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DISTRIBUTION OF SEISMIC LINKS IN HYSTERETIC DEVICE SYSTEMS

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SUMMARY

Three typical office buildings with hysteretic device systems (Hyde systems) were studied to show the effects of different types of distributions of Hyde forces. The safety of the buildings was calculated using the β-index concept of modern codes, taking the elastic story drift of the secondary horizontal stiffening system (SHS system) as limit criterion. The standard deviations of the story drifts were calculated from 500 non-linear time histories for this purpose. The study was performed for an excitation statistically equivalent to the 1995 Kobe earthquake. It showed the importance of the slenderness of the SHS system: The less slender the SHS, the less effective are the Hydes in the seismic links (SL) and with them, the whole Hyde system concept. The study also showed that with typical SHS designs, a SL in every 5th story is preferable to a full distribution yielding a smaller total of Hyde forces. Again, it was shown that the Hyde system concept not only provides considerable performance advantages over conventional structural concepts but also yields very economical structures because of the slenderness requirement on the SHS that allows the use of simple connections and small x-sections through most of the structure.

INTRODUCTION

The concept of capacity design [Paulay, Bachmann, Moser, 1990] requires the designer to choose the relevant non-linear mechanism and must make sure that the structural system acts that way. This requires elastic behavior in all the structural components except where the non-linear action is to take place. There, special care must be taken to ensure full elasto-plastic hysteresis loops. This concept is now entering all international codes.

The hysteretic device or Hyde system concept, first conceived in 1986 at the Ruhr-University Bochum, Germany, and published internationally at the 5th NCEE in Chicago, Il. [Dorka, 1994] takes this approach an important step further: If you need elasto-plastic hysteresis loops, then provide them in special elements, so called hysteretic devices (Hydes), that are easily replaceable. That way, no repairs are required in the structure itself and the devices can be subjected to adequate quality control measures and on-site monitoring, thus providing an extra margin of safety. But this is not the only advantage that this concept offers: Extra economy is also provided by a Hyde system through a twin-system approach (Fig. 1). It features a primary horizontal stiffening system (PHS) with seismic links (SL) and a secondary horizontal stiffening system (SHS) where most of the mass is located.

The PHS must be very stiff in order to attract the horizontal forces to the seismic links where the Hydes are placed. Hydes must provide an elasto-plastic hysteresis loop. Therefore they are based on friction or metal yielding. That way, they limit the horizontal forces in the PHS to their respective friction or yield levels. They must be very stiff to complement the stiffness of the PHS and react non-linearly at small deformations. This ensures dissipation of large amounts of energy in the oscillating system. A well designed Hyde system dissipates over 80% of the input energy. It has displacements known only from stiff systems and forces known only from very ductile systems. As a result, a Hyde system combines the performance advantages of both traditional approaches without their drawbacks.

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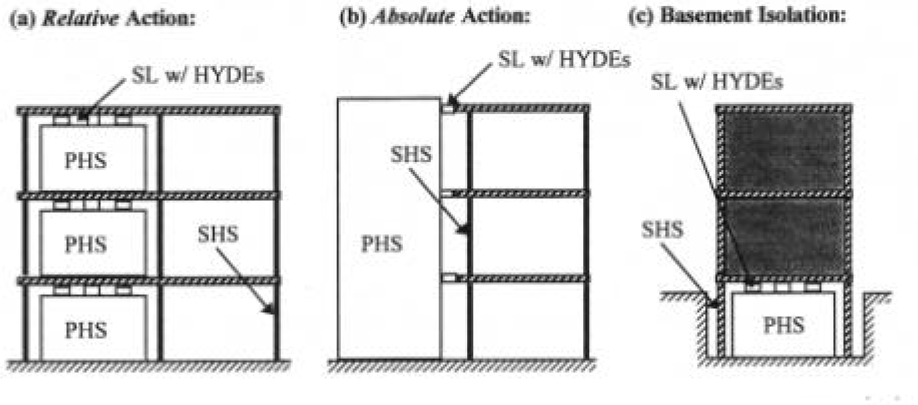

Figure 1: Three versions of applying the hysteretic device concept.

