

Seismic Performance of a Hospital with Base Isolation

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Abstract

The demographic growth of the population and the contemporary environmental disasters are two of the main challenges faced by civil engineers. As buildings are getting taller and their seismic isolation systems are getting more sophisticated, understanding the structural behaviour of these isolated structures is a complex task. Assessing the behaviour of base isolated structures in seismically active countries is a main topic of the research work conducted by the Prof. Juan Carlos de la Llera at the Pontificia Universidad Católica (PUC) de Chile. Indeed, Chile is one of the most active seismic regions in the world and is the home to the tallest skyscraper in Latin America. Furthermore, the city of Santiago is a vast city, with a dense population and a complex healthcare network system that is also growing with new healthcare facilities.

This presentation focuses on the seismic performance of base isolated buildings such as hospitals and more specifically on the effect of higher modes on the response of the structure (in displacement and acceleration). The higher mode effect relates to the influence of high vibrational frequencies on the displacement or acceleration. These high modes are that more important when considering non-structural elements such as acceleration sensitive equipment present in hospitals.

Through the implementation of linear and non-linear models of base isolated buildings that share the same geometry of typical Chilean hospitals on the open-source software OpenSees,

- The effect of higher modes is evaluated and quantified by conducting dynamic history analyses using various sets of natural ground motion records.
- The base case for the comparison and extraction of the higher modes is analysed and a methodology using a physical filter and a numerical filter is elaborated.

The objective being to identify the different modes and to extract their contribution to the response. The results obtained indicate that the first mode governs the displacement regardless of the isolator, however, the second mode and third modes have an important contribution to the acceleration response of the upper floors of the tall buildings. A result that is even more apparent for the non-linear isolator.

The key takeaway would be to incorporate the higher mode effects in the design codes and to be able to use the findings in practice when studying tall isolated buildings.



SEISMIC PERFORMANCE OF A HOSPITAL WITH BASE ISOLATION

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1 ABSTRACT

The demographic growth of the population and the contemporary environmental disasters are two of the main challenges faced by civil engineers. As buildings are getting taller and their seismic isolation systems are getting more sophisticated, understanding the structural behaviour of these isolated structures is a complex task. Assessing the behaviour of base isolated structures in seismically active countries is a main topic of the research work conducted by the Prof. Juan Carlos de la Llera at the Pontificia Universidad Católica (PUC) de Chile. Indeed, Chile is one of the most active seismic regions in the world and is the home to the tallest skyscraper in Latin America. Furthermore, the city of Santiago is a vast city, with a dense population and a complex healthcare network system that is also growing with new healthcare facilities.

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2 INTRODUCTION

The design, and construction, of buildings in seismically active regions is a very complex and challenging task for structural engineers. The seismic performance assessment of these buildings and the accurate modeling of the dynamic properties of isolated structures has been a prominent research topic in the structural dynamics engineering field.

The research work is developed with Prof. Juan Carlos de la Llera at the Pontificia Universidad Católica (PUC) de Chile, supervised by Prof. Katrin Beyer from EPFL, and also supported by José Gallardo and Juan Pablo Muñoz. The focus is put on health care facilities in Santiago, Chile, which are mostly designed with seismic isolation. Chile is one of the most seismically active countries in the world due to the subduction zone at the Nazca-South America plate. As a consequence, it has experienced several earthquakes with magnitude 8 or larger with a recurrence period of around 25 years. The most prominent civil structures as well as the residential homes in the country are protected by seismic devices.

Indeed, seismic isolation has emerged as an effective strategy to mitigate the damaging effects of earthquakes on structures. Due to their effectiveness in protecting the structural and non structural components in residential buildings, healthcare facilities or important infrastructures, seismic isolation devices usually work as filters able to control the behavior of the structure. The behavior of these devices is however highly non-linear and most times very difficult to analyse, especially when considering structures with high modes. Modes are the different patterns or shapes of vibration that a structure can have when subjected to a dynamic loading. Each mode is associated with a frequency at which the structure vibrates. High modes refer to modes with high or very high frequencies of vibration. They are often characterised by complex vibrational patterns or localized movements of the structure. Indeed, the "higher mode effect" on the behavior of seismic isolated structures and its implications on the seismic performance has not been extensively studied, especially when considering large deformations of the isolation devices.

The objective is to enhance the performance of the structures and their non structural components at different hazard levels and to minimize the use of the facilities during and after an earthquake. The following project aims to evaluate at what level of deformations of the isolation system are the effects of higher modes triggered (significantly) and to what extent do higher mode effects influence the seismic performance of a seismically isolated hospital structure in Chile.

Objective and methodology:

There are many existing types of seismic protection devices that are incorporated in structures. On one hand, energy dissipators are capable of working within the structure to dissipate as much energy as possible using the relative deformations and velocities between different points of a structure. These deformations could be amplified by higher modes and add energy to the devices. Seismic isolators on the other hand introduce a filter that changes the dynamic properties of the system by elongating the fundamental period and increasing the energy dissipation capacity. The ones that will be studied here are high-damping rubber bearings.

High-Damping Rubber Bearings (HDRBs) are one of the most widely used isolation devices in practice due to their great performance. These devices are composed of intercalating and vulcanizing layers of rubber material and thin steel shims. The force-deformation constitutive behavior of the rubber is highly non-linear and complex, and consequently not easily modeled analytically. Indeed, several mathematical models that consider the characteristic phenomena of the devices have been proposed for simulating the non-linear shear behavior of HDRBs under large deformations. Under small to moderate seismic loads the structure undergoes significant lateral displacements but the bearings provide large flexibility. For really small deformations, these devices get very stiff. However, when the seismic demands increase significantly, the rubber material experiences stiffening, which could engage higher modes effects and increase the demand on the elements above the isolation interface.

The work is divided in multiple sections, the structural archetypes of the models considered for the study are presented in a general manner (the superstructure and the isolation system) and later on in detail in the section 3. Several types of models are developed, a 2D Moment Resisting Frame (MRF) and a Sub-assembly model of the frame which is a portion unit extracted from the frame that can be repeated indefinitely, as well as a Matlab benchmark model of the Sub-assembly. The focus is then put on the Sub-assembly model from OpenSees in section 4 where the dynamic properties of the model are presented as well as the static analyses that are conducted to verify and validate the model. Furthermore, a section 5 dedicated to the dynamic analysis of the models is developed looking at the selection of the ground motion records, the outputs recorded and the results. The various methods developed to extract the higher modes are illustrated as well. A section 6 dedicated to the parametric analysis of another taller building where the effects of higher modes are noticeable is then presented as part of the final analysis. The validation of the higher mode effect findings is then presented in section 6.3, followed by a conclusion of the research work.

3 PRESENTATION OF THE STRUCTURAL MODELS

Within the scope of this project, various finite element models were examined for simulating the behavior of base isolated reinforced concrete structures. Most of the models were created on OpenSees (Open System for Earthquake Engineering Simulation) [1] which is an open-source software for simulating the response of structural and geotechnical systems subjected to earthquakes or other dynamic loads.

Although the research work focuses on the behavior of Chilean hospitals, using the finite element model of an existent hospital and running it forehand is not the best approach to capture the higher mode effect due to the complexity of the structure and the running time on OpenSees.

Model name	Superstructure	Isolation system
2D Frame linear	Linear	Linear
2D Frame non linear isolator	Linear	Non Linear
Sub-assemblage linear	Linear	Linear
Sub-assemblage non linear isolator	Linear	Non Linear
Matlab Benchmark	Linear	Linear
Rigid body	Linear	Linear
Rigid body	Linear	Non Linear
Taller building	Linear	Linear
Taller building	Linear	Non Linear

TABLE 1
 List of the models developed

The table above shows the different combinations that were made possible concerning the linearity of the superstructure and the linearity of the isolation system to capture the effective behavior of linear systems in regards to the higher mode effect. In parallel to the OpenSees models of the Frame and the Sub-assembly, a linear elastic Matlab model was created by Francisco Bertin to serve as a benchmark model for the modal properties made of five lumped masses and allows to have a direct access to the mass, stiffness and damping matrices of the model, which are elements not easily accessible on OpenSees. Furthermore, a Rigid body model is created as a single degree of freedom structure with both a linear and non linear isolator, it will be presented in the following chapters. Finally, a taller 15 story building is created also on OpenSees and analysed with a linear and non linear isolator.

3.1 REVIEW OF THE MODELS

The design properties of the initial 3D structure have been calculated using the Chilean standard code [2] and they are presented below.

