SEISMIC RESPONSE OF BASE ISOLATED PLAN IRREGULAR STRUCTURES

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ABSTRACT

Nine spatial five storey structures with different type and degree of plan irregularity are analysed in this paper. The seven structures have rectangular shape, while the other two have T shape in plan. The first structure with rectangular shape is regular. Three of the remaining six structures with a rectangular base, analysed as fix supported, do not comply the condition for maximum allowed eccentricity between the centre of mass and centre of stiffness and two of the other three do not comply the condition for torsional sensitivity according to which torsional radius should be greater than the radius of gyration of the floor masses. Base isolation significantly reduces eccentricity between centre of stiffness and centre of mass of the structures with stiffness eccentricity and increases the torsional radius on each floor of torsionally sensitive structures, which leads to compliance of previously mentioned criteria. Fast nonlinear time history analysis is applied to determine the dynamic response of base isolated structures. The results obtained for the isolated rectangular structures show great reduction of the torsional effects and the interstorey drifts, compared with the corresponding fixed base structures. Fixed base structures with a rectangular shape, has 4 to 5 times larger rotations compared with the isolated. In contrast, the maximal rotations of structures with T shape occurred at base isolated models. The maximal interstorey drifts at base isolated models are about 2.5 times smaller in comparison with fixed based.

Keywords: Eurocode 8; plan irregularity; base isolation; dynamic analysis

1. INTRODUCTION

The irregularity in plan may have a negative implication on the design process and on the response of the structures exposed to earthquake. A large number of constructed plan irregular buildings have collapsed and as a most common reasons for that are the large torsional effects that occur in the event of a strong earthquake. In that direction, the main purpose of modern seismic codes for design and construction of buildings in seismic regions is to mitigate the risk of structural damages and humans injury in the case of expected earthquakes. There are two design approaches that can be used to satisfy this purpose. The first is the conventional (ductile) approach, in which the seismic energy is dissipated by developing a plastic hinges in structural elements, while the second one is the application of systems for structural protection, which includes design of base isolated structures. Despite the large number of researches carried out in the field of the application of base isolation systems for plan

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irregular structures in the last few decades, research community have not reached a consensus on many topics in this area. Summary of the most relevant findings on the torsional response of base isolated structures can be found in Tena-Colunga and Gómez-Soberón (2002), De Stefano and Pintucchi (2008).

The most common analysed parameters that have an influence on the behavior of the base isolated plan irregular structure are: eccentricity of the mass and the stiffness of the superstructure, eccentricity of base isolation system, type and stiffness of the system for isolation, location of isolation interface, etc. Nagarajaiah et al., in two companion papers investigate a torsional coupling in base-isolated structures with inelastic elastomeric isolation system, (Nagarajaiah et al., 1993) and with sliding isolation system (Nagarajaiah et al., 1993a) due to bidirectional lateral ground motions. They investigated the influence of various system parameters on the lateral torsional response of such systems, including the eccentricity of the isolation system. It is shown that, although the total superstructure response is reduced significantly due to the effects of elastomeric base isolation, torsional amplification can be significant, depending on the isolation and superstructure eccentricity and the lateral and torsional flexibility. Jangid and Datta (1994) studied the nonlinear response of torsionally coupled base isolated systems subjected to random ground motions. From obtained results they concluded that eccentricity in the superstructure does not have a significant impact on the displacement of the isolation system and that the isolator eccentricity decreases the effectiveness of isolation for torsional deformation, increase the base displacements and decreases the superstructure displacement perpendicular to the direction of eccentricity to a much lesser extent. Tena-Colunga and Zambrana-Rojas (2004) used the nonlinear dynamic analyses to investigate the torsional response of base-isolated structures when eccentricities are set in the isolation system. Among other relevant issues, they concluded that eccentricities in the isolation system lead to a torsional response that adversely affects the design of the isolation system. In general, the amplification factors for the maximum isolator displacement of the asymmetric system with respect to the symmetric system increase as the eccentricity increases. Kilari and Koren (2009) investigate the influence of distribution of lead rubber bearing base isolation system under asymmetric four storey RC frame building. The results obtained by 3D nonlinear dynamic analyses indicate that all considered distributions of bearings, however differently, substantially reduce the unfavourable torsional effects, which are with different extent transferred from the superstructure to the base isolation system. Khoshnoudian and Imani Azad (2011) considered mass eccentricity of a superstructure as well as stiffness eccentricity of isolators in their investigations. They illustrated that effects of bidirectional near-fault ground motions would magnify torsional intensification comparing with unidirectional ones in a bilinear isolation system. The application of base isolation systems is still in low range, which is due to the complex procedure and the conservative design approach.