In contrast to the PHS, the SHS must be as slender as possible in order not to attract too much force and remain elastic even under larger displacements. It should be just stiff enough to stabilize the vertical loads. The slender structure of the SHS with its simple connection details and its elastic performance allows for a very economical building since the SHS makes up the bulk of the structure.

Because all non-linear action is concentrated in the Hydes, exchange or repair concentrates on them. Yielding devices must be replaced after one major event but friction devices may be designed to withstand several major earthquakes. Because of their prominent role in the performance of the system, the Hydes are vital for the safety of the structure. Therefore, they should only come from companies who are able to provide the required hysteresis parameters with high accuracy in their devices.

The verification of a Hyde system is done by non-linear time history analysis. The elastic story drift limits of the SHS are typically the design criteria. A sophisticated but easy to handle software module has been developed that allows to estimate the safety index β of the story drifts as it is defined in modern codes and thus allows for a direct estimate of the building's safety. This is accomplished by a statistical evaluation of 500 non-linear time history analyses [Dorka, Pradlwarter, 1993]. For a typical 10 story building, the whole procedure takes about 15 minutes on a regular PC. This software module is implemented in [**SLang** 1998], the software system that has been used in this paper. The module may be used within other software systems as well.

A question not fully answered yet is the distribution of seismic links in the PHS and the choice of the respective yield levels therein. This problem is addressed in this paper by studying the application of a Hyde system in three typical office buildings subjected to the 1995 Kobe earthquake.

A STUDY ON THREE TYPICAL OFFICE BUILDINGS

These office buildings have 5, 10 and 15 stories respectively. They all have the same ground plan (Fig. 2). The story height is 3.0 m throughout. The buildings are designed as steel-concrete composite structures. Slabs and beams are hinged to the continuous columns allowing for simple and inexpensive connection details. The columns are fixed to the base and are tapered at the 5^{th} and 10^{th} level. They act as SHS and therefore have been designed for vertical loads only. Their elastic rotational capacity allows for an elastic story drift of 24 mm. Taking a β-index of 3.5, typical for earthquake loads, this allows for a standard deviation of the story drifts of about 7 mm which is taken as limit state in this study.

The PHS may be added to this structure in the form of rc-walls with horizontal slits that act as seismic links. The Hydes there may be of the two types shown in Fig. 3 [Dorka, Ji, Flygare, 1998]. These Hydes may have yield or friction forces from as little as 50 kN to over a 1000 kN. Thus, the engineer can choose the force envelope in the PHS in an optimal way.

The buildings were modeled as detailed 3D systems with slab and beam elements (Fig. 4). Because the Hydes shown in Fig. 3 act on story shear, the PHS must be designed such that, story shear deformations are prominent. This required a layout for the PHS of the 10 and 15 story buildings that was different from the 5 story building.

The deformation plots of the two system types (Fig. 4) show the prominence of story shear deformations in both systems.

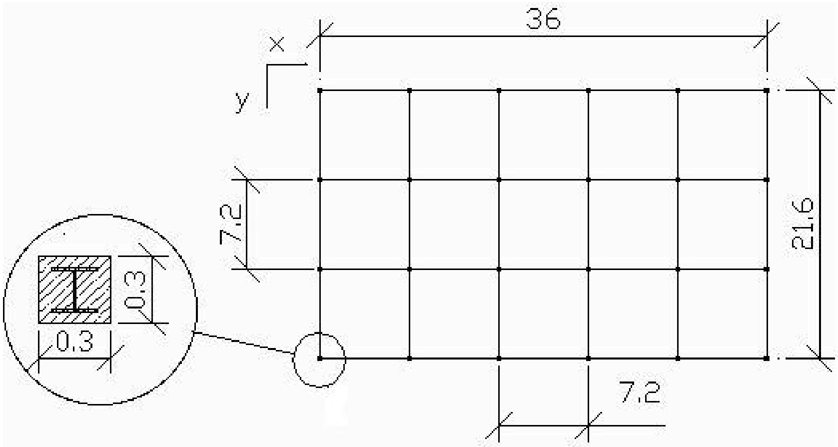

Figure 2: Ground plan of office buildings. Measures are in meters.