Characteristics	Santiago Metropolitan, seismic zone 2	Soil type C (stiff gravel)	Damping of structure: $\xi = 10\%$
Dimensions	Geometry of common Chilean hospital	Reinforced concrete	4 Spans of 7.5m, Height story of 4 m
Materials	Steel bars A630-420H grade	Concrete C25/30	
Loads	Dead load on slab 200 kgf/cm^2	Live load on slab (hospital) 400 kgf/cm^2	
Isolator	Annular shaped HDRB diameter 700 mm	34 bearing layers and 33 Steel shims	Shear modulus 5 MPa

TABLE 2
 4 Storey building base isolated design properties

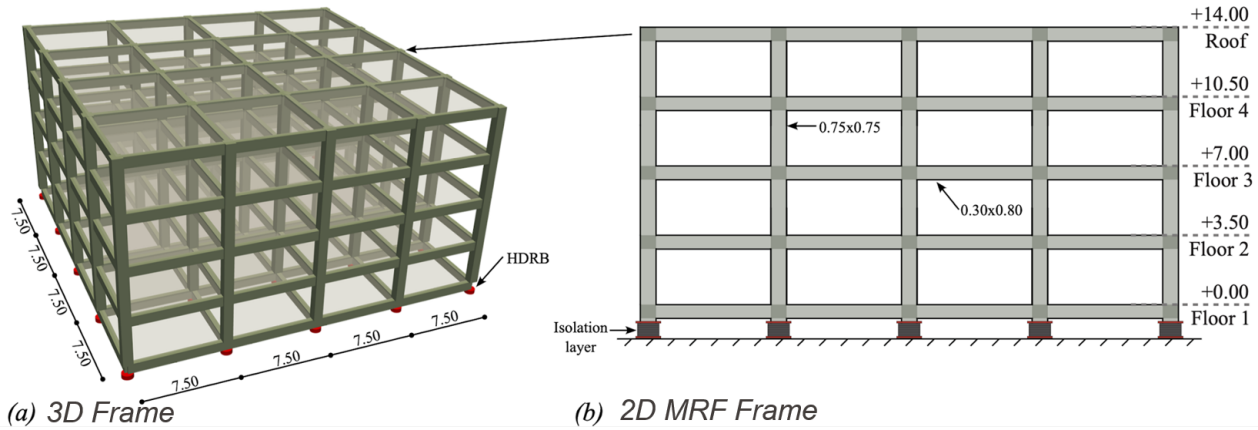


FIGURE 1

Structural archetypes taken from [Gallardo et al. 2023a]

The analysis properties are the following. The 3D building was adapted into an equivalent 2D MRF in order to be implemented on OpenSees with the different isolators, which are better implemented in a 2D space rather than a 3D space. Then, the Sub-assembly model of the 2D Frame is created to run the analyses.

Damping	Damping target of the superstructure: $\xi = 1\%$	Rayleigh with values on K only
Seismic mass	Self weight + 50% live loads	
Isolated periods	Isolator fixed at the base	$T_1 = 3,430s$, $T_2 = 0,411s$, $T_3 = 0,185s$
Assumptions	Mass contribution of transversal beams: nodal masses	

TABLE 3

4 Storey building base isolated analysis properties

All the models, although different, follow the same design procedure on OpenSees. The process begins with the definition of the nodes, the definition of the structural elements such as the beams or columns and their structural properties (the materials, area, elastic modulus, inertia and distributed mass along the element line), the definition of the masses, the load patterns, the isolation system and the damping. For the analysis, the parameters which are important to study are recorded and later on post processed.

The modeling uncertainties coming from the model geometry simplification, the materials used or the loads uncertainties have been directly taken into account with security factors from the Chilean design code and the final values are directly implemented on the FE model definition files.

3.2 THE SUPERSTRUCTURE

The numerical model of the superstructure is developed by considering first of all a structural idealization and a consideration of the degrees of freedom as well as the dimension in which it is built. The nodes situated at the base of the isolation system are fixed.

The damping in the superstructure is responsible for a part of the energy dissipation during an earthquake due to the slight inelastic behavior of the elements modeled as elastic or the non structural elements that

are not taken into account in the model. The damping matrix is given by the equation :

$$C = a_0M + a_1K \tag{1}$$

where M and K are the mass and stiffness matrices of the structure.

In the case of isolated buildings, the damping matrix C is assembled as a combination of the damping matrix of the superstructure C_s and the damping matrix of the isolation system C_b .

However, modeling the damping in this manner can lead to an overestimation of the damping in the isolated and higher modes of the structure, which is referred to as damping leakage. In the models used for this research, all the coefficients related to the mass component of the Rayleigh damping in the superstructure have been put to zero to avoid the leakage to the first mode (the isolated mode).

3.3 THE ISOLATION SYSTEM

Modelling the isolation system is a complex task because it implies a certain compromise between capturing the actual behavior of the high-damping rubbers and making the implementation practical on a finite element software. [3] The more advanced and sophisticated the model of the HDRBs, the larger the number of parameters to calibrate. Two types of isolation systems are considered, both using OpenSees elements; one that is a linear isolator and one non linear isolator that was proposed by authors Jose Gallardo, De la Llera, Restrepo and Chen in the paper named " A numerical model for non-linear shear behavior of high damping rubber bearings" which is referenced below [4].

The linear isolator uses the OpenSees command *twonodelink* with elastic materials to symbolize the axial, shear and rotational stiffness of the rubber. The values of the axial, shear and rotational stiffness were calculated considering the mean stiffness value obtained after performing an OpenSees analysis of the isolator alone and getting the mean of the hysteretic response. The rotational stiffness was increased to insure that the isolator does not rotate much. A viscous damping element is added in parallel to the materials with a damping value c and added to the *twonodelink* element.

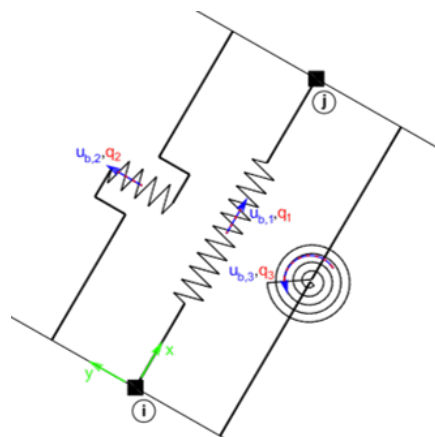


FIGURE 2
Twonodelink element from OpenSees (to insert between nodes i and j)

The other isolator used for the models which is non linear is called the New High Damping Rubber (NHDR) by the authors mentioned above. It uses the *twonodelink* command of Opensees but with an estimation of a total of 17 parameters where the shear response is defined using a *uniaxialmaterial*, and the axial and bending elements are modeled as linear elastic. It is essentially made of a hyperelastic spring connected in parallel with a dissipative element.

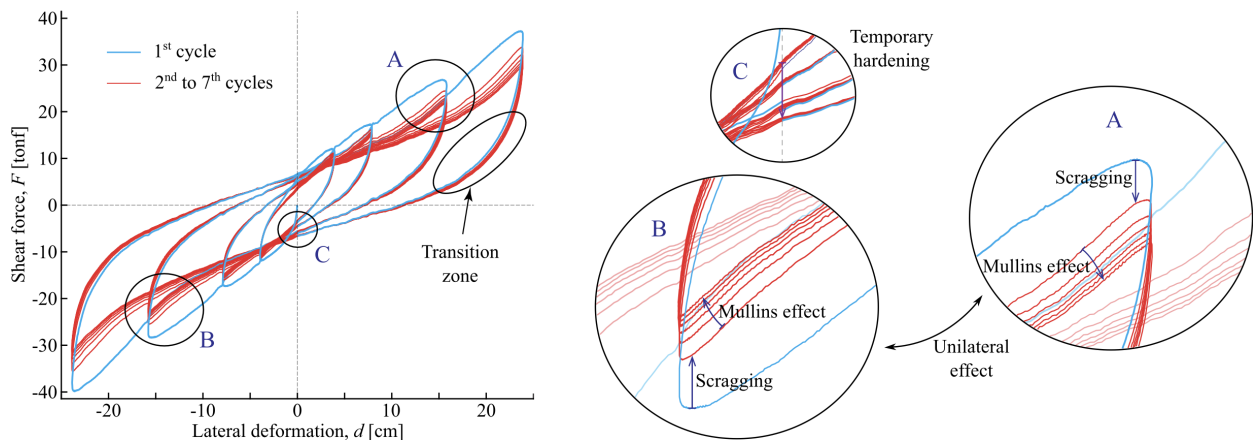


FIGURE 3

Characteristics of the shear force–deformation response of an HDRB taken from [Gallardo et al. 2023a] [4]

4 CALIBRATION OF THE SUB-ASSEMBLAGE MODEL

From the initial building and the 2D Frame modeled on OpenSees, a sub-assembly was designed and modeled on OpenSees because it is overall more efficient and allows a reduction in the complexity of the problem.

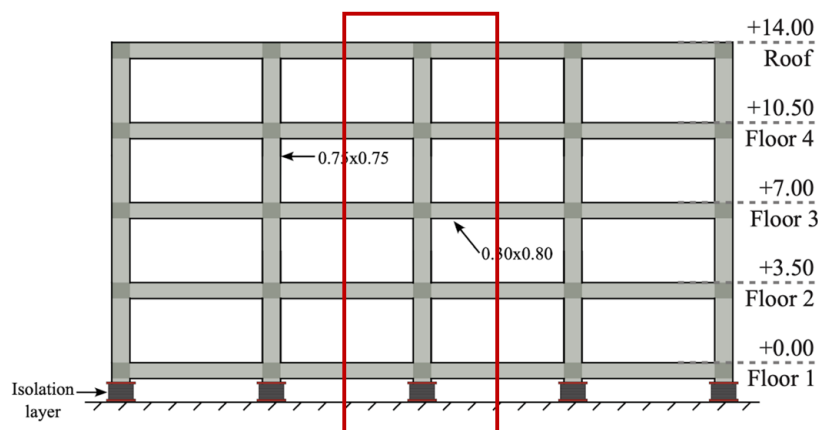


FIGURE 4

Sketch of the extraction of the Sub-assembly

Two different sub-assembly models were created: one with a linear superstructure and a linear isolator,

one model with a linear superstructure and a non linear isolator. Having linear models helps to test the behavior of the superstructure and the isolator.

But for these models to correctly capture the behavior and properties of the initial building, it is important to fine tune and verify both the dynamic properties and run a static analysis on the model.

