

Application of HYDE structural control system for RC buildings



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SUMMARY

Contrary to conventional multi-storey systems which are subjected to vibrations during an earthquake, causing severe amplifications of internal forces, a well-designed Hysteretic Device “HYDE” system exhibits rigid body motion, which are controlled by simple “hysteretic” devices such as friction elements. Rigid body motions are free of amplification and it is known from many studies that such systems drastically reduce kinetic and potential energy in a structure and thus, forces and deformations. Except in the “hysteretic” devices, no inelastic deformation or damage occurs in the structure, which makes this a very robust structural concept for earthquakes. In this paper is presented a 3D model of a typical 7 story RC building, designed both as a conventionally and a HYDE system. Seismic responses of both structural systems are demonstrated and compared under various scaling of 3 componential ground accelerations of Izmit earthquake.

Keywords: structural control, hysteretic friction devices

1. GENERAL INTRODUCTION

In order to achieve earthquake safe buildings, conventional multi-story RC buildings are generally designed by consideration of certain capacity design rules. Inevitably, this leads to large cross-sections and an increased amount of reinforcement at critical regions when compared to a non-seismic design. Conventional multi-storey RC buildings can be designed to withstand strong earthquakes but this comes along with an additional level of financial investment and also with a risk of severe structural damages or complete financial loss under strong earthquake events.

Alternatively to the classical concept of earthquake resistant structures by providing adequate lateral strength capacities along storey heights emerged various modern structural concepts. One of these concepts is the HYDE structural concept which, as will be demonstrated in this paper, shows much better performance than the classical concept of buildings, when subjected to earthquake actions.

For this study, a typical 7 story RC residential building, recently built in the city of Shkup, Macedonia, has been designed conventionally and as a Hyde system. 3D mathematical models of both structures have been generated using advanced Finite Element Method. This paper demonstrates and compares the seismic response of both structural systems subjected to 3 componential ground accelerations of the devastating Izmit earthquake of 1999 (with a magnitude $M_w=7.4$), which killed 17000 people, injured 44000 people and left approximately half a million people homeless.

2. MATHEMATICAL MODELS

In order to better demonstrate the differences between conventional and HYDE structural systems there have been generated three variations of mathematical models representative for the 7 storey building which was recently constructed in Shkup, Macedonia (Fig. 1), using SAP2000 v.14 program.

The first model (Fig.2 left), represents a conventional structural system, while second and third models (Fig. 2 middle and right) represent the implementation of a HYDE structural concept by imposing structural modifications on the ground story of the first model. Hereon we shall refer to the first model as the “CONV” model, to the second model as “HYDE-A” and to the third one as “HYDE-B”.

The "CONV" mathematical model is a 3D representation of the existing building that is shown in Fig. 1. This model was also used during the design and construction phases of this building 3 years ago. Based on the load analysis performed on this model, it can be outlined the overall gravitational load (self weight, dead load and live load) weighting about 6000t. The material used for all structural members (columns, walls, beams and slabs) is reinforced concrete with concrete class C30/35 and steel class S400. Proportioning of bearing members, amount of reinforcement and reinforcement detailing along all structural elements has been adopted according to the seismic design criteria of Eurocode 8. All column cross sections at the ground story are with dimensions 50x50cm and the thickness of the core walls is 40cm. A detailed representation of the geometrical properties for all other bearing elements is not of particular importance for the results demonstrated in this paper.

In addition to CONV model, both the "HYDE-A" and “HYDE-B” mathematical models (Fig. 2 middle and right) show the implementation of hysteretic devices (HYDEs) on the ground story of the CONV model. All material properties of structural elements and loading characteristics for HYDE-A and HYDE-B models are identical to the CONV model, aside the geometrical properties of columns and shear walls on the ground story, which are modified in order to satisfy the physical conditions for achieving the HYDE structural control system.

The first structural modification imposed to the CONV model, so to achieve HYDE structural system, occurs on the RC core walls which constitute the so called Primary Horizontal stiffening System (PHS). This means that the RC core walls are primarily intended for resistance of the seismic actions. To both HYDE models, the RC core walls are split at the mid-height of the ground storey while along their split gap were attached special link elements, namely hysteretic friction devices (HYDE Devices), primarily intended to dissipate large amount of seismic energy through their limited strength and perfectly stiff-plastic hysteretic feature. It is of crucial importance that shear walls must be very stiff in order to maximize the attraction of seismic forces to the seismic link elements, i.e. hysteretic devices, where earthquake dissipation is ensured through their stable elasto-plastic hysteretic behavior.

Column elements of the ground story, for both HYDE-A and HYDE-B models, form the so called Secondary Horizontal stiffening System (SHS) and following the HYDE structural concept they should be as slender as possible in order not to attract too much force and remain elastic under larger displacements. Additionally, columns should have sufficient lateral stiffness so to stabilize the gravitational structural loads in terms of the P-Delta effect. Structural stability in terms of P-delta effect is of utmost importance when HYDE devices are detached from the structure for the purpose of repair or resetting the structure to its initial condition after any seismic event.

