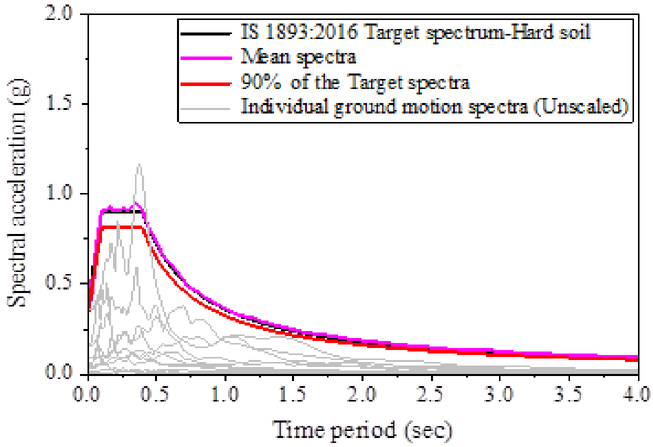


Fig. 3. Target and mean acceleration spectra

Table 1. Details of ground motions

Earthquake	Year	Station	Moment magnitude (Mw)	Joyner Boore distance (Rjb), km	Vs30 (m/s)
Helena_ Montana-01	1935	Carroll College	6	2.07	593.35
Helena_ Montana-02	1935	Helena Fed Bldg	6	2.09	551.82
Kern County	1952	Pasadena - CIT Athenaeum	7.36	122.65	415.13
Kern County	1952	Santa Barbara Courthouse	7.36	81.3	514.99
Kern County	1952	Taft Lincoln School	7.36	38.42	385.43
Southern Calif	1952	San Luis Obispo	6	73.35	493.5
Parkfield	1966	Cholame - Shandon Array #12	6.19	17.64	408.93
Parkfield	1966	San Luis Obispo	6.19	63.34	493.5
Parkfield	1966	Temblor pre-1969	6.19	15.96	527.92
Borrego Mtn	1968	Pasadena - CIT Athenaeum	6.63	207.14	415.13
Borrego Mtn	1968	San Onofre - So Cal Edison	6.63	129.11	442.88

4. Results and Discussion

The following sections investigate the influence of a dynamic interaction between the PS and SS on the dynamic behavior of the elastic SDOF secondary structure. The acceleration time-history response of the secondary structure and the floor response spectrum (FRS) are studied in this research.

4.1 Acceleration Time-History Response

In this section, the acceleration response of the secondary structure is presented as shown in Fig. 4. To investigate the effect of the dynamic interaction on the dynamic behaviour of the SS, the system shown in Fig. 1 is subjected to the ground motions. The two ground motions are randomly chosen from Table 1 for this analysis. The effect of the mass ratio (μ) and the damping ratio of the SS (ξ_s) on the acceleration response of the SS is investigated. The mass ratio (μ) is the ratio between the secondary structure's mass to the primary structure's mass. The μ values 0.001, 0.01, 0.1, and 0.5 are considered for the coupled analysis. The vibration periods of the PS (T_p) and the SS (T_s) are taken as 0.5 sec in this analysis. The damping ratios of the SS (ξ_s) are taken as 5%, and 1%.