2. CRITERIA FOR REGULARITY IN PLAN

In the modern seismic codes for design of earthquake resistant structures, irregularity has implication in relation to seismic design, i.e. it is reflected on the mathematical model of structure, the method of analysis, the intensity of the seismic action etc. In principle, conventional designed structures with respect to the lateral stiffness and mass distribution shall be approximately symmetrical in plan with respect to two orthogonal axes. According to EN 1998-1 (CEN 2004), buildings can be characterized as regular in plan, if six different conditions at all storey levels are satisfied. Some of these conditions are qualitative and can be checked in the preliminary design stage. The conditions that are based on the eccentricity between the centre of mass and the centre of stiffness or torsional radius are quantities that have to be calculated additionally.

\[ e_{ox} \leq 0.3r_x; \quad e_{oy} \leq 0.3r_y \]  \hspace{1cm} (1)

\[ r_x \geq l_x; \quad r_y \geq l_y \]  \hspace{1cm} (2)

In these equations, \( e_{ox/oy} \) is eccentricity and \( r_{xy} \) is torsional radius in the considered direction, while \( l_x \) is the radius of gyration of the floor mass in plan. Torsional radius, as a structural characteristic, represents the potential for torsional vibration of structure exposed to earthquake ground motion. In
multi-storey buildings only approximate definitions of the centre of stiffness and of the torsional radius are possible, because those parameters are not uniquely defined and depend on the distribution of lateral load.

3. PRINCIPLE OF BASE ISOLATION SYSTEM

Base isolation is a technique for passive structural control that has been used for protection of structures from the damaging effects of earthquake, (Naeim and Kelly, 1999). Passive systems do not require any additional energy source to operate and they are activated by the earthquake input motion only. The energy dissipation is done by converting kinetic energy into heat energy or by redistributing the energy between the mode shapes. The basic principle of base isolation is to isolate the structure from the ground, in order to avoid damages and to enable the structure to withstand severe earthquakes in elastic domain. The link between the base ground and the superstructure is achieved by installing of bearings with certain characteristics (stiffness and damping), providing the reduction of the inertial force, whereby it partially or wholly constrain the diffusion of seismic waves through the body of the structure. The installation of isolators in building at base level significantly increases the fundamental period of the structure, modifies the shape of fundamental mode and increases the damping, which significantly reduces the risk of damage to structural elements and leads to better seismic performance of the building.

4. NUMERICAL EXAMPLE

4.1 Description of analysed structures

The analysed structures are spatial five storey RC structures with different type and degree of irregularity, Figure 1. All rectangular structures are composed of 3 frames in direction X and 5 frames in direction Y. The other two structures are with T shape and differ between them by number of frames in Y direction. All frames are positioned at distance of 5 m. The storey height is 3 m. The columns of the first two stories are 50/50 cm and 45/45 cm on the above 3 stories. All beams are 40/45 cm, while the slab’s thickness is 15 cm. The first rectangular structure is regular. In the remaining six structures the middle column in the first or third frame in Y direction is replaced with a RC wall with dimensions 120/40 cm, 160/40 cm and 200/40 cm respectively.

In the mathematical models, all beams are modelled taking into account the slab contribution. The dimensions of sections are determined in reference with Eurocode 2. Flange width of external beams is 110 cm, while for internal beams it is 180 cm. The structures are loaded with uniform distributed gravity loads which are applied on the beam elements. The value of the permanent load at the top of the structures is 14 kN/m’ on internal beams and 10 kN/m’ on external beams and at the other stories 26 kN/m’ and 17 kN/m’ respectively. All stories are loaded with live load of 5 kN/m’ on internal beams and 2.5 kN/m’ on external beams.
4.2 Properties of isolator