In reference to Figure 2 it can be observed that for the HYDE-A model, the cross-section dimensions of all columns of the ground story have been reduced down to 35x35cm and at the top column end-joints have been assigned moment releases on all three orthogonal directions. In difference to HYDE-A, in HYDE-B model the columns have been changed to boxed cross-section of steel material with cross-section dimensions 24x24cm. Actually, the only difference between HYDE-A and HYDE-B are the column properties on the ground story. The reason for adopting HYDE-B model and presenting its obtained results on this paper is, as will be explained later, to demonstrate the effects of buckling factor and elastic displacement capacity of SHS on the efficiency of the HYDE structural system.

Once the aforementioned criteria for both RC columns and RC walls are met, the only parameters left to be determined are the HYDE device stiffness and strength. HYDE devices are designed based on the maximal allowable lateral displacement of the structure which represents the maximal lateral displacement of SHS under seismic actions. There has already been established a consistent

methodology for optimal design of strength and stiffness of HYDE devices using methodology of design curves. HYDE devices utilized on both HYDE-A and HYDE-B model, are designed using this methodology.

In many previous studies on HYDE structural systems, it is stated that for a well designed HYDE system, over 80% of the input energy can be dissipated merely by the hysteretic devices (HYDEs). This paper will demonstrate that this thesis holds true for low to medium building heights subjected to medium earthquake intensities, while for large buildings subjected to large devastating earthquakes arise serious difficulties that require making additional structural modifications.



Figure 1. 7 storey constructed building in Shkup, Macedonia, 2009

3. NONLINEAR MODELING CONSIDERATIONS

During phases of modeling generation there have been adopted many parametric assumptions which greatly affect the dynamic nonlinear behavior of all three models. Some of these parameters are the properties of infill wall brick units, nonlinear modeling of RC wall and slabs and plastic hinge modeling of RC frame elements at critical regions.

As infill wall panel constituents have been adopted the solid brick units consisted of clay material. The thickness of infill wall panels, respectively clay brick units, has been adopted 16cm. The compressive strength of brick units was assumed 7,5MPa. Using SAP2000 computer program, the nonlinear modeling of these infill wall panels has been done using the layered shell elements and adopting the concept of diagonal strut model. As constituent material of layered shell elements was adopted the unconfined concrete material of strength class C16. Moreover, the thickness of these layered shell elements was adopted 5cm. The layered shell elements have also been used for nonlinear modeling of RC shear walls and RC slabs of the CONV model, similarly to the modeling of infill wall panels.

In order to realistically estimate the nonlinear response of RC frame elements (columns and beams), which is crucially important for the estimation of structural performance of CONV model, the fiber hinging approach was used. The length of fiber hinges was adopted to be 30% of the relative length of frame elements it was assigned to, while control physical parameters of hinges are automatically obtained from the cross-sectional geometry of frame elements and their reinforcement detailing. The type of frame hinging was assumed as fiber P-M2-M3 for both column and beam elements. The frame hinges were generated for all column and beam elements located on the basement, ground story, story 1 and story 2, since the nonlinear behavior of the bottom stories of the building is to our greatest concern.