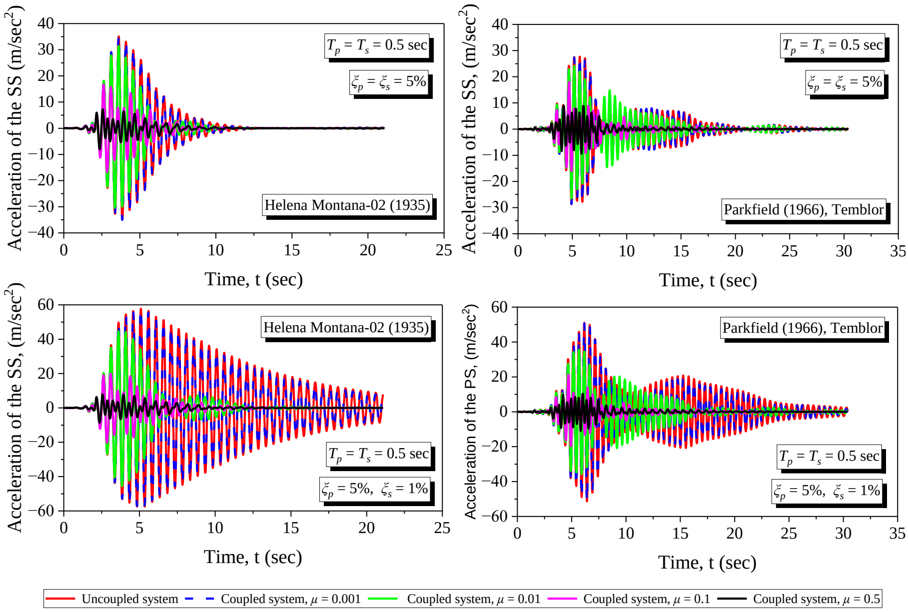


Fig. 4. Acceleration time-history response of the secondary structure

The amplitude of the acceleration response increases as the damping ratio of the SS decreases, as expected. The dynamic interaction between the primary structure (PS) and secondary structure (SS) demonstrates a minimal effect on the seismic response of the SS when the mass ratio is as low as 0.001 (0.1%). This is evident as the acceleration response with μ = 0.001 closely aligns with that of the uncoupled system. Hence, the seismic demands on the secondary structure can be calculated at this mass ratio using the uncoupled analysis. This observation is in line with the conclusions made in past research [26]–[28] As the μ increases (μ = 1%, 10%, and 50%), the dynamic interaction between the PS and SS shows a substantial impact on the acceleration response of the SS. For such mass ratios, the uncoupled analysis does not provide precise results.

Table 2. Peak acceleration of the SS (m/sec^2) for ξ_s = 5%

Ground motion	Uncoupled Analysis	Coupled Analysis			
		μ=0.001	μ=0.01	μ=0.1	μ=0.5
Helena_ Montana-02 (1935)	35.08	35.11	31.46	16.65	7.24
Parkfield (1966)	27.68	27.44	24.14	18.02	8.96

Table 2 illustrates the SS's peak acceleration response since peak values of any seismic response quantity give valuable insight into structural behavior. Table 2 clearly shows that for μ=0.01, 0.1, and 0.5, the peak acceleration response of the SS is lowered by 10%, 52.5%, and 79.3%, respectively, when compared to the uncoupled study under Helena_ Montana-

02 (1935) ground motion. Similarly, Parkfield (1966) ground motion reduces the peak acceleration response of the SS by 12.7%, 34.8%, and 67.6% for μ=0.01, 0.1, and 0.5, respectively, when compared to the uncoupled study. A similar pattern was seen for the ξ_s = 1%. Therefore, the coupled analysis is to be carried out to study the seismic behavior of the SS for higher mass ratios.

4.2 Floor Response Spectrum (FRS)

The maximum design forces for the design of the SS can be obtained from the floor response spectrum (FRS) approach [9], [29]. The FRS method disregards the PS and SS's dynamic interaction [30]. As a result, the current study made an effort to examine the FRS by taking into account the coupling effect between the PS and SS. The SS's peak responses to input ground motion are represented by the floor response spectrum. The effects of the mass ratio (μ) and the damping ratio (ξ_s) on the floor response spectrum are studied. Fig. 5 shows the FRS for different damping ratios and mass ratios of the SS for the given damping characteristics of the PS (T_p = 0.5 sec, ξ_s = 5%). The uncoupled system can be used to estimate the seismic demands on the SS for a tiny mass ratio (μ = 0.1%), as seen in Fig. 5 for this particular case.