For the base isolated structures, elastomeric bearings, made by Italian company FIP Industriale, are used. Total horizontal effective stiffness of the isolation system is determined from the requirement that the period of base isolated structure should surpass 3 times the period of the superstructure. The fundamental periods of vibration for analysed structures are in range of 0.62 s to 0.67 s. These values are obtained for models of structures in which cracking of elements is included, i.e. bending and shear stiffness is 50 % from the stiffness of sections without cracks, in accordance with recommendations of Eurocode 8, (CEN 2004).

$$K_{eff} = \frac{(2\pi)^2 \cdot M}{T_{eff}^2} = \frac{(2\pi)^2 \cdot 1109.6}{(2 \cdot 2.5)^2} = \frac{7001.7 \cdot 10940.2}{} kN/m$$

In case of installation of one isolator below each column, required effective stiffness of one isolator will be 470 kN/m - 730 kN/m. In compliance with the required stiffness, isolator type SI - N 350/125, with effective secant stiffness $K = 620 kN/m$ and maximal horizontal displacement of 250 mm was selected.

$$T_{eff} = 2\pi \sqrt{\frac{M}{K_{eff}}} = 2\pi \sqrt{\frac{1109.6}{15 \cdot 620}} = 2.17s.$$  

All analysed structures satisfy the requirement $3T_f < T_{eff} < 3s$. Selected isolator is with diameter 350 mm, height 213 mm, total thickness of elastomer 125 mm, weight 138 kg and vertical stiffness 480000 kN/m. Maximal shear force that isolator can bear is 155 kN.
Typical hysteretic curve of an elastomeric isolator achieved during dynamic tests with increasing shear strain amplitude is shown in Figure 2. The isolator is modeled as link element with a bilinear behavior. The initial stiffness of the selected isolator is 1240 kN/m, the yield strength is 31 kN and the post yield stiffness ratio is 0.44. Effective damping of isolator is 15 %. This values are determined as a function of the elastomer’s shear strain γ.

4.3 Irregularity in plan

As the analysed structures have ideal symmetry of lateral stiffness and mass distribution with respect to X axis, the structures are analysed for seismic action in Y direction and the provisions for verifying the regularity in plan are considered with respect to Y axis. For the regular structure and the structures with wall at the third frame of the structure, the centre of mass coincides with the centre of stiffness. For all other structures determination of the centre of stiffness i.e. the eccentricity is performed for each level individually. For that purpose, two load cases are defined for each storey level, single force in Y direction and torsional moment about the vertical axis, which are applied in the centre of mass. After determination of the eccentricity, similar procedure is repeated for determination of the torsional radius, but in this step the loads are applied in the centre of stiffness. The eccentricity between centre of stiffness and centre of mass, for fixed and base isolated models, at all storey levels are presented in Figure 3. From the presented results it is noticed that as the length of RC wall increases the eccentricity between the center of stiffness and center of mass is also increasing. For fixed models, the eccentricity is in range of 1.40 m to 2.67 m and from 2.72 m to 5.52 m for the model with length of the edge RC wall 120 cm and 200 cm, respectively. Whereupon, the eccentricity has highest value at the first storey and it decreases as going in height. At the base isolated models, the eccentricities are lower as far as 25 times with respect to fixed models. In contrast, the eccentricity at T shape structures is larger at base isolated models. This is due to the impact of the stiffness of the isolation system.
The structures with T shape are irregular due to the shape at plan, the incompatibility, the set-backs and the various dynamic characteristics of the wings of the structure. For the rectangular structures the others necessary structural characteristics for verification of conditions of regularity are additionally calculated. The torsional radius is defined as the square root of the ratio of the torsional stiffness and the lateral stiffness in the considered direction, Equation 5. The radius of gyration of the storey masses, for uniformly distributed storey masses and dimensions of structures in plan B/L = 10/20 m can be calculated as equation 6:

$$r_{x,i} = \frac{K_{M,i}}{\sqrt{K_{M,i}}}$$

$$I_s = \frac{L^2 + B^2}{12} = \frac{20^2 + 10^2}{12} = 6.45m$$

From the obtained results it can be determined that the structures with RC wall at the edge, for the fixed base models, do not comply the condition which control the ratio between the eccentricity and 30% of the torsional radius. For the structure with RC wall 120/40 cm this condition is not satisfied only at the first storey, where the largest eccentricity occurs. For the structure with RC wall 160/40 cm the condition is not satisfied for the first three stories. The structure with RC wall 200/40 cm does not comply this condition at any storey level. This type of irregularity occurs due to unsymmetrical distribution of the lateral stiffness in plan, which depend on the dimensions of the RC wall. The stiffness of the isolation system, for base isolated models, has large impact on the eccentricity in plan. The largest reduction of the eccentricity occurs at the first story, for the structure with highest degree of irregularity in plan and is around 25 times and the smallest reduction is around 6 times, at the highest storey of the structure with lowest degree of irregularity in plan. From the presented results in Figure 4 it can be noticed that all base isolated models comply the condition $e_{ox,i} \leq 0.3 \cdot r_{x,i}$ at every story level, therefore they are characterized as regular in plan.
Figure 4. Control of criteria for structural regularity in plan \((e_{\alpha} \leq 0.3r_x)\)

Two of the three structures with RC wall in the third frame, for the fixed base models, do not comply the condition where torsional radius should be greater than the radius of gyration of the floor masses. The structure with RC wall 120/40 cm comply this condition, therefore it is characterized as regular in plan. For the structure with RC wall 160/40 cm the condition is not satisfied only at the first storey. The structure with RC wall 200/40 cm does not comply this condition for the first three stories.

Figure 5. Control of criteria for structural regularity in plan \((r_x \geq 1)\)

From the presented results in Figure 5, it can be noticed that all base isolated models comply this condition. By increasing the length of the RC wall, the ratio of the torsional radiuses of base isolated and fixed base models is also increasing. The largest ratio is around 1.5 times, at the highest storey of the structure with RC wall 200/40.

For assumption of linear increasing, the base isolated models will reach up the regularity limit for approximate length of RC wall of 1750 cm and 1350 cm for structures with RC wall at the edge and RC wall at the centre, respectively. That cannot be fulfilled for this two types of structures, because the dimension of the structure in plan in that direction is 1000 cm. This is indicator of the advantages of the base isolated structures in case of regularity in plan.
4.4 Seismic action

Response of the regular structure, structures with RC wall at the edge and structures with T shape is determined with application of dynamic time history analysis, whereupon 3 input motions from previous earthquakes (Imperial Valley - El Centro 1940, Chi - Chi Taiwan 06 - CHY028 1999, Victoria Mexico - Chihuahua 1980) are used. In order to satisfy the Eurocode 8 requirements for ground motion selection, original registrations of selected earthquakes are scaled by amplitudes and frequency. Target spectral ordinates are determined for spectrum Type 1, soil class C, and peak ground accelerations of 0.24 g. Original acceleration spectra and spectra obtained from scaled input motion, as well as the acceleration time histories are presented in Figure 6. Base isolated structures were analyzed for three levels of seismic hazard, which corresponding to PGA of 0.12g, 0.24g and 0.36g. All analyzed structures are exposed to seismic action only in one direction, perpendicular to eccentricity.

![Figure 6. Elastic spectra and ground motion acceleration time histories](image)