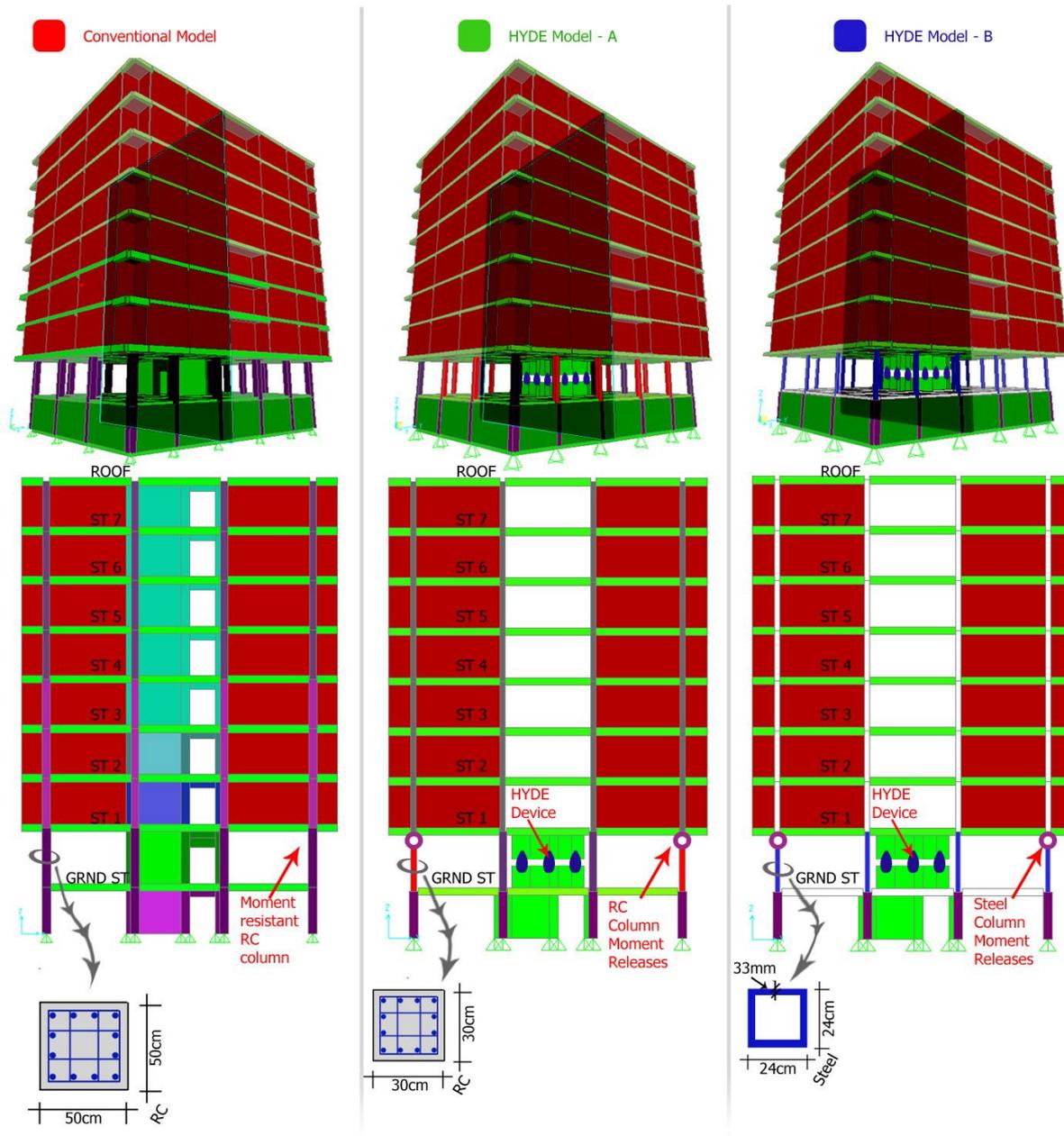


Figure 2. 3D mathematical models representative for the 7 storey building constructed in Shkup, Macedonia

4. STRUCTURAL ANALYSIS

After careful modeling of CONV, HYDE-A and HYDE-B models, they were subjected to several types structural analysis procedures, respectively modal analysis, buckling analysis, response-spectrum and pushover analysis. The results obtained from these analysis are crucial for the design of HYDE devices, respectively for the generation of HYDE design curves.

4.1. Modal and buckling analysis

Modal and buckling analyses are both linear analysis techniques used to determine the vibration and buckling modes of a structure. All of the three models were subjected to these analysis and the obtained results are given in Figure 3.

Vibration modes (Figure 3, left) are primarily useful for understanding the behavior of the structure. Moreover their corresponding vibration periods are important input parameters for the generation of HYDE design curves, which are crucial for a stable HYDE system design. In Fig. 3 (left) are given the first 3 modal periods of vibration for all three study case models CONV, HYDE-A and HYDE-B. From this figure can be observed that both HYDE system models, with no seismic links (HYDE devices) attached, show notable increase in flexibility in respect to the CONV model for about 6 to 10 times. This effect is mainly reflected due to the discontinuation of the core RC wall and reduction of cross-section dimensions of columns on the ground story of both HYDE models. Moreover, when seismic links are attached to HYDE models, the vibration periods of both HYDE models are again reduced down to 0.50s, thus under elastic response they respond equivalently to CONV model.