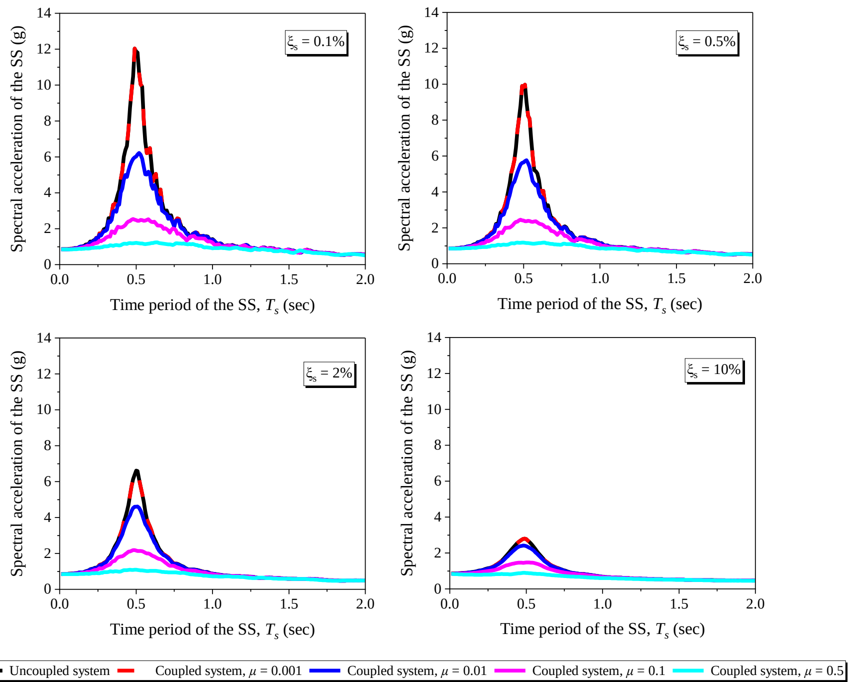


Fig. 5. Effect of damping and mass ratios of the SS on the FRS

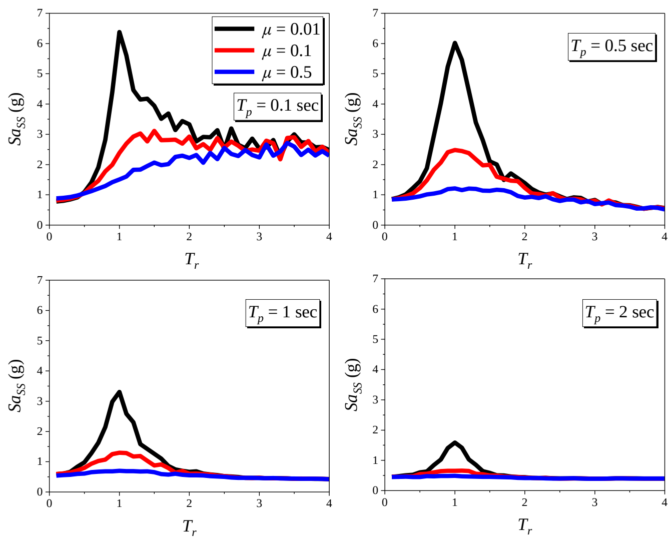
The coupled effect of the PS and SS on the FRS is seen when the mass ratio increases for all damping ratios of the SS. The dynamic interaction between the PS and SS shows a substantial impact on the magnitude of the spectral acceleration of the SS (Sa_{SS}) at T_s = 0.5 sec. Such effect is negligible on the behaviour of very stiff and flexible secondary structures irrespective of their damping ratio. For the mass ratio of 1%, the peaks of the FRS reduce about 49.2%, 41.8%, 30.4%, and 13.3% at the damping ratios of 0.1%, 0.5%, 2%, and 10%, respectively. From this particular case of analysis, it can be concluded that coupled analysis is required only if the SS is tuned to the vibration period of the PS. Otherwise, the uncoupled analysis is sufficient to analyses the seismic behavior of the secondary structure. It can also be deduced that the larger coupling effect on the FRS is observed for the lower damping ratios of the SS.

4.2.1 Effect of Vibration Period of the PS on FRS

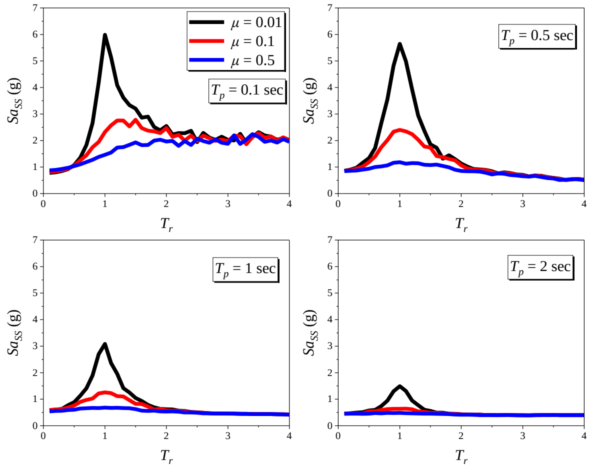
In the preceding section, it was examined how the damping and mass ratios of the SS affected the FRS for a specific primary structure vibration period (T_p = 0.5 sec). The dynamic characteristics of the primary structure substantially affect the secondary structure's seismic demands [26], [27]. As a result, an effort has been made to investigate the influence of a PS vibration period on the FRS for a specific mass and damping ratio of the SS in this section. The damping ratio of the PS (ξ_p = 5%) is kept constant for all the analysis cases. In this analysis, the tuning ratio is introduced as a key parameter. It is defined as the ratio between the vibration period of the secondary structure (SS) and the fundamental vibration period of the primary structure (PS), as indicated in Eq. (6). This parameter is employed to encapsulate the impact of the dynamic characteristics of the primary structure on the overall system.