4.5 Comparison of results

In this section the most important results obtained from performed analysis are presented. The range of stories displacements for fixed and base isolated models of the rectangular structures are given at Figure 7. From the graphs it can be noticed that the maximal displacement at the top of the structures occur for the base isolated models. Displacements of the base isolated regular structure are larger for 9.2 cm than the fix supported structure, i.e. 65%, while in structure with RC wall 200/40 the variation is 3 cm, i.e. 14%. With increasing of the degree of irregularity, the maximal displacements at fixed models are also increasing, while for the base isolated models this increasing is insignificant. The range of displacements for the T shape structures has a similar trend.
At base isolated structures more than 80% of the total displacements are concentrated at the level of the isolation system. This leads to significantly reduction of the interstorey drifts and lower risk of damages of structural and non-structural elements compared with the fixed base structures. At Figure 8 the distribution of interstorey drifts for fixed base and base isolated models obtained for PGA 0.24g are presented. Increase of the degree of irregularity of rectangular structures results in increase of interstorey drifts, which are extreme at the flexible side of the structure. Maximal interstorey drifts obtained for PGA of 0.24g is equal to 5.57 cm and occurs at the third storey for the fixed base model with RC wall 200/40 cm. This maximal interstorey drift is almost two and a half times greater than the maximal interstorey drift of the respective base isolated structure. Maximal interstorey drifts of the base isolated T shape structures occur at the first storey and are equal to 2.01 cm. For all structures the maximal values are obtained from analysis with Victoria Mexico input motion, except for the regular fixed base structure where maximal interstorey drifts are obtained from Chi Chi Taiwan input motion.
The figures below present the displacements on the left and on the right edge of the structures and rotation in plan at the top storey obtained from the analysis for PGA 0.24g, for fixed and base isolated models. Because of the symmetry in plan in both direction of the structure and the seismic action in one direction, the displacements on both edges of regular structure are equal i.e. has translational movements only. For the other structures due to the eccentricity between the centre of stiffness and centre of mass, rotations of floors occur. For all analysed structures, maximal displacements are obtained for base isolated models. The difference between the displacements on the left and on the right edge of the structures is larger at rectangular structures compared to T shape structures. It can be noticed that for fixed based models, the displacements on the left edge of the structure, where the RC wall is placed, are decreasing as the degree of irregularity in plan increases, while on the right edge are increasing. This leads to increasing of storey rotation, and amplification of torsional effects. From the diagrams of the base isolated models it can be noticed that although the absolute displacements of the two edges are increasing, the difference between them is irrelevant, and the rotation of the analysed storey is negligible compare with the same obtained from the fixed model. At fixed base T shape models the maximal displacements occurred on the left edge of the structures. Contrary, at base isolated models the maximal displacements occurred on the right edges of the structures. Due to the impact of the stiffness of the isolation system i.e. the increasing of the eccentricity between the projection of the centre of masses and the center of stiffness of the entire structure, the rotation at the highest storey of the structure T2 is larger for base isolated model.

![Figure 9. Displacements and rotation at the top storey (Victoria Mexico input motion)](image)

Diagrams of the horizontal displacements and lateral force at the left and right edge of the structures obtained from non-linear dynamic analysis of Victoria Mexico input ground motion are presented in Figure 10. The maximal initiated force in isolators for PGA 0.36 g is in range of 177 kN to 180 kN for rectangular structures and in range of 163 kN to 185 kN for T shape structures, whereof the maximal horizontal displacements are in range of 29.24 cm to 29.89 cm and 26.74 cm to 30.73 cm, respectively.

![Figure 10. Diagrams of lateral force and horizontal displacements for isolators](image)
Independent of the degree of irregularity of the analysed rectangular structures and the level of seismic hazard, the behavior of the isolators from the left and from the right edge of the structure is uniformly for all obtained analyses. In contrast, at the T shape structures, due to the large floor rotations of the isolated models and the increased eccentricity, the differences between the initiated forces in the isolators and the horizontal displacement are larger than 20%. This is reflected negative on the behavior of the base isolation system.

5. CONCLUSIONS

By increasing the length of the RC wall at the edge, the eccentricity between the centre of stiffness and the centre of the mass increases. The eccentricity of base isolated structures is up to 25 times smaller compared to the fixed base structures, which is due to the position and influence of centre of stiffness of the isolation system. By increasing the length of the RC wall in the middle frame, the ratio of the torsional radiuses of base isolated and fixed base models is also increasing. The largest ratio is around 1.5 times, at the highest storey of the structure with RC wall 200/40. Although the total displacement of base isolated models is higher, interstorey drifts for the base isolated structures are significantly smaller compared to those obtained for fixed base structures. At rectangular structures, by increasing the degree of irregularity the displacements on the flexible side at fixed base models significantly increase, while at the base isolated structures they are negligible. Base isolated structures have lower floor rotations comparing with the fixed base, whereof the differences are significantly increasing at the upper floors. Low rotations are mainly due to uniform behavior of base isolation system. These advantages are indicators for the effectiveness of the base isolation system in relation to regularity at rectangular structures, as well as to significantly lower risk of damages of structural and non-structural elements. Due to the impact of the stiffness of the isolation system, the increase of the eccentricity between the projection of the centres of masses and the center of stiffness of the entire structure, the rotation at the highest storey of the structure T2 is larger for base isolated model. This has a negative reflection on the behavior of the base isolation system. Differences between the forces and the horizontal displacement in the isolators at both ends of the structures are larger than 20%.

6. REFERENCES