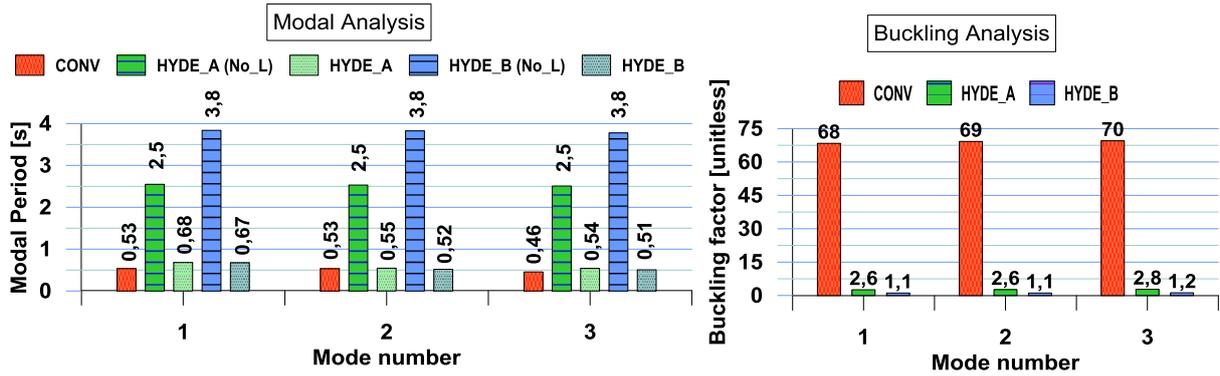


Figure 3. Results obtained from modal analysis (left) and buckling analysis (right)

On the other hand, buckling modes show the instability of structures due to the P-delta effect under specified loads. Buckling analysis involves the solution of the generalized eigenvalue problem:

$$[K - \lambda G(\mathbf{r})]\Psi = 0 \quad (5.1)$$

where \mathbf{K} is the stiffness matrix, $\mathbf{G}(\mathbf{r})$ is the geometric stiffness (P-Delta) due to the load vector \mathbf{r} , λ is the diagonal matrix of eigenvalues, i.e. buckling factor, and Ψ is the matrix of corresponding eigenvectors, i.e. buckling modes. Buckling factor, λ , can be also viewed as a safety factor in a way that if $\lambda < 1$ the structure is unstable due to its gravitational load, respectively due to the P-Delta effect.

The buckling analysis tool is particularly useful for optimal design of HYDE structural systems, respectively in controlling the flexibility of SHS elements (by reduction of cross-section geometry and end-joint releases of column elements) while insuring structural stability due to the P-Delta effect.

Along the modeling process of both HYDE models used for this study, buckling analysis technique was used extensively, and the results obtained for all three models are presented in Fig. 3 (right). In reference to Figure 3, the buckling safety factors of the CONV model reach up to 70 for the first three buckling modes. On the other hand, model HYDE-A shows buckling factor values of 2.6 to 2.8 and HYDE-B shows buckling factor values even closer to unity.

Finally, according to both graphs of figure 3 can be concluded that the SHS (secondary horizontal system) has been designed with maximal allowable flexibility in order not to absorb too much seismic energy from PHS, while securing the structural stability in terms of P-Delta effect on the cases when HYDE devices are detached from the structure.

4.2. Response-spectrum analysis

By use of modal response spectrum analysis are calculated the deformations and forces of HYDE devices under the assumption that HYDE devices remain ideally elastic. Thus, response-spectrum

analysis is used primarily to determine the elastic features of HYDE devices, i.e. initial stiffness. Under the response-spectrum analysis, Eurocode 8 response spectra with $PGA=0.35g$ (Figure 4) is used as a design criteria. Moreover, in figure 4 are shown the acceleration spectra of Izmit earthquake for X and Y directions, which will be used for the verification of seismic performance of both HYDE models. All of these spectra are shown in one figure, with the intention to visually compare their characteristics.

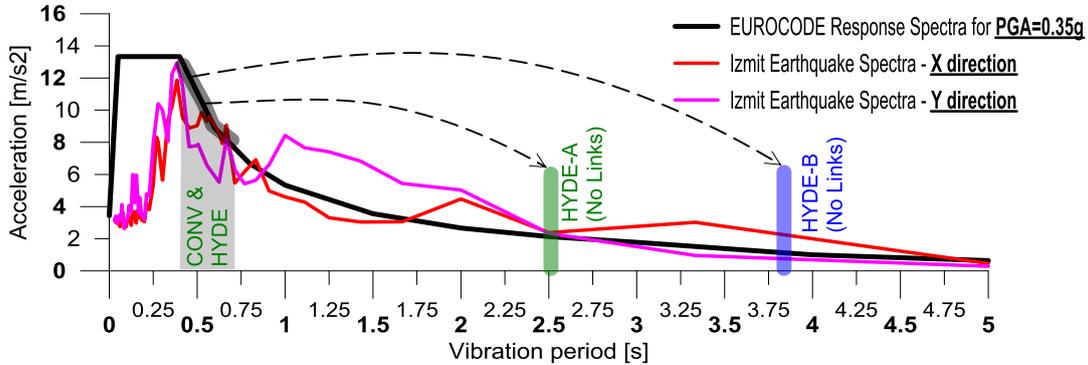


Figure 4. Eurocode response spectra ($PGA=0.35g$) vs. Izmit earthquake response spectra

In addition, in figure 4 have been presented the corresponding areas of the modal vibration periods given in Figure 3-left. It can be observed that the vibration periods of all three models (on their linear state) are ranging around 0.5s-0.7s, in difference to both HYDE models without attached HYDE devices which are located far right to 2.5s and 3.75s respectively. Figure 4 also shows that under the events of strong seismic actions the sliding mechanism of HYDE devices attached to both HYDE models get activated, thus the vibration periods of models shift to the right where vibration amplification levels are much lower. This feature facilitates both HYDE models to evade the amplification of vibrations under seismic response.