$$\text{Tuning ratio}\ (T_r) = T_s/T_p \tag{6}$$

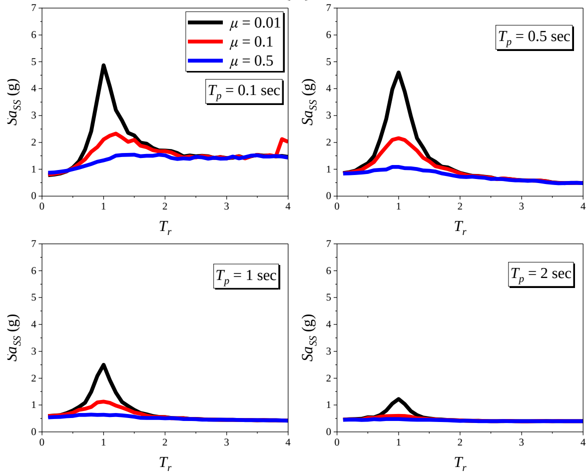
Fig. 6 shows the variation of the spectral acceleration of a SS with a tuning ratio for different mass and damping ratios of the SS. The FRS for the small mass ratio (μ = 0.1%) is not shown in this figure since at such a small mass ratio, the coupling effect on the FRS is negligible, as shown in Fig. 5. Looking at Fig. 6, it becomes evident that the influence of dynamic interaction on the FRS is substantial within the range of $0.8 \leq T_r \leq 1.2$. Conversely, for the ranges of $T_r < 0.5$ and $T_r > 2$, it's apparent that the impact of dynamic interaction on the FRS is negligible across all the considered values of ξ_s and μ. Hence, it can be concluded that the coupling effect on the FRS can be considered only if the vibration period of the SS is in the vicinity of that of the primary structure. Regardless of the μ, the Sa_{SS} reduces with an increase in the primary structure's vibration period for a given damping ratio of the SS.



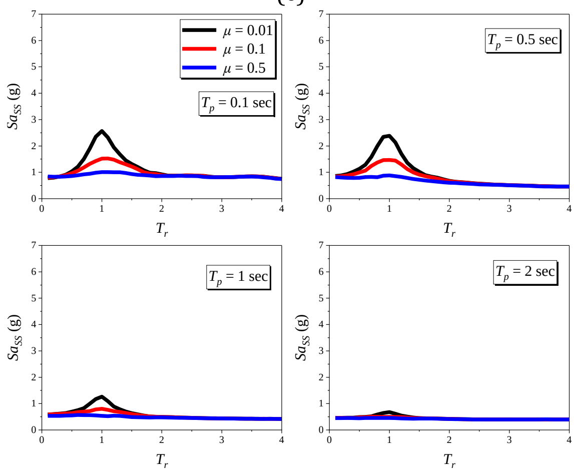
(a)



(b)



(c)



(d)

Figs. 6. a, b, c, d. Variation of floor response spectrum with tuning ratio for (a- ξ_s = 0.1%; b- ξ_s = 0.5%; c- ξ_s = 2%; d- ξ_s = 10%)

4.3 Component Dynamic Amplification Factor (CDAF)

The component's (secondary structure) acceleration relative to the floor acceleration to which it is coupled is examined in this section. Fig. 7 displays the FRS normalized by the associated peak floor accelerations (PFAs). A component dynamic amplification factor (CDAF) is the ratio of FRS to PFA. The CDAF of the building models is checked with the definitions of ASCE 7-16 [22] and FEMA P-750 [31] in the current study. According to ASCE 7-16, for flexible SSs with time periods greater than 0.06 seconds, the components amplification factor (a_p) is 2.5.