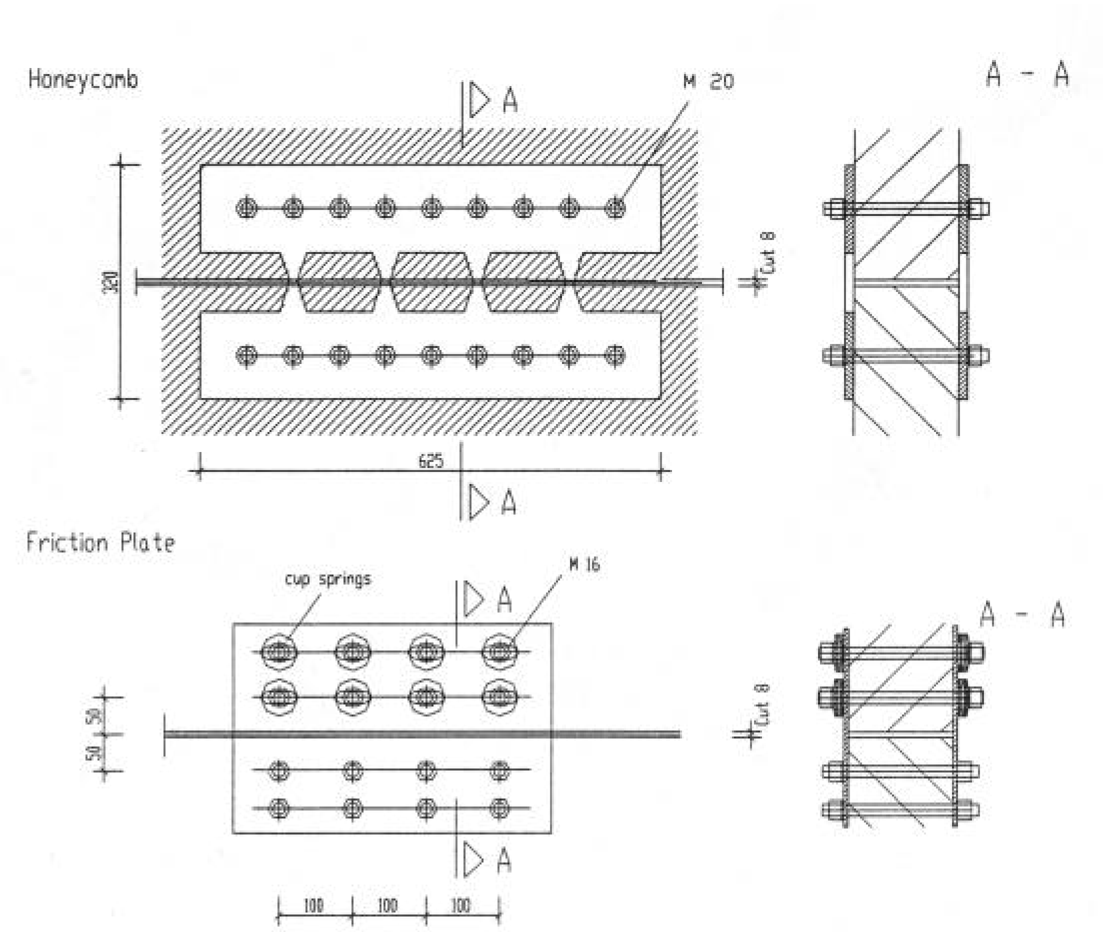

Figure 3: Two types of simple Hydes based on yielding and friction.