The beams and columns are elastic elements, modelled with the command *element elasticBeamColumn* where the corresponding values for the inertia, the area, the elastic modulus and the distributed mass of the element are set. All the elastic elements from OpenSees are automatically linear. The half beams are simply supported at their ends, which is materialised by the constraint *fix* allowing movement in the x and z direction but not the y direction. The masses added on the nodes are built with the command *mass* followed by the value for the distributed mass in the horizontal and vertical directions. The loads are created with the command *eleLoad* when associated to the columns and the nodal loads are created with the command *Load*. It is important to note that the mass and the loads of the beams are multiplied by a factor 5/6 that accounts for the fact that extra beam elements are added when laying 5 sub-assemblies in series. The damping on the superstructure alone is calculated with Rayleigh damping considering a 1% damping ratio.

The Matlab benchmark model mentioned above is created using the linear properties of the Sub-assembly and a simple representation of the model is illustrated below. The mass m1 represents the sum of the lumped mass coming from the slab and the out of plane beams as well as the mass m2 but for the roof.

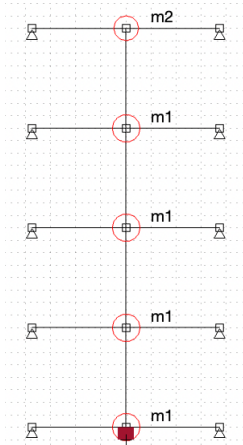


FIGURE 5
 Matlab Benchmark model

4.1 DYNAMIC PROPERTIES

To begin, a modal analysis is run on OpenSees to access the modal periods and modal shapes of both the Frame and the Sub-assembly. The modal report obtained from the OpenSees analysis gives access to the eigenvalues associated with each mode, the frequency, the period and mass related parameters like the center of mass of the structure and the prominent direction of contribution of the masses.

The results from the modal report show that the fundamental period between the Frame and Sub-assembly have a 4.8% difference (3.6s for the Sub-assembly versus 3.43s for the Frame) which is acceptable and allows a first validation of the Sub-assembly model. The modal shapes that are presented below 7 also illustrate the similarities between the models. As shown in the graphs below, the modes one and two are identical for both models, whilst the modes three and four are inverted from one model to the other. The higher modes are slightly different in both models which is expected and allows to identify which modes are local modes such as the mode five for example (related to the model alone) and which ones are global modes such as the modes one, two and three.

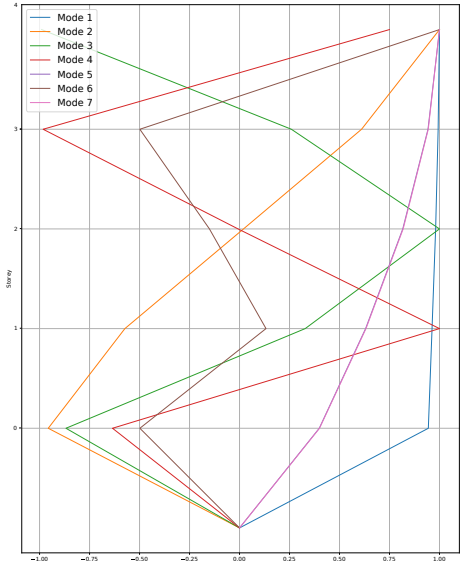


FIGURE 6
2D Frame modal shapes

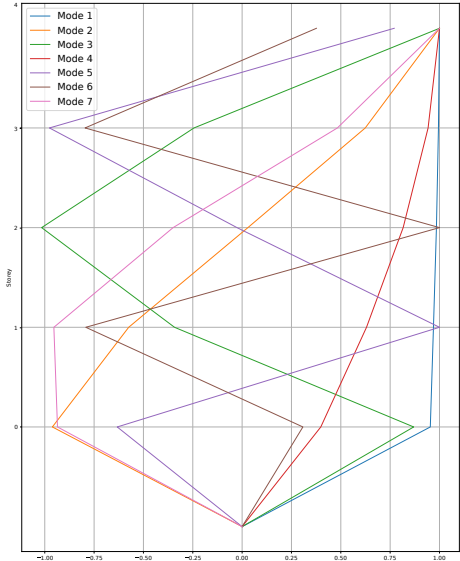


FIGURE 7
Sub-assembly modal shapes

5 DYNAMIC ANALYSIS

The dynamic analysis refers to the simulation of the structural response to time-varying loads which here are earthquakes.

5.1 SELECTION OF THE GROUND MOTION RECORDS

First and foremost, a set of sample records were used to perform the analysis and to view the difference between the responses of the models. Then, the time histories of the ground motion records were chosen considering the seismic model properties and the location of the Hospital Emergency Public Assistance in Santiago (HUAP) geography coordinates for a single period of 2,5 seconds for the conditional spectrum. Furthermore, the selection process of the ground motion records does not give the best results when a very long period is used because the spread in the short and medium range is immense.

5.2 DYNAMIC COMPARISON OF THE SUB-ASSEMBLY AND THE RIGID BODY

The results provided by the Matlab benchmark provide an insight into the seismic behavior of the structure, going back to the Sub-assembly model on OpenSees, the objective is to extract the modal contributions of higher modes for both the linear and non linear model for various hazard levels.

The first method used to visualise the different modes and extract the higher modes is using a "physical filter" characterising the first mode that is embodied by a rigid body model on OpenSees. If the isolated system is well designed the superstructure should behave like a rigid body. That Rigid body FE model is a single degree of freedom (SDOF) isolated element that captures solely the first mode (thus the isolated mode). This assumption is considered reasonable as most of the seismic isolation preliminary design considers the structure as a rigid body controlled by the first mode.

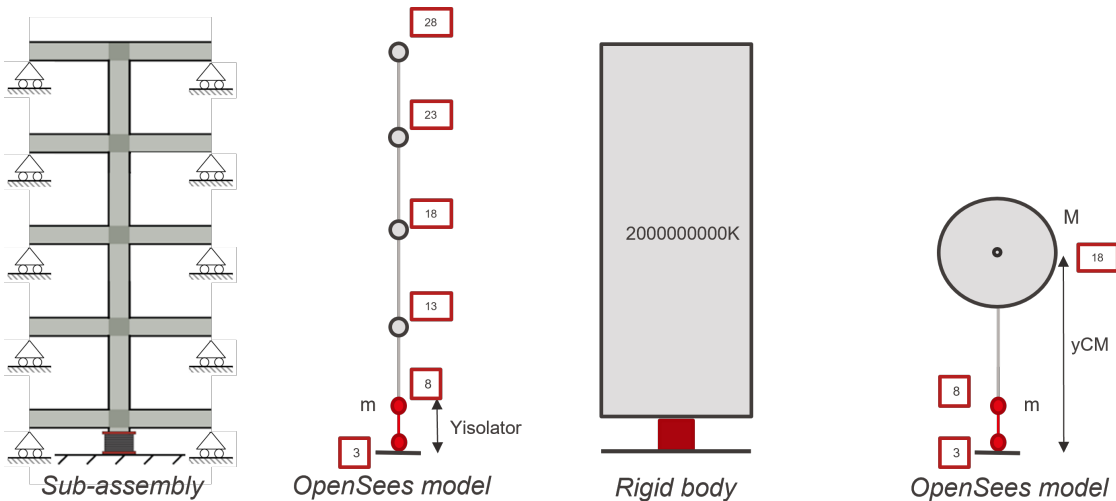


FIGURE 8
 Sketch of the Rigid body model

The analysis that is conducted is a dynamic analysis comparison of the time history responses in displace-

ment and acceleration of the linear Rigid body and the linear Sub-assembly at first, then the non linear Rigid body and non linear Sub-assembly using the *groundmotion000* of the hazard level *IM000*. A FAS comparison of the models is also conducted.

First, the displacement at the base is evaluated as well as the upper floors of the linear Sub-assembly. The results are presented below in the time domain and frequency domain to visualise the different modes. Indeed, each peak is characterised by a mode, with its angular frequency corresponding to the modal report values obtained showing the natural frequencies of each modes. For the comparison, the base, the second floor and the roof responses are showed. The orange curves represent the responses of the Rigid body model from Opensees and the blue curve represent the responses of the Sub-assembly model from OpenSees. The black curve is the residual value obtained after calculating the difference of the time history response of the Sub-assembly minus the Rigid body.

The results indicate that the first mode dominates the displacement response regardless of the floor level because the curves are almost exactly the same for the Sub-assembly and the Rigid body.

For the acceleration response, as the Rigid body represents the first mode (the isolated mode), it is expected that the FAS response of the system only shows one peak value, which is the case. The Sub-assembly however presents higher mode peaks corresponding to the second and third modes that are more or less important depending on the floor level.

Higher modes have an influence on the acceleration response of the Sub-assembly, especially the second mode that contributes to the base and the roof but not the second floor. The third mode is also present at the base and the roof.

After performing the same dynamic analysis using the Rigid body and Sub assembly models containing the non linear isolator (NHDR) the results are presented below. In comparison to the linear case, the residual of the difference between the maximum of the Sub-assembly and the maximum of the Rigid body is larger for the acceleration responses as seen on figure 12, indicating a higher importance of the effect of higher modes to the response of the structure. The results regarding the displacement for the base, the second floor and the roof are presented below followed by the results regarding the acceleration.