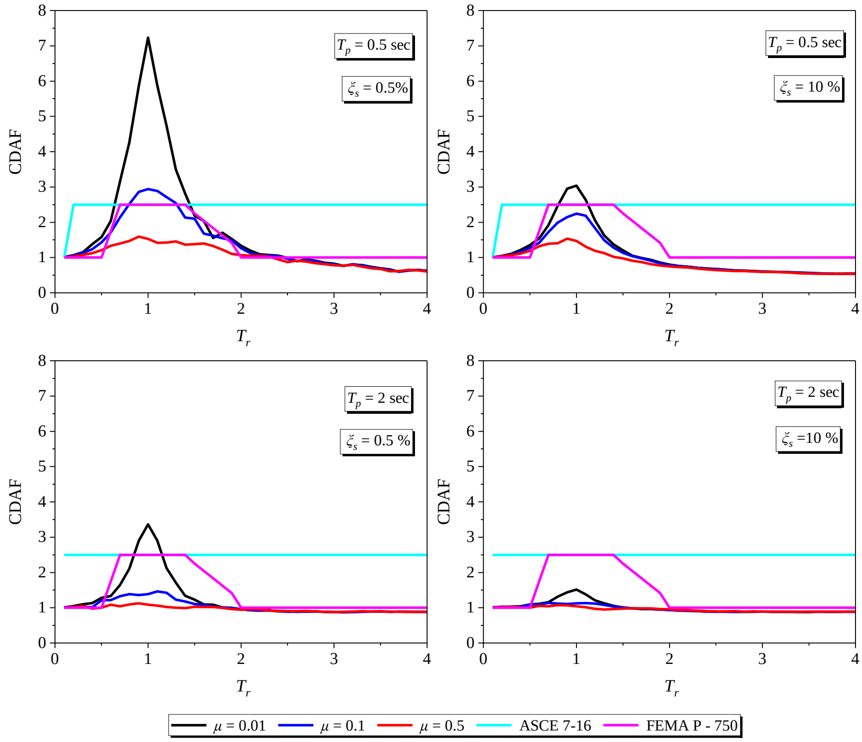


Fig. 7 Component dynamic amplification factors at different vibration periods of the PS and damping ratios of the SS

The value of the amplification factor for stiff SSs (T< 0.06 sec) is 1. Fig. 7 provides a clear depiction of the trends: the definitions outlined in ASCE 7 and FEMA P-750 tend to underestimate the CDAF for periods in proximity to the primary structure's vibration periods, specifically when $T_r \cong 1$ for a mass ratio of 1%. Conversely, these definitions tend to overestimate the CDAF at $T_r \cong 1$ when dealing with a flexible primary structure (T_p = 2 sec) and a substantial damping ratio in the secondary structure (ξ_s = 10%). The CDAF values specified by the code definitions start to become more conservative at a mass ratio of 10% as the SS damping ratio increases for a specific primary structure. When the mass ratio is raised to 50%, the estimated amplification factors provided by the code definitions are conservative. As shown in Fig. 7, this underestimation is also included in the definitions of FEMA P-750. The current code-based definitions should thus be modified to take into consideration the effects of the dynamic interaction between the PS and SS as well as the damping ratio of the SS.

5. Conclusions

This study aims to examine how a dynamic interaction affects the seismic requirements of a secondary structure. For good secondary structure design, a thorough understanding of the interaction between the primary and secondary structures is necessary. This article discusses a parametric investigation on the dynamic interaction of primary and secondary structures. The single-degree-of-freedom (SDOF) system is used for both the elastic primary structure (PS) and the elastic secondary structure (SS). The numerical approach is used to develop and solve the governing equations of motion for the coupled and uncoupled systems for a certain set of ground motions. The conclusions and main highlights in the present study are as follows:

- The dynamic interaction between the PS and SS shows an insignificant impact on the SS's seismic demands for the mass ratio 0.001 (0.1%). Hence, at this mass ratio, the seismic demands on the SS can be calculated using the uncoupled analysis.
- The dynamic interaction between the PS and SS shows a significant impact on the acceleration response of the SS as the mass ratio increases. The coupled analysis is required only if the SS is tuned to the vibration period of the PS, i.e., $0.8 \leq T_r \leq 1.2$. The uncoupled analysis is sufficient to analyse the seismic behaviour of the SS for $T_r < 0.5$ and $T_r > 2$.
- The larger coupling effect on the FRS is observed for the lower damping ratios of the SS. For a given damping ratio, the secondary structure's spectral acceleration decreases with an increase in the vibration period of the primary structure, irrespective of the mass ratio.
- The current code definitions underestimate the CDAF for a period closer to the fundamental vibration period of the primary structure.
- The mass ratio and damping ratio of the secondary structure have a significant effect on the CDAF.