4.3. Pushover analysis

The pushover analysis was used as a tool to determine the elastic displacement limit of SHS, which is a crucial parameter for definition of HYDE forces. Therefore this analysis technique was applied only to HYDE models without HYDE devices attached to them. As lateral pushover force was used a set of concentrated horizontal forces acting on the beam-column joints above the ground story (at the level of Story 1). The results obtained from this type of analysis are shown in figure 5.

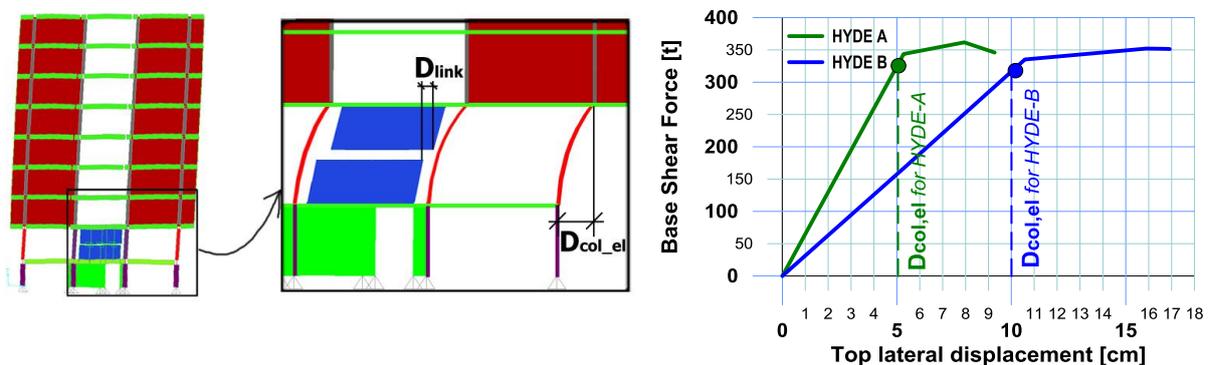


Figure 5. Elastic lateral displacement limit of SHS - Pushover analysis

According to Figure 5, it is observed that the elastic lateral displacement limit of SHS for HYDE-A model is 5cm, while for HYDE-B it is 10cm. This difference in elastic displacement limits, has a significant impact on the design of HYDE systems, as will be shown in the following section.

5. HYDE SYSTEM DESIGN

Besides the structural configuration measures that should be initially considered for achieving a HYDE structural system, it is very important to properly design them, in order to achieve stable dynamic response.

The HYDE systems are designed by means of the so-called "design-curve" which are used to determine the necessary yielding force of HYDE devices with respect to the allowed storey drift in the soft storey. The design curve can normally be calculated by use of non-linear modal time-history analysis for different yield levels of the devices. However, for this study a simplified design method has been used in order to reduce expenditures for the design.

By using this design method, only modal and response-spectrum analysis are needed. In addition, pushover analysis can be used for the determination of maximal elastic lateral displacement of SHS. The parameters obtained from these analysis, for both HYDE models, were shown in figures 3, 4 and 5. In respect to these obtained parameters, the initial stiffness level and yielding force levels of HYDE devices were calculated using simple equations. Finally, by varying the displacement level of HYDE devices are found the corresponding yield HYDE forces. Thus, a set of solution points of HYDE displacements vs. HYDE forces forms the design curves.

Following these design procedures, there were generated the design curves for both HYDE-A and HYDE-B models, which are presented in figure 6 below. These design curves have been generated based on the Eurocode response spectra with PGA=0.35g with damping factor of 1% for HYDE-A model and 0.5% for HYDE-B model.

A detailed explanation on the calculation procedures and equations used under the "simplified design method" can be found on literatures listed on the reference section.