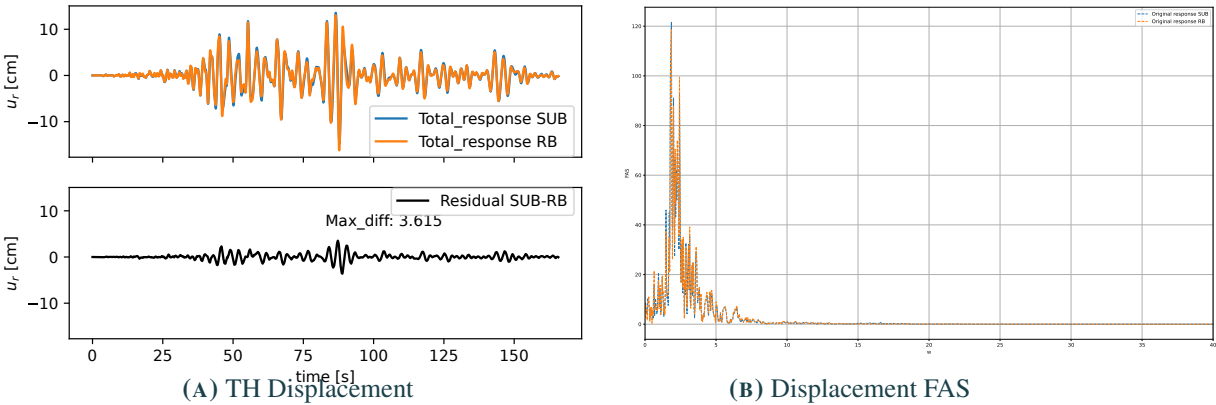


FIGURE 9
 Comparison of the non linear Rigid body and Sub-assembly for the Base

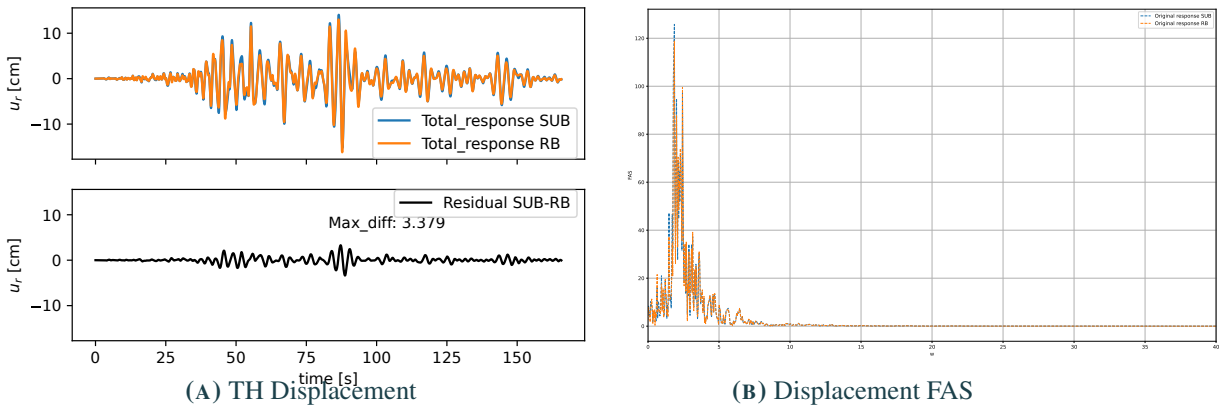


FIGURE 10
Comparison of the non linear Rigid body and Sub-assembly for the Second Floor

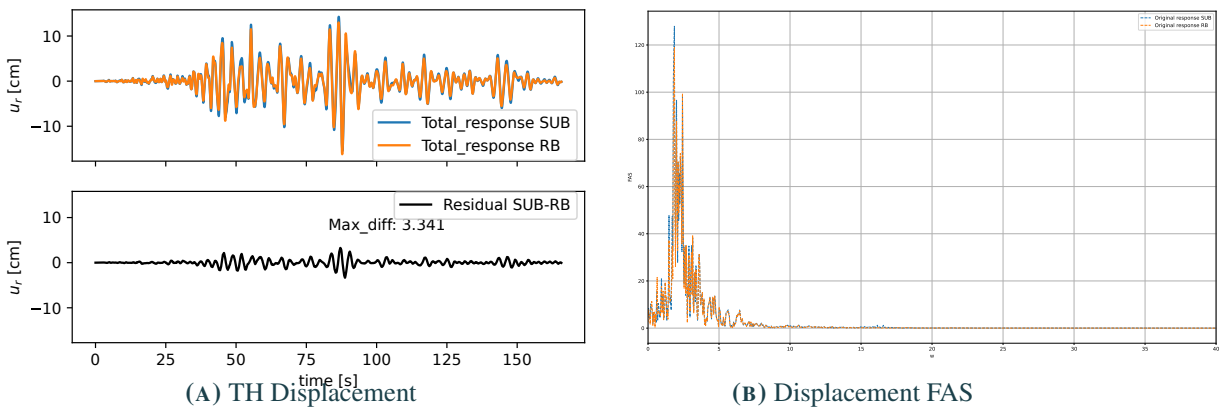


FIGURE 11
Comparison of the non linear Rigid body and Sub-assembly for the Roof

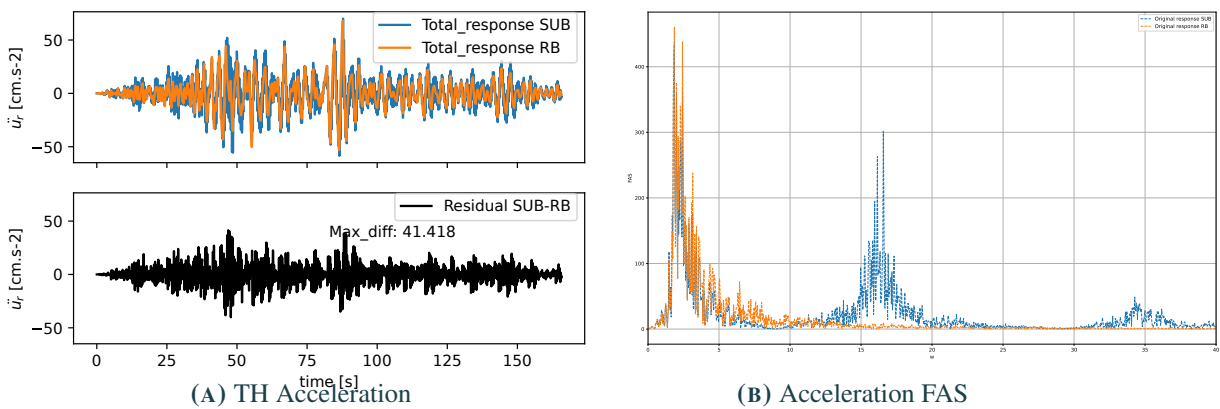


FIGURE 12
Comparison of the non linear Rigid body and Sub-assembly for the Base

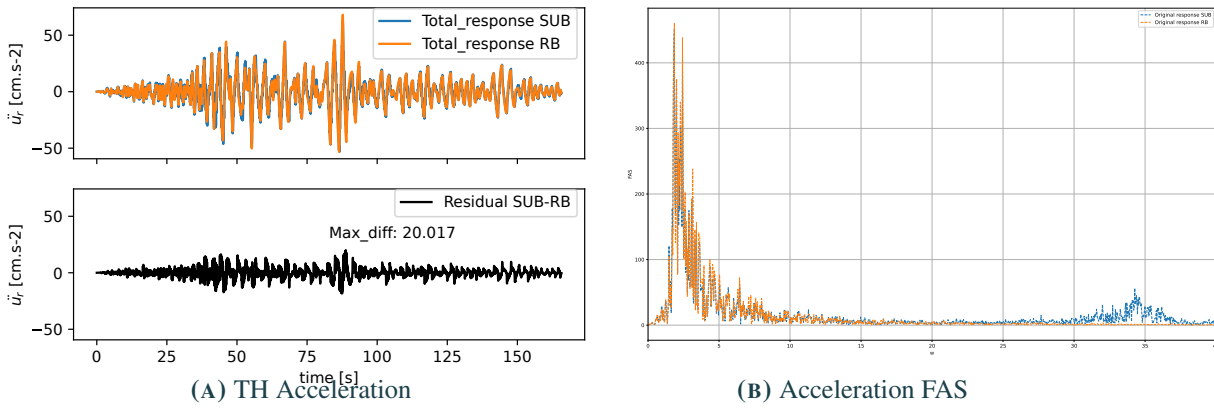


FIGURE 13
Comparison of the non linear Rigid body and Sub-assembly for the Second Floor

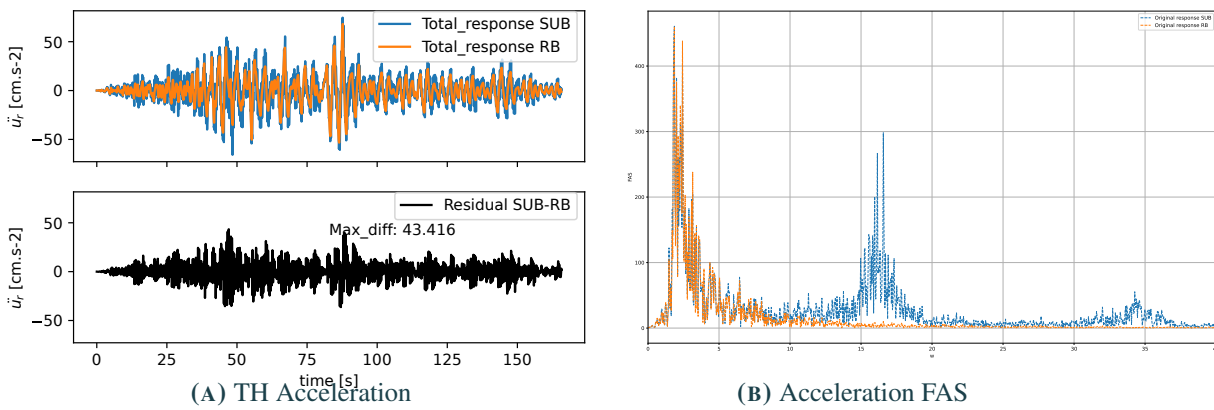


FIGURE 14
Comparison of the non linear Rigid body and Sub-assembly for the Roof

As seen previously, the second mode has a strong impact on the base and the roof but not the second floor, whereas the third mode has an important impact on the second floor but not the other floors. The fact that the Rigid body model does not show any peak other than the isolated mode in the FAS indicates that it is possible to extract only the contribution of the higher modes, when filtering the high frequencies.