The existing code-based definitions need to undergo modification to account for the dynamic interaction occurring between the primary structure (PS) and secondary structure (SS). Additionally, these revisions should also incorporate the damping ratio specific to the secondary structure. This adjustment is necessary to ensure that the structural design and evaluation procedures accurately reflect the dynamic complexities that emerge due to the interaction between these components and the influence of damping in the secondary structure.

List of Abbreviations

Abbreviation	Full form
FRS	Floor Response Spectrum
PS	Primary Structure
SS	Secondary Structure
PGA	Peak Ground Acceleration
SDOF	Single Degree of Freedom
CDAF	Component Dynamic Amplification Factor
PFA	Peak Floor Acceleration
FEMA	Federal Emergency Management Agency
ASCE	American Society of Civil Engineers

Acknowledgement

The authors acknowledge that this study is supported by Department of Civil Engineering, Koneru Lakshmaiah Education Foundation (KLEF), Vaddeswaram, Guntur, India.

References

[1] Murty CVR, Goswami R, Vijayanarayanan AR, Kumar RP, Mehta V V. Earthquake Protection of Non-Structural Elements in Buildings. 2012.

[2] Taghavi S, Miranda E. Estimation of Seismic Acceleration Demands in Building Components. 13th World Conf Earthq Eng Vancouver, BC, Canada. 2004;(3199):3199.

[3] Kamble V, Dayal Bharti S, Kumar Shrimali M, Kanti Datta T. Control of Secondary Systems Response in a Base-Isolated Building under Tridirectional Ground Motion. Pract Period Struct Des Constr. 2022;27(1):1-12. https://doi.org/10.1061/(ASCE)SC.1943-5576.0000641

[4] Wang T, Shang Q, Li J. Seismic force demands on acceleration-sensitive nonstructural components: a state-of-the-art review. Earthq Eng Eng Vib. 2021;20(1):39-62. https://doi.org/10.1007/s11803-021-2004-0

[5] Sullivan TJ. Post-Earthquake Reparability of Buildings: The Role of Non-Structural Elements. Struct Eng Int. 2020;30(2):217-23. https://doi.org/10.1080/10168664.2020.1724525

[6] Filiatrault A, Perrone D, Merino RJ, Calvi GM. Performance-Based Seismic Design of Nonstructural Building Elements. J Earthq Eng. 2018;00(00):1-33.

[7] Villaverde R. Fundamental concepts of earthquake engineering. CRC Press; 2009. https://doi.org/10.1201/9781439883112

[8] Landge M V., Ingle RK. Comparative study of floor response spectra for regular and irregular buildings subjected to earthquake. Asian J Civ Eng. 2021;22(1):49-58. https://doi.org/10.1007/s42107-020-00297-1

[9] Berto L, Bovo M, Rocca I, Saetta A, Savoia M. Seismic safety of valuable non-structural elements in RC buildings: Floor Response Spectrum approaches. Eng Struct. 2020;205(October 2019):110081. https://doi.org/10.1016/j.engstruct.2019.110081

[10] Surana M, Singh Y, Lang DH. Effect of irregular structural configuration on floor acceleration demand in hill-side buildings. Earthq Eng Struct Dyn. 2018;47(10):2032-54. https://doi.org/10.1002/eqe.3054

[11] Kelly JM, Sackman JL. Response spectra design methods for tuned equipment-structure systems. J Sound Vib. 1978;59(2):171-9. https://doi.org/10.1016/0022-460X(78)90498-4

[12] Lim E, Chouw N. Prediction of the response of secondary structures under dynamic loading considering primary-secondary structure interaction. Adv Struct Eng. 2018;21(14):2143-53. https://doi.org/10.1177/1369433218768563

