METHOD OF MASS ISOLATION IN SEISMIC DESIGN OF STRUCTURES

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SUMMARY

Increasing the flexibility of the building and improving its damping characteristics reduces the level of earthquake force and energy on the system and enhances its structural performance. Flexibility and damping characteristics of the structure can be increased using isolation techniques. In this study the concept of vibration isolation is further expanded. It is proposed that the isolation layer to be applied in between of the mass and the lateral stiffness of the structure. In this method the share of the lateral load resisting mechanism of the structure from gravity loads can be kept unchanged. This technique is applicable to the short and tall buildings. In a numerical example the capability of this approach in reducing earthquake effects in tall buildings is shown.

INTRODUCTION

Isolation techniques in designing of earthquake resistance structures are meant to provide the structure with high flexibility and damping ratio within an isolation layer located horizontally at the base of the building. By adding to the flexibility and damping ratio of the structure, earthquake input energy imparted by the structural components of the system would be substantially decreased and seismic effects on the building reduced.

Application of isolation techniques in designing of earthquake resistance structures although not a fashion yet, has a high profile in designing of low rise structures. In tall buildings, however, this technique is not preferred because of the technical difficulties in the isolator technology. Nevertheless it has been shown that isolation layer can be used across the height of the structure [1,2] to be able to reduce seismic effects on the system. Prohibitive cost of the isolator devices and their implementation in buildings is also a major concern in designing isolated systems. Further expansion in application of isolation techniques requires an affordable isolation mechanism applicable to a wider range of structures.

The existing method of structural isolation is based on using a separation layer in the system. This layer horizontally passes through the building and separates the structure from its base. Such isolation mechanism is subjected to the weight of the structure and it needs to be vertically stiff to be able to prevent the undesirable rotational degree of freedom in the base of structure. However, an ideal isolation technology needs to isolate only the horizontal component of the mass of the structure and do not let its vertical component (i.e. weight of the building) to pass through the isolator.

From another point of view the current isolation technologies require both mass and stiffness of the structure to be isolated from the base of the system. However mass is the main cause in generating earthquake input energy and a direct approach suggests only the mass to be isolated. This study focuses on the possibility of application of this technique in short and tall structures.

MASS ISOLATION

Isolation is usually accompanied with a distinction layer between two separate parts of the system. Isolation layer either physically separates the system from its base or in a more sophisticated approach divides the

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structure to the smaller parts (Partial Isolation [1], for example). This approach of isolation can be interpreted as isolating the mass of the system in the expenses of interrupting in its stiffness. Introducing discontinuity in the stiffness of the system seems to be inevitable because mass and lateral stiffness of the structure are rigidly integrated.