5.3 NUMERICAL FILTERING OF THE SUB-ASSEMBLY

The second method that was considered to define and extract a base case of the comparison of responses and to highlight the higher mode effect is numerical filtering. Filtering allows a separation of different frequency components within a signal in order to analyse specific frequency bands or the isolation of particular signal features. In the case of this study the objective is to isolate the modes that are interesting and to remove the ones that are not wanted in the total response.

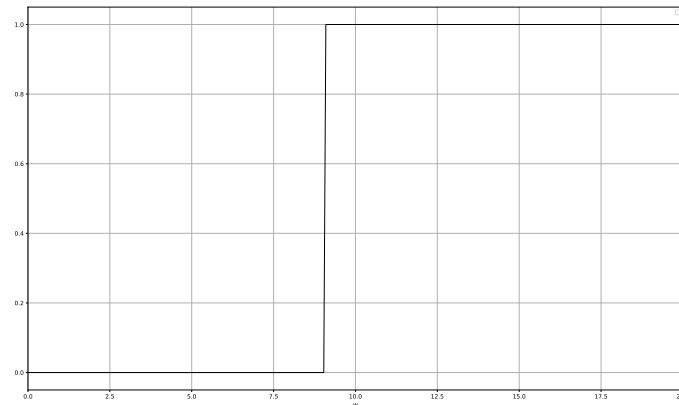


FIGURE 15
Heaviside step filter for middle cut-off frequency

When looking at the displacement response for the different ground motion records, the maximum displacement does not occur at the same time for all the floors of the building. Thus, the inter storey drift is calculated as the difference between the response of one storey to the storey under it and taking the maximum value and normalising it by the storey height. The results are then presented in percentage. The peak floor acceleration (PFA) however is obtained by calculating the maximum absolute value of the acceleration at each storey. Finally, the RMS of a storey is obtained by squaring the acceleration of the storey, doing the mean of those values and then taking the root value.

A modal comparison of peak values for the interstory drift and peak story acceleration is calculated.

Finally, the contribution of each mode for each floor is presented in percentage for each *IM* for the drift and the PFA. These graphs are calculated for both the linear and non linear model. Some of the floor results do not accumulate to 100% on the following graphs due to the method used to calculate the median value contribution of the mode from the histograms.

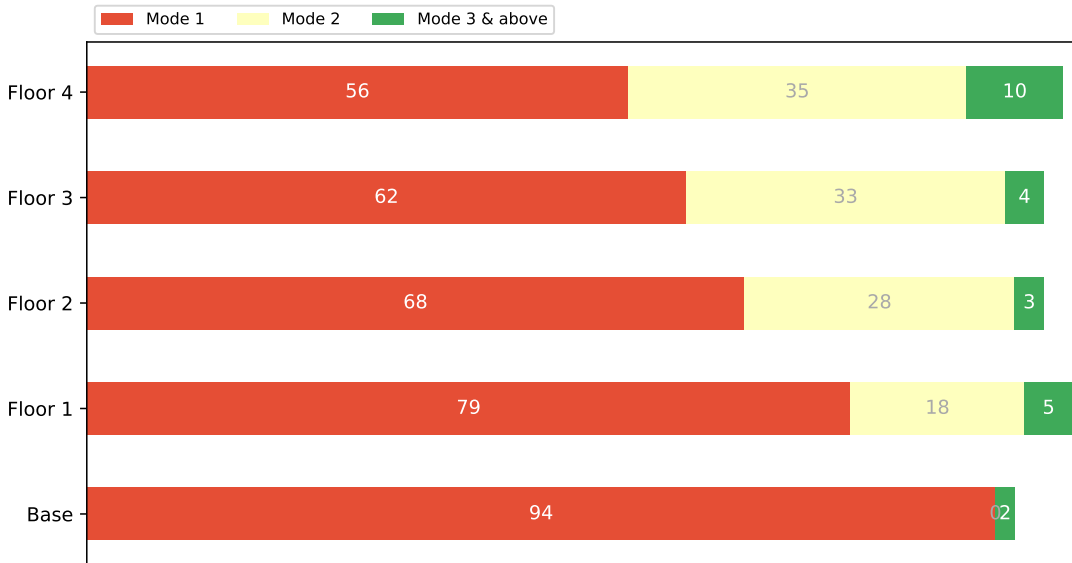


FIGURE 16
 Drift modal contribution for the linear Sub-assembly for IM000

Concerning the linear model, as expected, the maximum drift occurs at the base level because the isolator accumulates the most deformation, making the superstructure less influenced by the deformations. The higher modes responses to the drift at the base is very close to zero, suggesting that the higher modes do not control the displacement but solely isolated mode. However, the second mode controls the drift on the upper floors are controlled by approximately 30%.

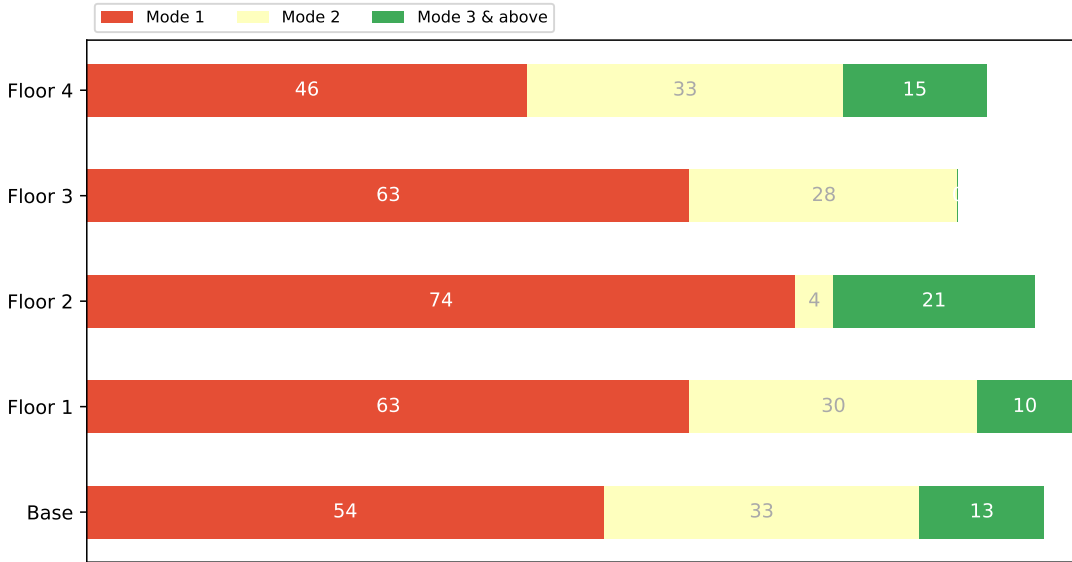


FIGURE 17
 PFA modal contribution for the linear Sub-assembly for IM000

The PFA results above show the contribution of the third mode, which was less apparent in the case of the drift. The second mode still has approximately 30% of contribution to the acceleration of the upper

floors and the first floor but not the second floor. This is no surprise as the result of the FAS between the Rigid body and the Sub-assembly indicated above. The following results are obtained for the non linear model (hence with the NHDR isolator). In comparison to the linear case, the second mode has a greater contribution in the responses of both the drift and the PFA. Indeed, on the last floor of the building the drift and the PFA are controlled by the second mode by more than 50 %.

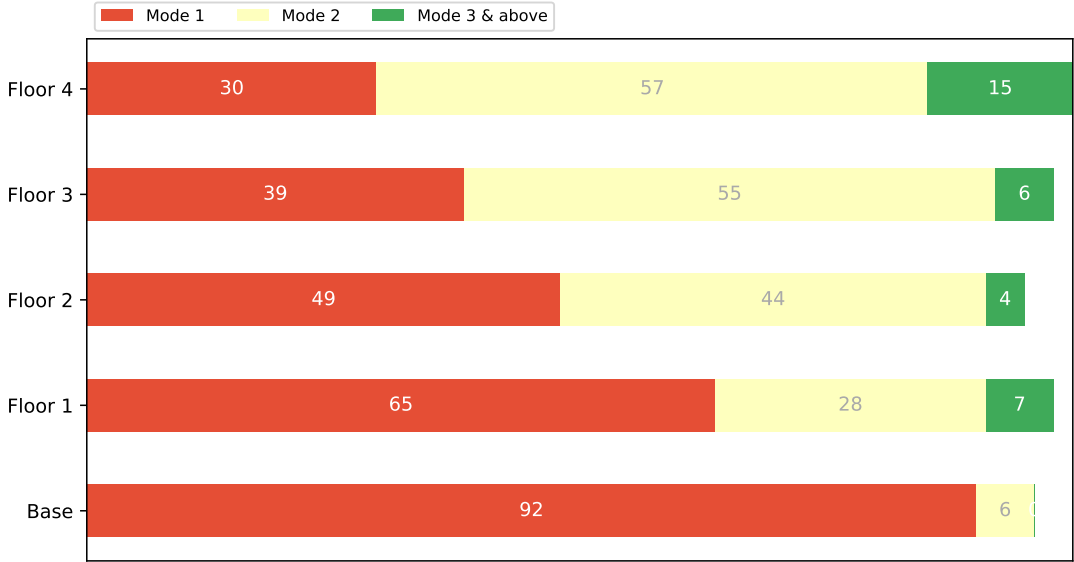


FIGURE 18
 Drift modal contribution for the non linear Sub-assembly for IM000

When looking closely at the PFA, the third floor and first floor are also strongly impacted by the second one whereas the second floor is mainly governed by the first mode, followed by the third. Again, this result was already witnessed when looking at the comparison with the Rigid body. 13