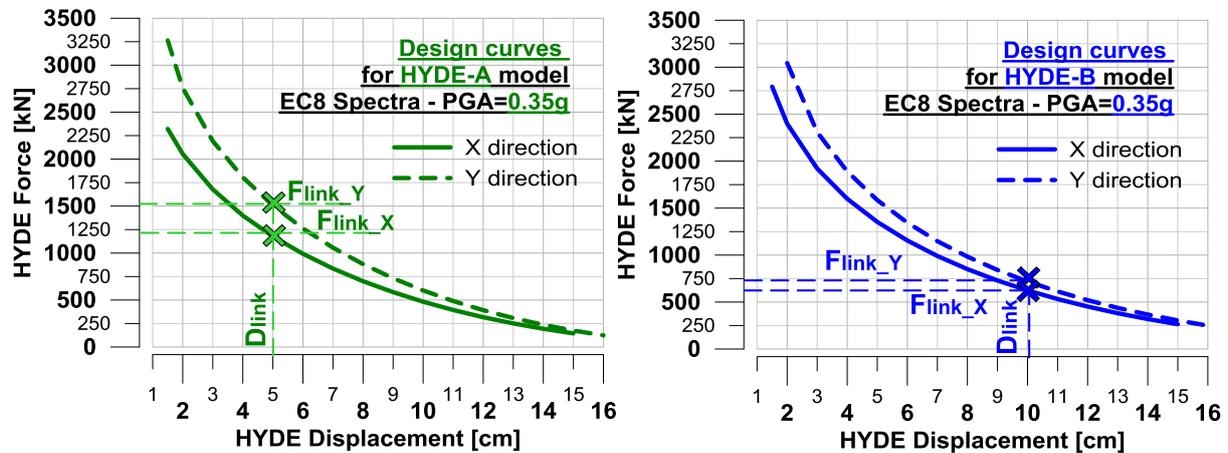


Figure 6. Design curves for HYDE-A and HYDE-B models representative for directions X and Y

Figures 6-left and 6-right show that HYDE device force levels are defined based on the maximal lateral elastic displacement of SHS which are given in Figure 5. Thus, according to the design curves representing the HYDE-A model (figure 6-left), a maximum lateral displacement of 5cm of SHS requires the HYDE device forces to be at least 1250kN for X direction and 1550kN for Y direction. While the distribution of design curves of HYDE-B model are very similar to design curves of HYDE-A model, it is noted that the required minimal forces of HYDE devices are reduced down to 600kN for X direction and 700kN for Y direction, due to the increased level of elastic lateral displacement of SHS up to 10cm.

In addition to the determination of HYDE device forces as shown in figure 6, the initial stiffness level of HYDE devices for both HYDE-A and HYDE-B models were set up to 2000000kN/m.

6. PERFORMANCE VERIFICATION OF HYDE SYSTEMS

The seismic response verification of HYDE design systems is done using direct integration time-history analysis. Direct-integration time-history analysis is the ultimate FEM based technique which takes in to account the full nonlinearity features of all elements constituting the mathematical models, and it requires significantly more calculation time to obtain results. While not being the most efficient tool in terms of time duration of calculations, it certainly is the most effective tool in analysis and detection of even the most complicated dynamic behaviors of structural models.

Under nonlinear direct-integration time-history analysis, all three models were subjected to the Izmit earthquake accelerations acting on all three orthogonal directions X, Y and Z. In addition, all three models were the considered with all nonlinear feature described earlier in section 2 and 3. For consideration of the perfectly stiff-plastic hysteretic behavior of HYDE devices it was used the plastic (Bouc-Wen) hysteretic model available in SAP2000 computer program.

Some of the most representative results, obtained from these analysis, are presented in figures 7, 8 and 9. These figures greatly facilitate in getting a clearer perception on the dynamic response of all three models.