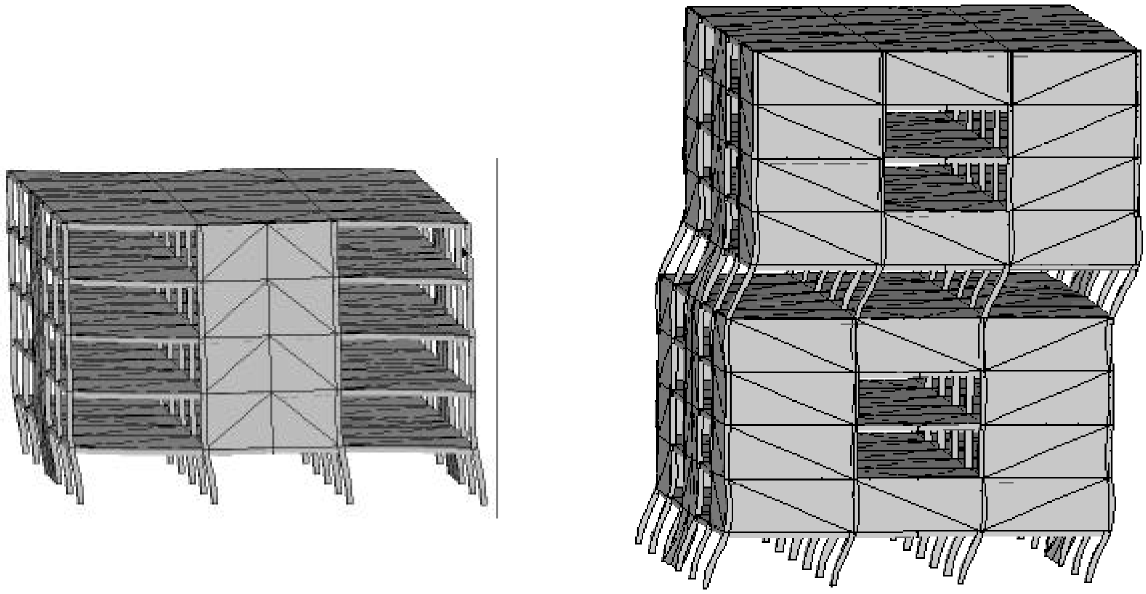

Figure 4: 3D finite element models of 5 and 10 story structure: Deformed states (scale factor 50).

Before the time history analysis, the models were statically condensed on the horizontal DOFs of the slabs in one direction only. The damping matrix was calculated from the condensed matrices as Rayleigh damping with coefficents adjusted to 5% damping in the first two modes. Finally, the non-linear characteristics of the seismic links were added as hysteresis models for the story shears (including the effect of the adjacent walls) before the non-linear time history analysis was performed. Only a static condensation prior to the time history analysis allows for a fast and efficient calculation of 500 records with acceptable accuracy. And it still allows for a detailed investigation of the structure using single states from single records and performing a back transformation on the detailed model. The deformation plots of Fig. 4 were produced that way.

In this study, the Hyde force distributions for the 5 story building were chosen as constant, linear with lower forces on top, linear with higher forces on top and a parabolic distribution based on the proposal by Dechent [Dechent, 1989]. Additionally, seismic links were only provided in every 5^{th} story as an extension to the recently developed concept of "basement isolation" [Dorka, Ji, Dimova, 1997]. The studied Hyde force distributions are given in Table 1 for all buildings. They are chosen such that, they all add up to about the same total for the respective building. That total was adjusted to provide the limit state for the best distribution only.

Table 1: Hyde force distributions (in kN) studied for the 5, 10 and 15 story buildings.