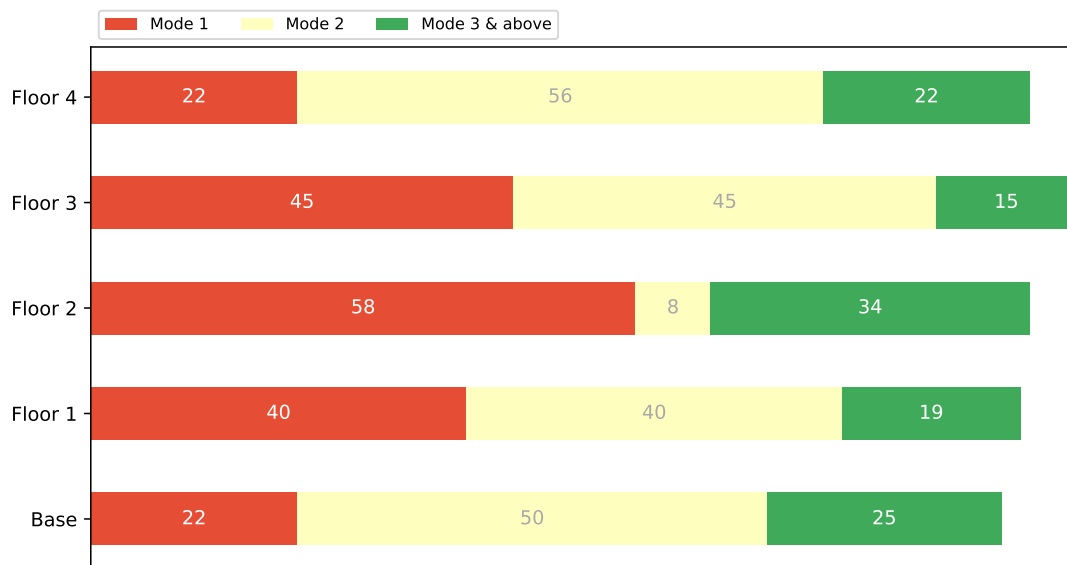


FIGURE 19
PFA modal contribution for the non linear Sub-assembly for IM000

6 PARAMETRIC ANALYSIS

6.1 DESIGNING THE STRUCTURE

To verify the results previously obtained, a taller building is designed and implemented on OpenSees. The building is essentially a fifteen story beam/column structure that is isolated at the base. The properties of the Taller building model has been kept to the same location as the initial 3D building used and thus the soil and seismic zones remain the same. From this initial design, the long term and short term reaction forces have been calculated as well as the total displacements in order to design an isolator fit for the structure.

Concerning the isolator, the properties are calculated and resumed in the table below. [5]

Internal diameter (cm)	20
External diameter (cm)	120
Total height of rubber (cm)	17,6
Number of rubber plates	22
Rubber thickness (cm)	0.8
Steel thickness (cm)	0.3
Lateral steel plates thickness (cm)	2,2
Design displacement (cm)	26.4
Maximum displacement (cm)	31,8
Shear stiffness (tonf/cm)	2,5
Axial stiffness (tonf/cm)	15618.7
Rotational stiffness (tonf/cm)	10900000

TABLE 4
15 Storey building base isolated analysis properties

The force deformation curve of the non linear isolator as well as the linear stiffness calculated is presented below.

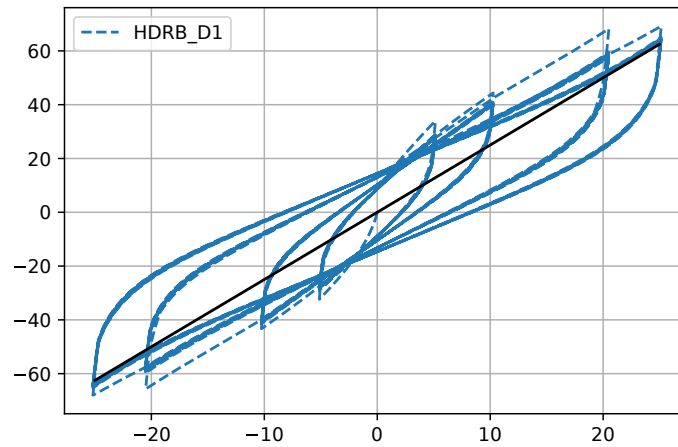


FIGURE 20

Force deformation of the HDRB used for the Taller building

In terms of the analysis properties, the non isolated building has a fundamental period of $T_1 = 2.25s$ and the target isolated building fundamental period is set to be $T_1 = 4s$. The ratio between the two periods does not verify the recommendation of the design code, but the model has not been modified.

The same procedure of extracting a sub-assembly from the frame model has been used to create a Sub-assembly model of the Taller building.

Mode	Omega (rad/s)	Frequency (Hz)	Period (s)
1	1.39	0.22	4.50
2	5.37	0.86	1.16
3	9.99	1.59	0.63
4	15.69	2.49	0.40
5	22.43	3.57	0.28
6	29.35	4.67	0.21
7	37.65	5.99	0.16
8	42.13	6.70	0.15
9	46.78	7.44	0.13
10	56.25	8.95	0.11

TABLE 5

Taller building sub-assembly linear modal properties

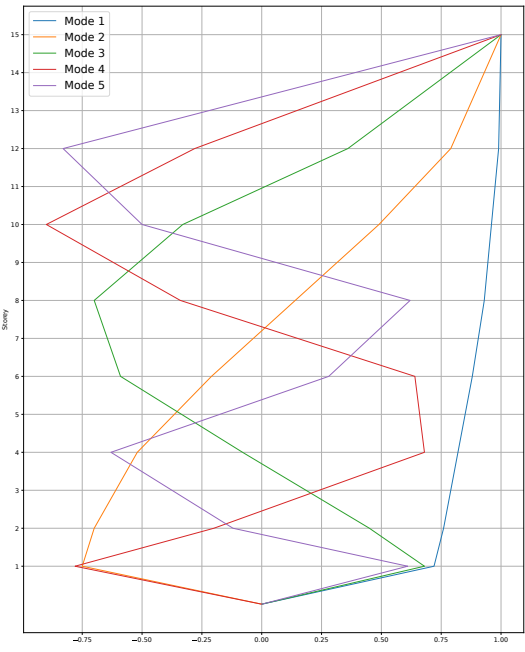


FIGURE 21
 Taller building sub-assembly modal shapes

6.2 DYNAMIC ANALYSIS OF THE TALLER BUILDING

To begin the process of filtering to extract the higher mode effect on the structure, a dynamic analysis is run on the linear Taller building (as a sub-assembly) for the *groundmotion000* of *IM000*. The displacement and the acceleration at the base, the 4th floor, the 8th floor, the 12th floor and the roof are evaluated in time and in frequency. The main takeaway are the results showing the FAS for the displacement and the acceleration at these floors for that ground motion record. The second mode is more prominent than the first mode at the base and has a important value in the upper floors (for this specific ground motion record).