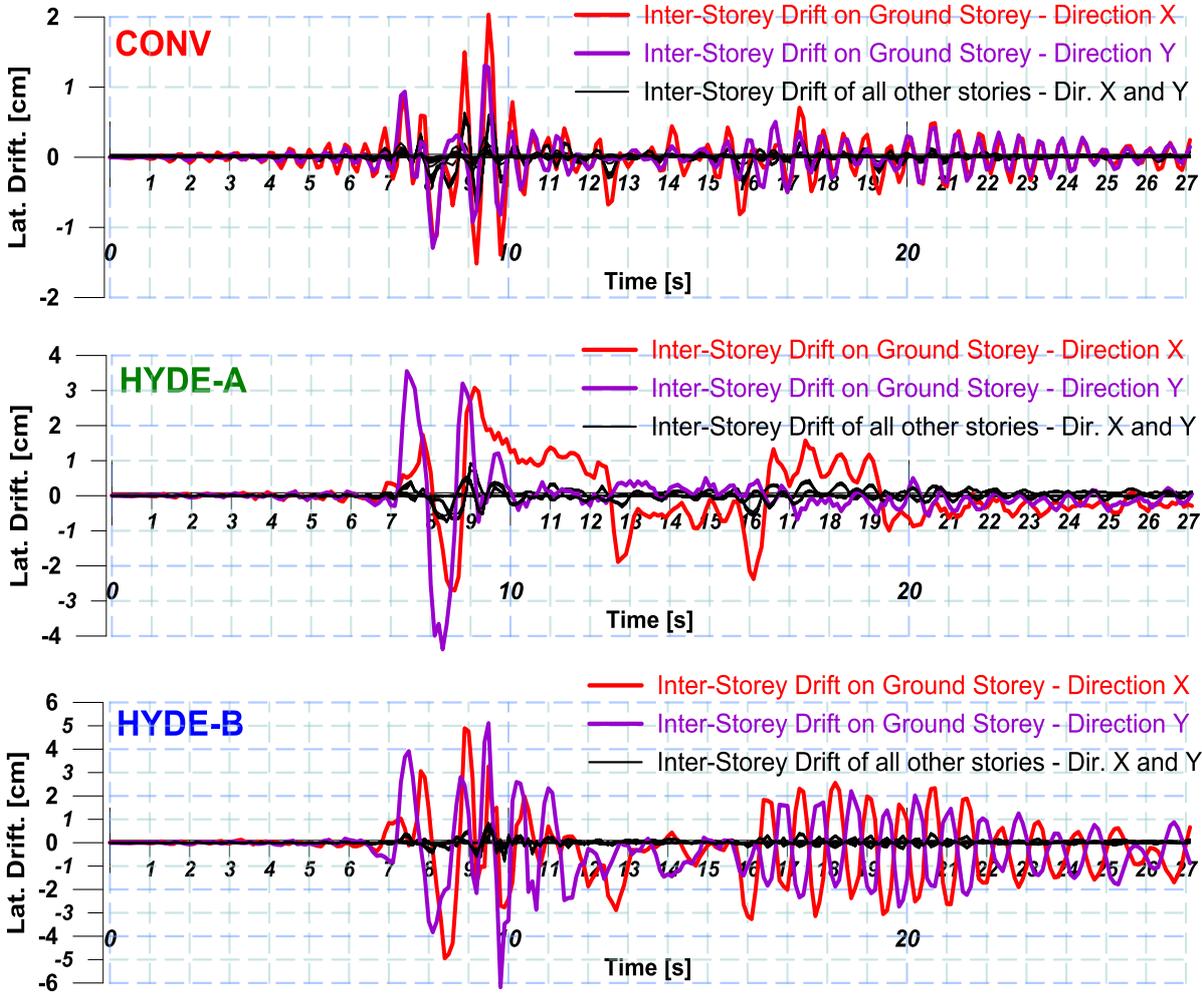


Figure 7. Time history of inter-storey drifts of all three models under Izmit earthquake, X and Y directions

Figure 7 shows the time-history response of inter-storey drifts of all three models, considering both orthogonal directions. Comparing the story-drift responses of all three models (CONV, HYDE-A and HYDE-B) in this figure, the first thing to be observed is that all three models express the highest inter-storey drift levels at their ground story. This feature is widely known as a "soft-storey behavior".

For the conventional concept of structural systems the 'soft-storey' feature represents a very dangerous response mechanism leading to fatal consequences for poorly designed structures. The time history response of the CONV model in figure 7 shows a stable dynamic response though, showing that the core wall of the structure has sufficient strength capacity to withstand the Izmit seismic forces.

Contrary to conventional systems, the HYDE structural concept is very effective on structures having soft-story features, like in multi-storey buildings having ground floor heights greater than their upper storey heights. Buildings with soft-stories show concentrated lateral displacements and storey-drifts, as shown in figure 7. The concentration of inter-storey drifts on the ground story of HYDE models greatly enhances the dissipation of seismic energy through the stiff-plastic hysteretic behavior of HYDE devices, attached to the core RC walls of the ground storey. Figure 8 demonstrates the stiff-plastic hysteretic behavior of HYDE link elements, attached to both HYDE-A and HYDE-B models and subjected to Izmit earthquake forces. It can be observed how the peak inter-storey drift of the ground storey corresponds to the extreme shear displacement of HYDE link elements.

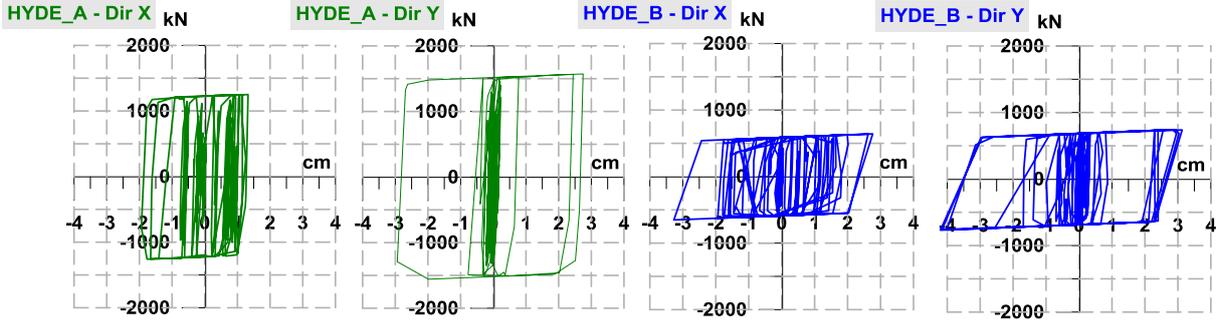


Figure 8. Hysteretic behavior of HYDE devices under Izmit earthquake

The second important thing to be observed from figure 7 is that inter-storey drifts of higher stories, for all three models, are noticeably lower and they don't exceed 1cm at any time. This indicates that linear response is secured to all elements on higher stories of all three models, especially to infill walls elements which due to their weak and brittle nature usually crack after exceeding drift values of 1cm.