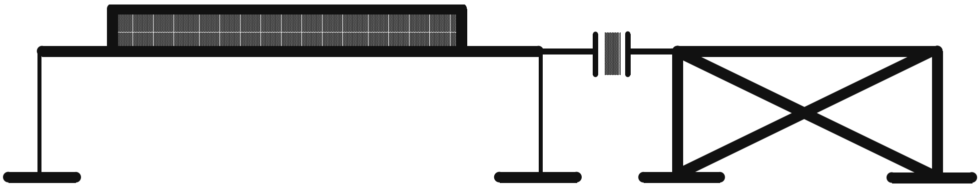


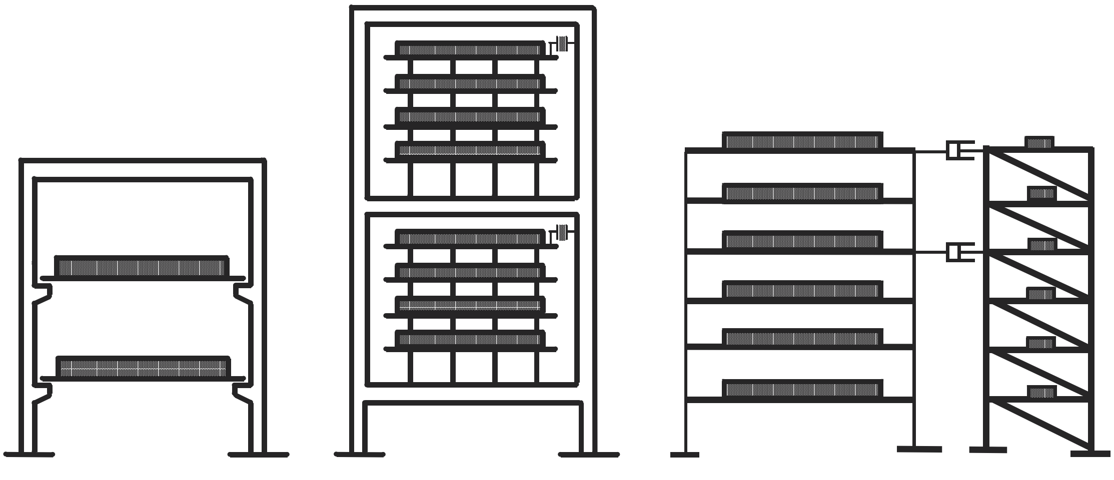
Fig.1 – The Mass Isolation Concept

The concept of isolation can be extended to a more general form. Since mass is considered the main source of earthquake input energy in the system, the target of isolation, in a more rational approach, should be directly the mass of the system. Isolation of the mass without causing discontinuity in the stiffness of the structure would be possible if mass and stiffness are not rigidly integrated. This concept suggests that the isolation layer to be located in between of the mass and the stiffness of the structural system. An isolation technique based on this notion requires the horizontal component of the mass to be isolated from the lateral stiffness mechanism of the structure. Figure 1 schematically shows this idea of isolation.

Methods of mass isolation

Ideally it is impossible to isolate the whole mass of the building from the lateral stiffness of the structure. However, there are some practical means to be able to isolate a large amount of the mass of the system.

The most direct method of mass isolation is to locally isolate the mass of the system from the lateral stiffness of the structure (see, Fig.2-a). This method can be applied to the structure by isolating each floor in the building. Application of local isolation is practically limited to the structures with heavy concentrated masses (e.g. industrial structures).



(a) (b) (c)

Fig. 2 – Different Methods of Mass Isolation

Since local isolation might not be practical in usual buildings, mass isolation can be applied in a more sensible form by isolating a group of mass of the system from the lateral stiffness mechanism of the structure. Figure 2-b shows an example of this technique. Group isolation is a practical technique in high-rise structures where the lateral load bearing system is subjected to large bending moment and it needs the weight of the building to counteract tensile forces in the columns.

A simple approach in mass isolation is to vertically isolate the mass of the system from the lateral stiffness of the structure. This technique divides the system into two different subsystems as shown in Fig. 2-c. The left-hand side subsystem carries almost the whole mass and weight of the building (it is called, hereinafter, mass subsystem). The lateral stiffness of this part of the structure is kept at the least possible level (a minimum stiffness is required for the stability of the mass subsystem). The right hand-side subsystem, however, possesses the main part of the lateral stiffness of the structure (hereinafter, stiffness subsystem).

The connection of these two subsystems is in fact the vertical isolation layer, VIL, which has stiffness and damping properties of its own. Virtually there is no need for stiffness in the vertical isolation layer except in the conditions where stability of the mass subsystem requires additional stiffness (to be borrowed from the stiffness subsystem). However, damping requirements for the VIL is quite important because while damping regulates the earthquake forces passing to the stiffness subsystem, it also dissipates the earthquake-input energy in the system.

Vertical isolation serves the main purpose of the isolation in shifting natural periods of the system to the zones of lower earthquake force and energy. This has been achieved by using lower stiffness associated with higher mass in the mass subsystem. In this technique the role of stiffness subsystem is to control the lateral movement of the system and to dissipate the earthquake input energy in the system.

There are some other techniques in mass isolation of high rise structures in which the stiffness of the structure can be partitioned, naturally, using the rotational degree of freedom at the top of the building.

Mass Isolation Features

Application of mass isolation techniques brings some phenomenal changes in the structural characteristics of the building.

The dominant distinction between mass isolation and other techniques is in its indirect method of isolation. Mass isolation transfers a large amount of the mass of the structure to the zone of lower earthquake forces without using a sophisticated isolation layer carrying the whole weight of the building. Therefore some of the difficulties associated with design and implementation of isolation layers (compromising on the lateral and vertical stiffness as well as damping characteristics and cost of the system) can be easily resolved.