[13] Salman K, Tran TT, Kim D. Grouping effect on the seismic response of cabinet facility considering primary-secondary structure interaction. Nucl Eng Technol . 2019; 52(6): 1318-1326. https://doi.org/10.1016/j.net.2019.11.024

[14] Smith-Pardo JP, Reyes JC, Ardila-Bothia L, Villamizar-Gonzalez JN, Ardila-Giraldo OA. Effect of live load on the seismic design of single-story storage structures under unidirectional horizontal ground motions. Eng Struct. 2015;93:50-60. https://doi.org/10.1016/j.engstruct.2015.03.020

[15] Sackman JL, Kelly JM. Seismic analysis of internal equipment and components in structures. Eng Struct. 1979;1(4):179-90. https://doi.org/10.1016/0141-0296(79)90045-2

[16] Igusa T, Der Kiureghian A. Dynamic characterization of two-degree-of-freedom equipment-structure systems. J Eng Mech. 1985;111(1):1-19. https://doi.org/10.1061/(ASCE)0733-9399(1985)111:1(1)

[17] Singh MP, Suarez LE. Seismic response analysis of structure-equipment systems with non-classical damping effects. Earthq Eng Struct Dyn. 1987;15(7):871-88. https://doi.org/10.1002/eqe.4290150708

[18] Suarez LE, Singh MP. Floor response spectra with structure-equipment interaction effects by a mode synthesis approach. Earthq Eng Struct Dyn. 1987;15(2):141-58. https://doi.org/10.1002/eqe.4290150202

[19] Bagheri B, Nivedita KA, Firoozabad ES. Comparative damage assessment of irregular building based on static and dynamic analysis. Int J Civ Struct Eng. 2013;3(3):505.

[20] Senaldi I, Magenes G, Penna A, Galasco A, Rota M. The effect of stiffened floor and roof diaphragms on the experimental seismic response of a full-scale unreinforced stone masonry building. J Earthq Eng. 2014;18(3):407-43. https://doi.org/10.1080/13632469.2013.876946

[21] Center P. PEER ground motion database. Pacific Earthq Eng Res Center, Univ California, Berkeley, CA, http//ngawest2 berkeley edu. 2013;

[22] ASCE. Minimum design loads and associated criteria for buildings and other structures (ASCE/SEI 7-16). American Society of Civil Engineers (ASCE) Reston, VA; 2016.

[23] Council BS.S.. NEHRP recommended seismic provisions for new buildings and other structures. Rep. FEMA P, 750, 2009.

[24] Khy K, Chintanapakdee C, Wijeyewickrema AC. Application of conditional mean spectrum in nonlinear response history analysis of tall buildings on soft soil. Eng J. 2019;23(1):135-50. https://doi.org/10.4186/ej.2019.23.1.135

[25] Alatik L, Abrahamson N. An improved method for nonstationary spectral matching. Earthq Spectra. 2010;26(3):601-17. https://doi.org/10.1193/1.3459159

[26] Surana M, Singh Y, Lang DH. Effect of structural characteristics on damping modification factors for floor response spectra in RC buildings. Eng Struct. 2021;242(April):112514. https://doi.org/10.1016/j.engstruct.2021.112514

[27] Challagulla SP, Bhargav NC, Parimi C. Evaluation of damping modification factors for floor response spectra via machine learning model. Structures. 2022; 39: 679-90. https://doi.org/10.1016/j.istruc.2022.03.071

[28] Anajafi H, Medina RA. Damping modification factor for elastic floor spectra. Bull Earthq Eng . 2019;17(11):6079-108. https://doi.org/10.1007/s10518-019-00684-3

[29] Haymes K, Sullivan TJ, Chandramohan R. A practice-oriented method for estimating elastic floor response spectra. Bull New Zeal Soc Earthq Eng. 2020;53(3):116-36. https://doi.org/10.5459/bnzsee.53.3.116-136

[30] Adam C, Furtmüller T, Moschen L. Floor response spectra for moderately heavy nonstructural elements attached to ductile frame structures. In: Computational methods in earthquake engineering. Springer. 2013; 69-89. https://doi.org/10.1007/978-94-007-6573-3_4

[31] (BSSC) BSSC. Nehrp recommended seismic provisions for new buildings and other structures (fema p-750). Report Prepared for the Federal Emergency Management Agency (FEMA). National Institute of Building Sciences Washington, DC; 2009.