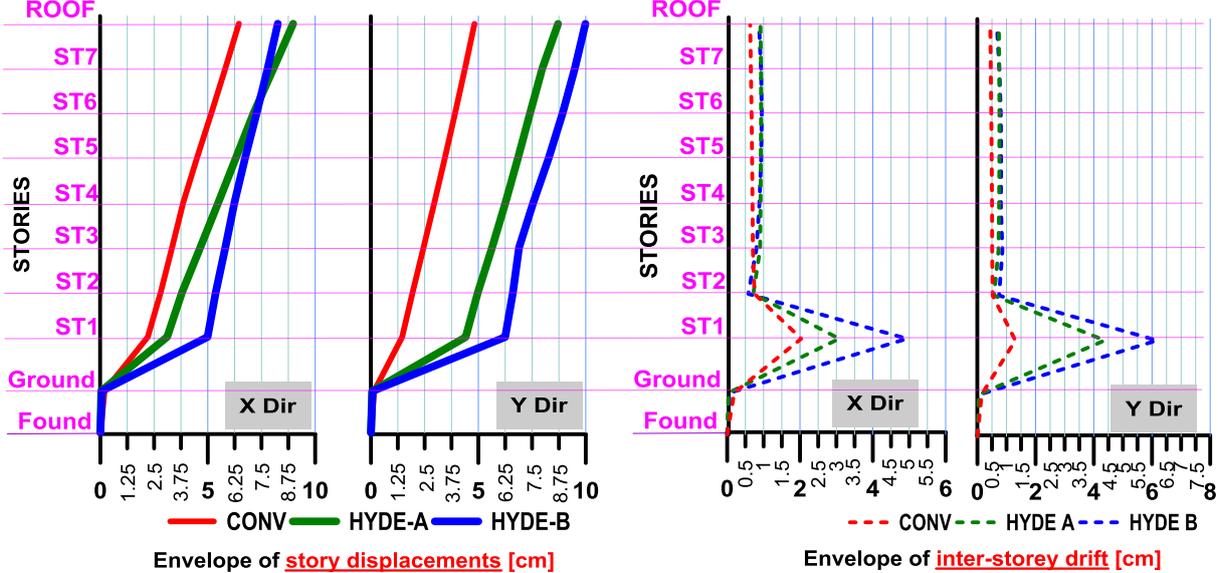


Figure 9. Envelopes of story displacements and drifts in X and Y dir, under Izmit earthquake

In Figure 9, presented are the lateral displacement (left) and story drift envelopes (right) along the height of all three models. Lateral storey displacement envelopes (figure 6-left) show once again the

notable increase of lateral displacement on the ground story especially to HYDE-A and HYDE-B models. Moreover, the envelopes of lateral storey drifts (figure 6-right) better demonstrate how the higher stories move altogether as a rigid body and showing no signs on nonlinear response.

Comparing the similarity between the generated design curves for HYDE-A and HYDE-B models, it can be concluded that a slight reduction of buckling safety factor does not make notable improvements in terms of HYDE efficiency. Consequently, it may be prudent to design HYDE structural systems with buckling safety factors not too close to unity, in order to have a higher safety margin of structural stability in terms of the effect of P-delta. On the other hand, based on the generated design curves and comparing the demonstrated results between HYDE-A and HYDE-B models so far, can be also observed that the replacement of RC columns of SHS with steel columns notably increases the elastic lateral displacement capacity of SHS and so the controlling forces of HYDE devices are notably reduced thus are easier to be achieved.

7. CONCLUSIONS

In order to draw a line of comparison between the conventional and HYDE structural systems, two of the most important factors should be considered, namely safety and economy.

In terms of safety, both structural systems, when properly designed may provide stable seismic response under severe earthquake actions. Moreover, the design of conventional and HYDE systems as well, is based on standardized code procedures that the ordinary engineer can easily implement.

In terms of economy, the differences are considerably. Comparing the models presented on this paper, it can be observed that both HYDE models do not have the RC core wall from the basement to the top of the building, as it is in the conventional CONV model. Moreover, to both HYDE models, all of column cross-section dimensions on the upper stories are with reduced dimensions and amount of reinforcement, thus no special reinforcement detailing is done on the upper stories. Ultimately, all of the aforementioned parameters contribute to a cheaper HYDE structural systems in respect to conventional systems, with equivalent structural safety level due to extreme seismic actions.

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