The second important feature of the mass isolation is the mode shapes of the isolated structures. Depending on the frequency content of the earthquakes, a number of different structural mode shapes contribute in defining the response of the structure. If structural system consists of a well separated mass and stiffness subsystems, modal shapes of these subsystems will be in different range of the frequencies. This phenomenon causes the subsystems to have large relative movements with respect to each other. A damping mechanism located between mass and stiffness subsystems triggers the interaction between these modal shapes. The interaction causes the mass subsystem to receive large reaction forces from the stiffness subsystem, consequently the level of force and deformation on this part of the structure will be substantially reduced. This reaction force possesses a frequency content different from the frequency range of the stiffness subsystem, therefore it can not provoke a strong dynamic excitation on this subsystem (they can be considered simply as variable static forces).

Mass isolation also has an effective means to increase damping characteristics of the system. The problem of damping mechanism in ordinary structures is the fact that inter-storey relative displacement and velocity in the structural systems is quite small. Therefore, sophisticated damping devices are required to be able to dissipate earthquake-input energy effectively. However, in mass isolation damping devices are subjected to relative movement of the mass and stiffness subsystems, which can be large in certain locations across the height of the structure.

Another feature of this technique is its potential for deformation control of the structure. Since the mass subsystem relies on the stiffness subsystem for resisting its lateral forces, the stiffness sub-system can also control its lateral deformations such as inter-story drift. Deformation control would be possible if the gap between mass and stiffness subsystem in each connection point is furnished with a clamping mechanism based on displacement, velocity or acceleration triggers to restrict the structural system from undesirable movements.

Stiffness and strength requirements

In mass isolation the required strength in the stiffness subsystem is not necessarily proportional to the stiffness requirement in this system. The demand for higher stiffness in this part of the structure is necessary to clearly separate the behavior of the mass and stiffness subsystems but higher stiffness does not indispensably absorb higher loads into the system. This is one of the notable features in this technique and leads to lower structural cost for stiffness subsystem (provides the possibility for using inferior constructional materials, smaller cross sections, smaller footings, etc.).

The constructional cost of the mass subsystem can also be reduced because stiffness of this part of the structure should be in its lowest possible level (defined by the stability requirements in this subsystem) to elongate its natural periods and increase the effect of mass isolation. Deduction of the constructional cost of the mass subsystem would be the results of using smaller cross sections and deployment of simpler types of structural connections (due to reduction in the required rigidity in the joints).

Retrofit applications

Retrofit of the structures can be considered as one of the potential applications of the mass isolation technique. By separating the lateral load mechanism of the existing structure (e.g. bracing) from the remaining parts of the system (through damping devices) or by adding a new lateral resisting system to the building, it is possible to improve earthquake resistance of the existing structures. Compare to the other retrofitting options and depending on the building, this technique might be justifiable in the tall structures.

VERIFICATION

In this study a simple example is used for verification of this technique. In the example the mass isolation technique is applied on the structure using vertical isolation approach.

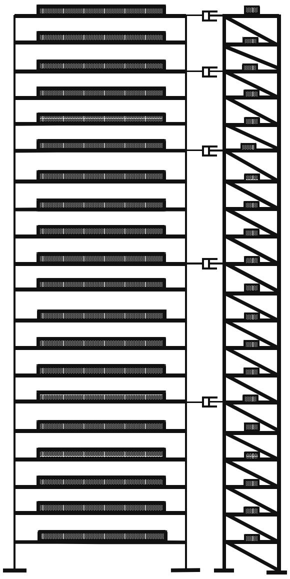
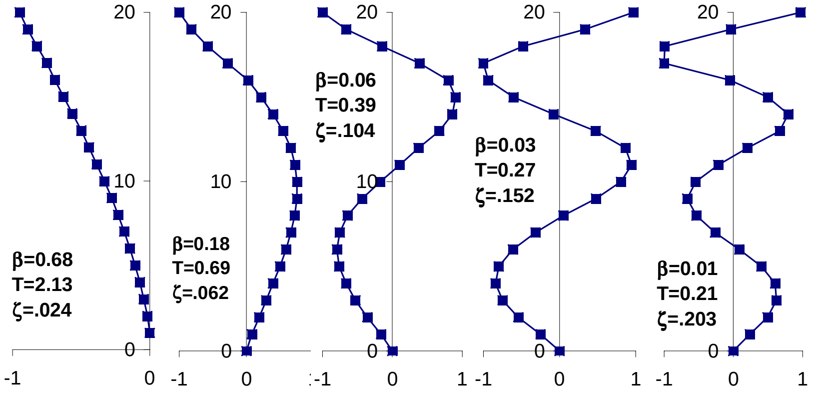