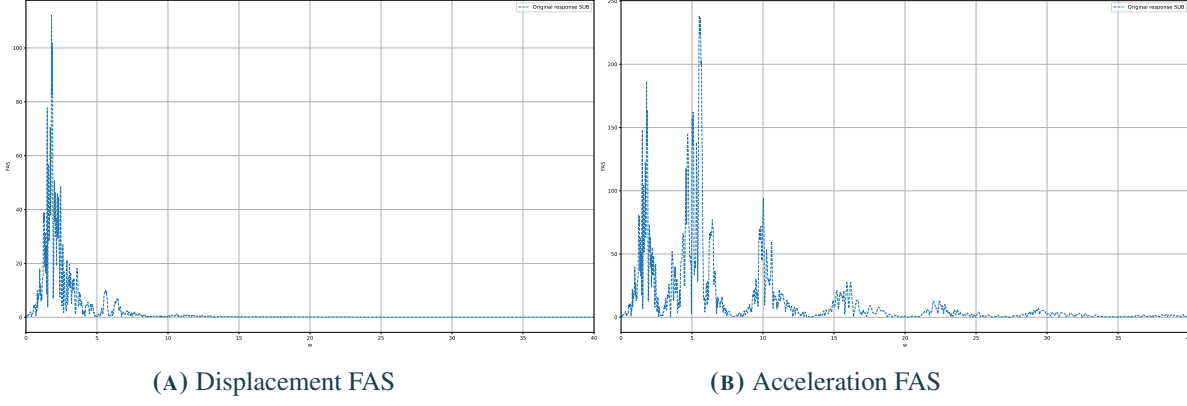


FIGURE 22
 Base level

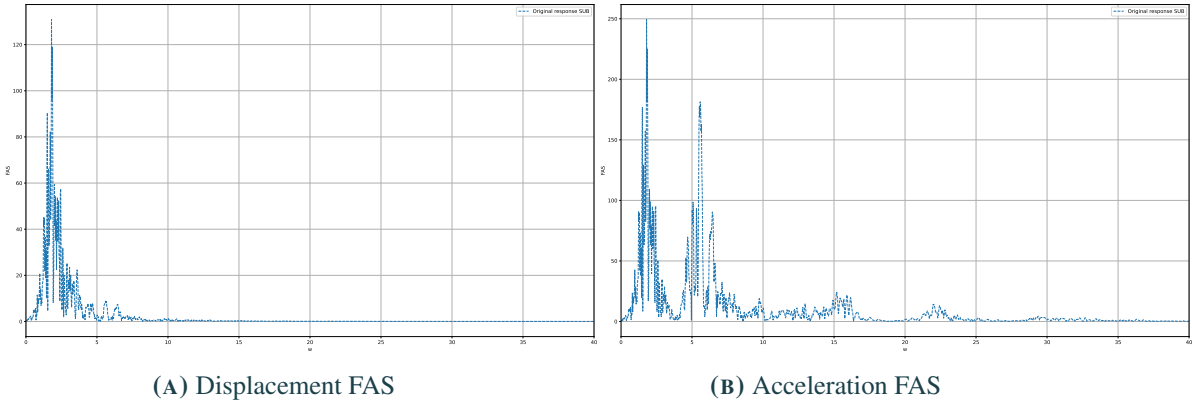


FIGURE 23
4th floor

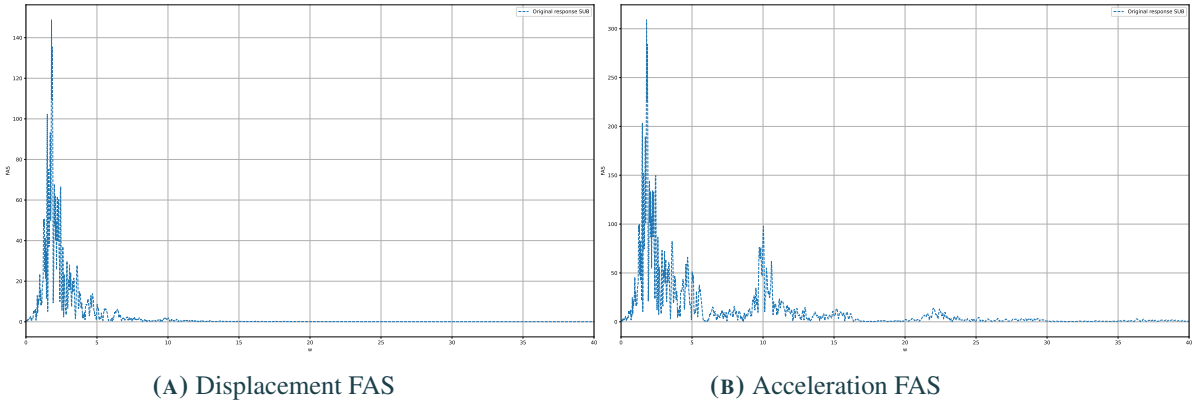


FIGURE 24
8th floor

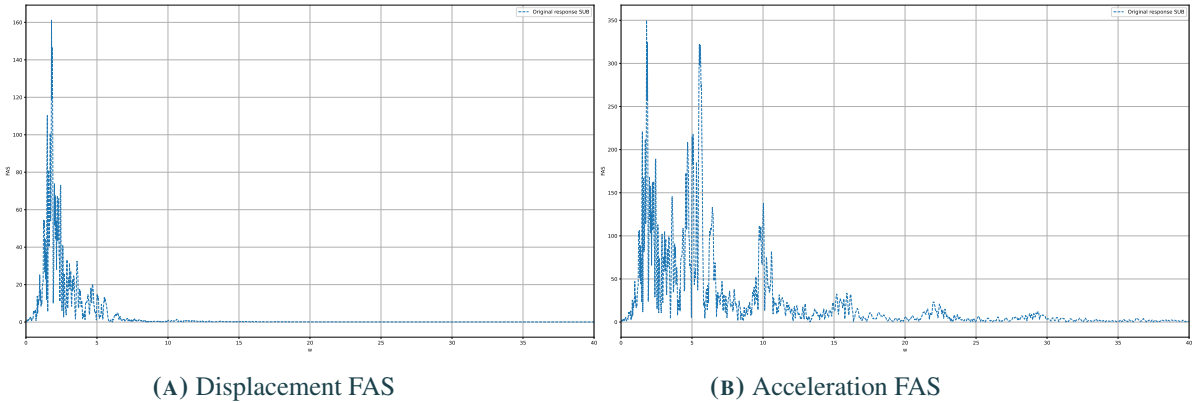


FIGURE 25
Roof

From these results, the peaks and the corresponding rotational frequency of the different modes are identified and can be used for the filtering to get the results for all the ground motion records of the different hazard levels. Indeed, using the same methodology as before, the idea is to calculate the cut-off

frequency between two peaks of the modes and to use that value in the Heaviside step high-pass filter. Through iteration that cut-off value is found using the FAS of the base level. The assumption that the "valley" between two peak values of two consecutive modes occurs at the same point for all the floor levels and for all the ground motion records has been made as a simplification. The red vertical lines correspond to the cut-off frequency (respectively $w = 2.8 \text{ rad.s}^{-1}$, $w = 8 \text{ rad.s}^{-1}$ and $w = 13 \text{ rad.s}^{-1}$ for the second, third and 4th mode) used for the filtering process .

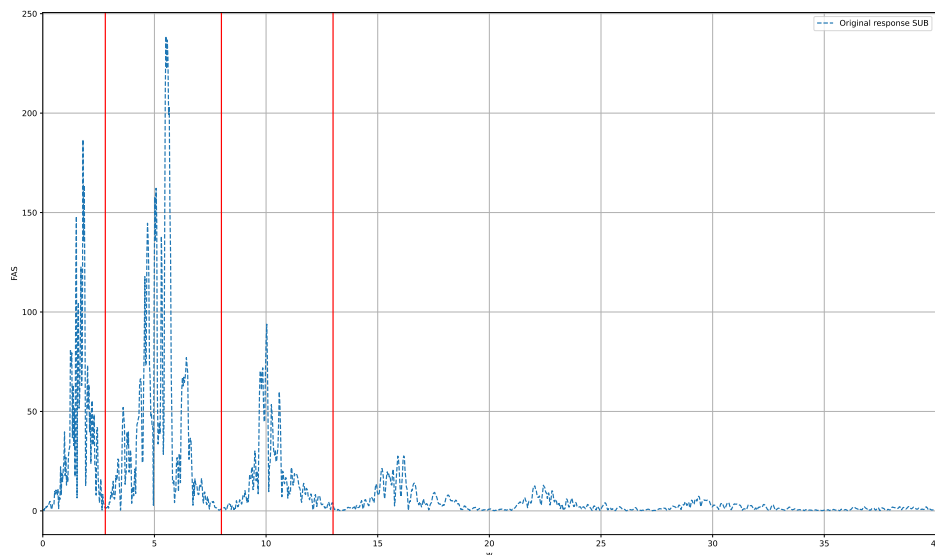


FIGURE 26
 Acceleration FAS for the Base and cut-off frequencies

6.3 VALIDATION OF THE HIGHER MODE EFFECT

Following the same methodology as before using the histogram median values of all twenty ground motion records of each hazard level, the final results of the modal contribution to the PFA and the drift for the linear Taller building are shown below. One can see the first mode controls the drift in a decreasing manner as the height of the building increases. Its contribution to the PFA is increasing until the 8th floor (around the mid point of the building) and then decreases. At the same time the second modes contribution to the PFA increases for the floor 2 then decreases until floor 8 and increases again. For the drift, the second mode has a great impact on the response as the levels increase. Regarding the higher modes (third and above) they strongly dominate the PFA response of each floors and participate to an amount of 20 to 50 % to the drift response.