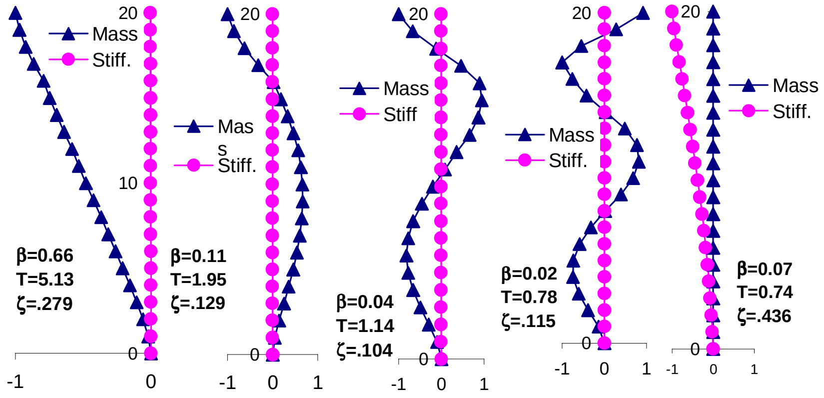
Fig. 3- A model for 20 storey mass isolated building

The example is a 20-storey hypothetical building, shown in Fig. 3. The schematic model resembles a typical high-rise building consists of a frame system which carries 90% of the mass of the system (with low lateral stiffness) and a braced frame which provides the lateral resistance to the structure (accompanied with 10% of the mass). Structural parts in this model have been proportioned to simulate dynamic behavior of a medium height structure. The cross section of columns and braces changes linearly from top to bottom (the change in the moment of inertia of columns is of second order) while the cross section of beams is kept constant through the height of the structure. In this building five viscous dampers with a linear distribution across the height are implemented between the mass and stiffness subsystems as shown in the figure. The same structure with rigid connections (in each floor) between mass and stiffness subsystems is also studied for comparison.

Figure 4 shows the first 5 mode shapes of the structure (the none isolated system with rigid links and the mass isolated structure). In this figure parameter βi is the mass participation factor [3] for the base shear in mode ϕi (which is a measure for the importance of each mode during earthquakes).



(a) Modal shapes of the non isolated structure



(b) Modal shapes of the mass isolated structure

Fig. 4 – Modal shapes of the structures

As it can be seen from the figure, the mass isolated structure possesses much longer natural periods and damping ratios for each mode. Also the factor βi for the 5th mode in mass isolated system has an unusual jump in its value compare to the structure with rigid links. This is an indication of the first natural mode of the stiffness subsystem. In fact the stiffness subsystem has contributed predominantly in the 5th mode shape and in the other modes its participation is similar to a rigid body.

An important point in the mode shapes of the mass isolated structure is the clear distinction between mass and stiffness subsystem ordinates, which indicates the potential of the mass isolation in damping the energy of the earthquake.

The mass and stiffness subsystems are connected through high capacity viscous dampers. This makes the structure a system with non-classical damping characteristics. In this view, determination of the response of the structure requires a time integration algorithm. A set of (time integration) analysis using program DRAIN-2DX [4] was carried out for three different earthquakes. Figure 5 shows the displacement at the top of the structure in the case of El Centro earthquake. In this figure displacement at the top of the structure for mass subsystem and stiffness subsystem is compared with the displacement of the structure without isolation. The results show that not only displacement at the top of the stiffness subsystem (an indication of the lateral force on the system) is substantially reduced, but reduction in the displacement is also manifested in the mass subsystem.

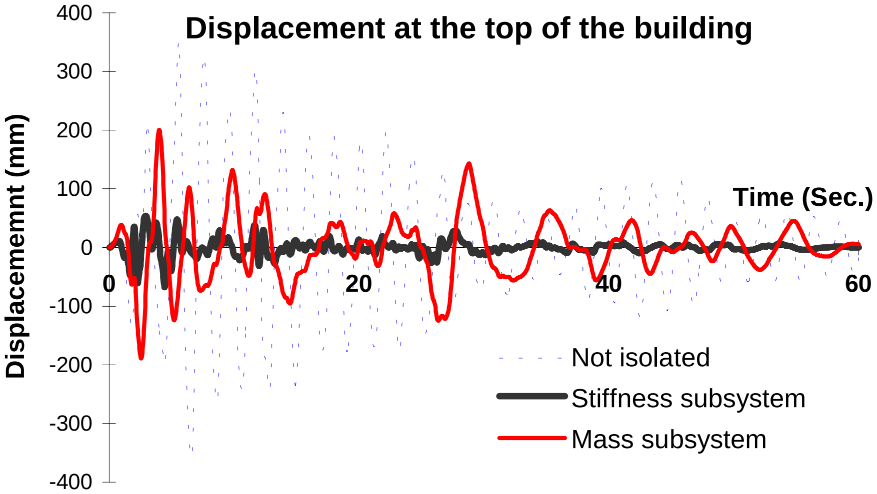


Fig. 5 –Time history displacement of building subjected to El Centro earthquake

In order to describe the characteristics of the mass isolated structure some other measures have been used. Table.1 contains some of the parameters used in this study to measure the performance of the mass isolated structure. Parameter $\mathbf{E_T}$ is indicating the ratio of the total earthquake input energy in the structure (mass isolated with respect to the structure with rigid links). This is a measure for effectiveness of isolation in reducing the earthquake input energy transferring to the system. $\mathbf{E_S}$ is the same ratio but for that part of the energy which was absorbed by the structural components of the system (while the rest of the energy is dissipated through damping devices). $\mathbf{E_S}$ is an indication of the distress encountered by the structural elements of the system. $\mathbf{D_{MM}}$ and $\mathbf{D_{MS}}$ are the ratios for maximum displacement at the top of the structure (mass and stiffness subsystems with respect to the structure with rigid links). The parameters $\mathbf{F_A}$ and $\mathbf{F_B}$ are the same ratios for the forces measured at the first storey of the structure (column and brace in the stiffness subsystem respectively). $\mathbf{F_A}$ and $\mathbf{F_B}$ can be considered as measures for base moment and base shear in the structure. Parameter $\mathbf{A_T}$ is the ratio for maximum acceleration at the top of the mass subsystem and $\mathbf{\Delta_D}$ is the same ratio for maximum drift across the height of the structure (mass subsystem with respect to none isolated system).

Earthquakes	E_T	E_S	D_{MM}	D_{MS}	F_A	F_B	A_T	Δ_D
El centro (S00E)	53.4%	16.6%	56.0%	18.8%	16.3%	15.7%	49.3%	113.5%
Hachinohe (EW)	73.9%	18.0%	60.9%	15.3%	16.5%	16.4%	51.5%	117.2%
Taft (EW)	70.5%	20.3%	85.0%	24.1%	19.8%	22.2%	43.4%	150.0%
Average	65.9%	18.3%	67.3%	19.4%	17.5%	18.1%	48.1%	126.9%

Table 1 – Performance ratios comparing mass isolated and none isolated systems

From this table it is obvious that the mass isolation approach considerably reduces the energy and force on the system. Reduction of the maximum acceleration at the top of the mass subsystem also demonstrates the potential of this technique in reducing seismic effects on tall buildings. The maximum drift across the height of the structure is the only parameter that shows increase with respect to the structure with rigid links. Considering the fact that mass subsystem has to be designed flexible enough to allow for mass isolation to happen, increase on the drift can be acceptable. Also an increase on the number of damping devices across the height or, as it was mentioned before, using a proper clamping mechanism can control the local drifts in the mass subsystem.

CONCLUSION

The concept of vibration isolation is extended to tall buildings using a technique that targets the mass of the structure as the main goal for the isolation purposes. Isolator layer in this approach is placed between the horizontal component of the mass and the lateral stiffness of the structure. By using this technique the main part of the mass of the system can be shifted to the low force and energy zone of the earthquake spectrum. This approach also increases the damping ratio of the structure to a level not conceivable by other techniques. Through a numerical example the ability of this technique in reducing seismic effects on tall structures has been shown, however, a more detailed numerical and experimental study is required to confirm this results and to establish this technique.

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