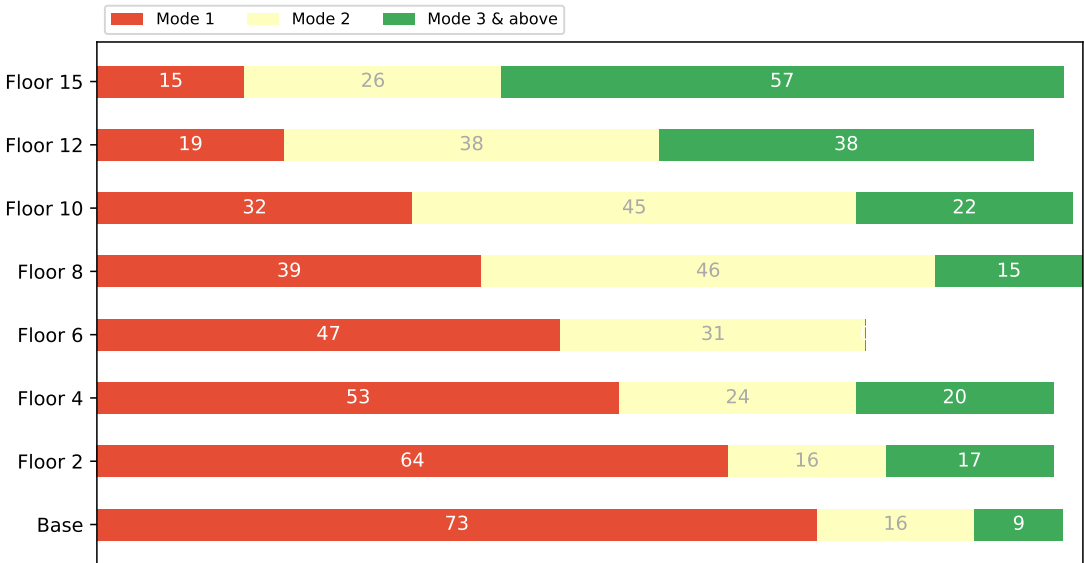


FIGURE 27
 Drift modal contribution for the linear Taller building for IM000

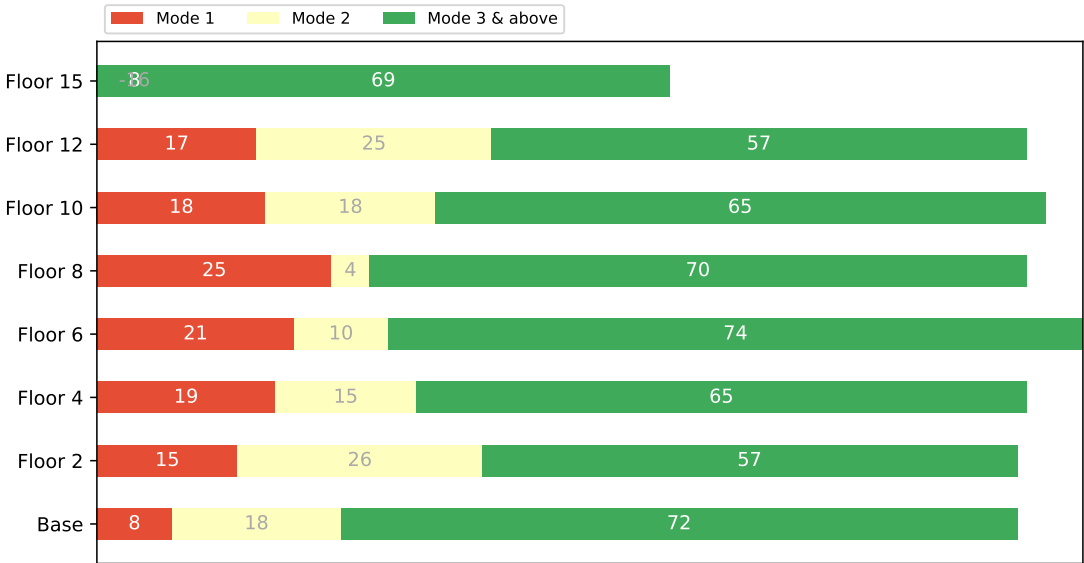


FIGURE 28
 PFA modal contribution for the linear Taller building for IM000

When looking at the modal participation, the second mode has a strong influence on the acceleration response of the upper floors and lower floors but not the middle floors. This result is that more apparent when looking at the results of the non linear Taller building presented below.

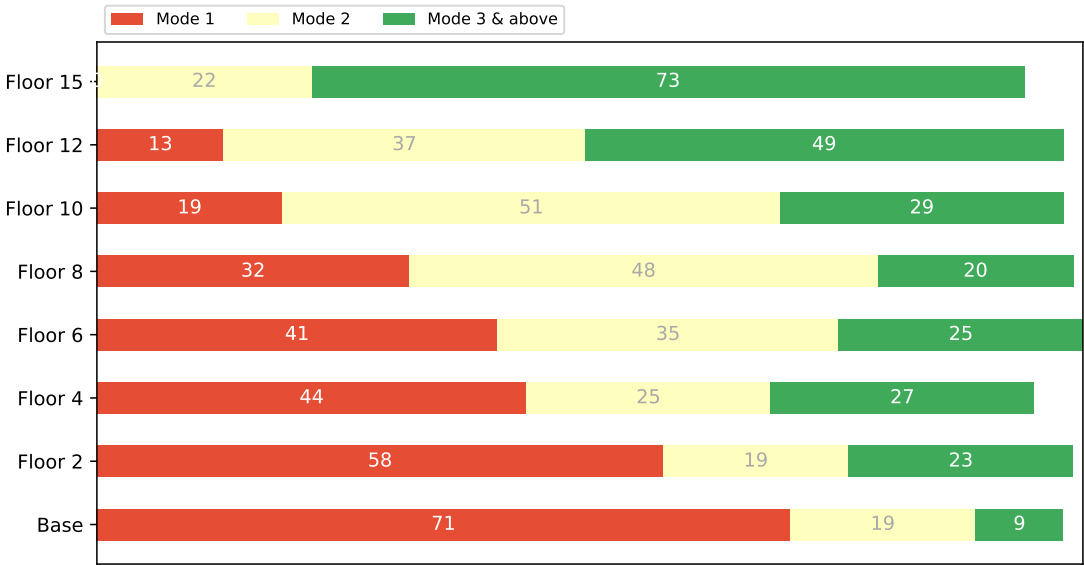


FIGURE 29
 Drift modal contribution for the non linear Taller building for IM000

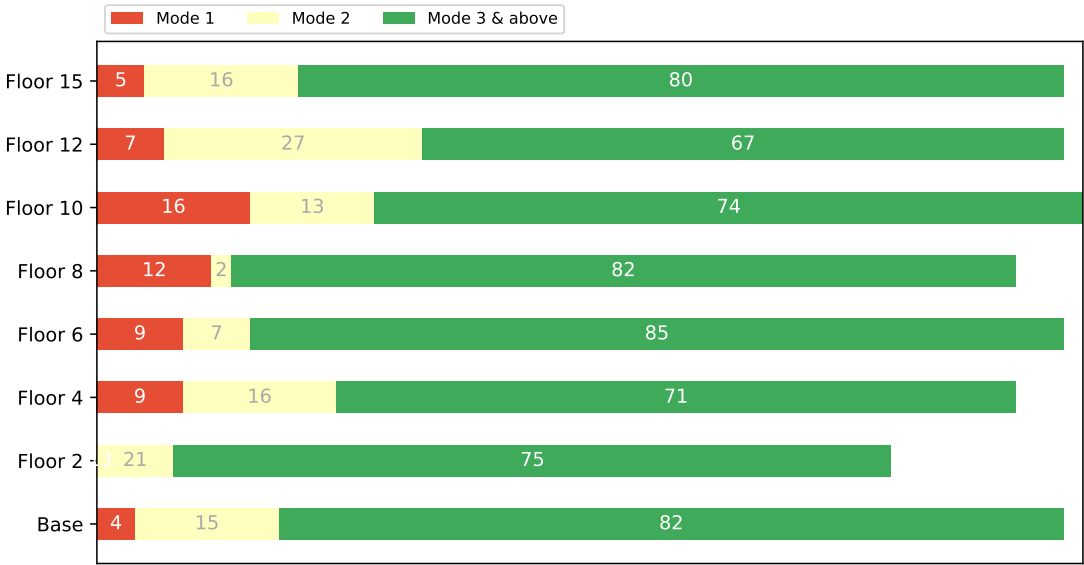


FIGURE 30
 PFA modal contribution for the non linear Taller building for IM000

Just like in the linear case, the drift is controlled by the first mode at the base but the first mode contribution slowly decreases as the story increases. The second mode contribution increases with the floor levels, which is the same for the third mode and above. When looking at the PFA however, the second mode contributes less to the response but the third mode and higher modes dominate the response by around 80%. This is a direct result of the stiffening of the NHDR (the non linear isolator) that triggers higher modes [6]. The same result was observed in the case of the smaller 4 story building but it more apparent

in the case of a taller building. To evaluate in an even more precise manner the effect of higher modes, the third and fourth modes should be filtered and extracted to view their respective contributions. Finally, the level of deformation of the isolator should be accounted for in regards to the effect of the higher modes.

7 CONCLUSION

Higher modes represent the high vibration frequencies that are present in the response of an isolated structure in addition to its fundamental mode. Base isolated structures are complex dynamic structures that need to be studied as buildings get taller and the technology of the isolation devices gets more sophisticated over time.

Various finite element models with linear and non linear isolators have been created and run on OpenSees. A dynamic time history analysis using three different sets of natural ground motion records is run and responses such as the drift and the PFA of the different stories is evaluated. Through different filtering methods, the contribution of the first three modes is analysed for all the floors of the models. The values are calculated for each ground motion records of different hazard levels and the median values are extracted as final results. The key results indicate that the second vibration mode has a strong impact on the acceleration response of the lower and upper floors but not the middle floors when considering a four story building. However, the third mode has a strong influence on the acceleration of the middle floor. This result can be generalised for a taller building, where the effect of the higher modes is even more apparent as the second mode controls the drift for the upper floors but contributes less to the PFA of the upper and lower floors. The third mode and the higher modes govern the PFA response for all the floors all whilst contributing to the drift response of a taller building. These results are in correlation to the stiffening of the isolator under large deformations.

When considering tall base isolated hospitals, it would be important to take into account the effects of the higher modes on the drift and the PFA acceleration because they have an incidence on the behavior of the structural and non structural elements present.

REFERENCES

- [1] Open system for earthquake engineering simulation, 2023.
- [2] Instituto Nacional de Normalizacion (INN). *Diseño estructural de edificios - Cargas permanentes y sobrecargas de uso*. 1999.
- [3] Damian N Grant, Gregory L Fenves, and Andrew S Whittaker. Bidirectional modelling of high-damping rubber bearings. *Journal of Earthquake Engineering*, 8(spec01):161–185, 2004.
- [4] José A Gallardo, Juan C de la Llera, José I Restrepo, and Michelle Chen. A numerical model for non-linear shear behavior of high damping rubber bearings. *Engineering Structures*, 289:116234, 2023.
- [5] James M Kelly and Dimitrios Konstantinidis. *Mechanics of rubber bearings for seismic and vibration isolation*. John Wiley & Sons, 2011.
- [6] Cenk Alhan, Hatice Gazi, and Hakan Kurtuluş. Significance of stiffening of high damping rubber bearings on the response of base-isolated buildings under near-fault earthquakes. *Mechanical Systems and Signal Processing*, 79:297–313, 2016.