	5 stories					10 stories		15 stories	
Story	**constant**	**Linear**	**Linear**	**parab.**	**5^{th} story**	**parab.**	**5^{th} story**	**Parab.**	**5^{th} story**
1	*400*	*200*	*600*	*456*	*2000*	*846*	*3400*	*834*	*4500*
2	*400*	*300*	*500*	*416*	-	*798*	-	*800*	-
3	*400*	*400*	*400*	*388*	-	*750*	-	*768*	-
4	*400*	*500*	*300*	*372*	-	*700*	-	*734*	-
5	*400*	*600*	*200*	*368*	-	*652*	-	*700*	-
6	-	-	-	-	-	*604*	*2550*	*664*	*3000*
7	-	-	-	-	-	*554*	-	*628*	-
8	-	-	-	-	-	*506*	-	*592*	-
9	-	-	-	-	-	*458*	-	*554*	-
10	-	-	-	-	-	*410*	-	*516*	-
11	-	-	-	-	-	-	-	*478*	*375*
12	-	-	-	-	-	-	-	*440*	-
13	-	-	-	-	-	-	-	*400*	-
14	-	-	-	-	-	-	-	*358*	-
15	-	-	-	-	-	-	-	*318*	-
sum	*2000*	*2000*	*2000*	*2000*	*2000*	*6258*	*5950*	*8784*	*7875*

As excitation, earthquake records where synthesized from a Kanai-Tajimi spectrum based on the power spectrum of the strong motion phase of the Kobe town hall record. Because of the building's symmetry, they were applied in one direction only (direction of the Hyde system).

Fig. 5 (next page) shows a typical development of the standard deviations of the story drifts vs. time. They stabilize after about 1.5 seconds only, which shows that the safety of the system does not depend on the duration of the earthquake. The curves also show the concentration of the drift in the stories with seismic links. For the system shown, the Hyde forces in the 1st and 5th story were adjusted such that, they produce about the same standard deviation for the drift which is close to the limiting value for the columns of the SHS and thus represents an optimal design choice.

Table 2 shows the stabilized standard deviations of the story drifts of all versions studied, with the maximums marked in bold. As can be seen from this table, the distributions with Hydes at every 5th story provide adequate safety whereas all other distributions would need a higher total Hyde force and therefore more and stronger devices. The reason for this can be seen in the energy vs. time plots given in Figs. 6 to 8 for the various Hyde force distributions under the same single earthquake record (Kobe town hall). Obviously, the distributions with Hydes at every 5th story not only provide for less energy to enter the building, but also allow for a larger percentage of that energy to be dissipated in the Hydes. In the other systems, the SHS still attracts a considerable amount of energy. This is demonstrated by the viscous energy curve which shows the dissipation that takes place in the SHS by linear damping (Rayleigh damping model). Therefore, more vibration takes place leading to larger displacements in the SHS.

It can also be seen from Table 2, that the type of Hyde force distribution hardly has an effect on the standard deviation of the story drift in these buildings. This result is somewhat in contradiction to earlier studies [Dechent, 1989] and needs further elaboration. A possible reason may also be found in the relatively large stiffness of the SHS, which then has more influence on the distribution of actions within the system than the Hyde force distribution itself.

Table 2: Standard deviations of story drifts (in mm).

	5 stories					10 stories		15 stories	
Story	**constant**	**Linear**	**Linear**	**parab.**	**5th story**	**parab.**	**5th story**	**Parab.**	**5th story**
1	7,5	5,2	6,5	7,2	**5,8**	7,4	**6,3**	3,0	**6,4**
2	13,0	16,3	12,5	13,6	0,8	**10,5**	0,4	4,0	0,8
3	13,9	**16,6**	**14,5**	**14,9**	0,8	10,2	0,3	5,1	0,8
4	14,3	14,5	14,2	14,2	0,8	9,9	0,3	5,8	0,8
5	**15,0**	12,7	13,3	13,2	0,8	9,5	0,3	6,3	0,8
6	-	-	-	-	-	9,0	**6,3**	6,6	**4,9**
7	-	-	-	-	-	8,3	0,3	6,8	0,7
8	-	-	-	-	-	7,2	0,2	6,9	0,7
9	-	-	-	-	-	5,9	0,2	7,0	0,7
10	-	-	-	-	-	4,6	0,2	**7,2**	0,7
11	-	-	-	-	-	-	-	**7,2**	**6,8**
12	-	-	-	-	-	-	-	7,0	0,5
13	-	-	-	-	-	-	-	6,9	0,5
14	-	-	-	-	-	-	-	6,7	0,5
15	-	-	-	-	-	-	-	6,5	0,5

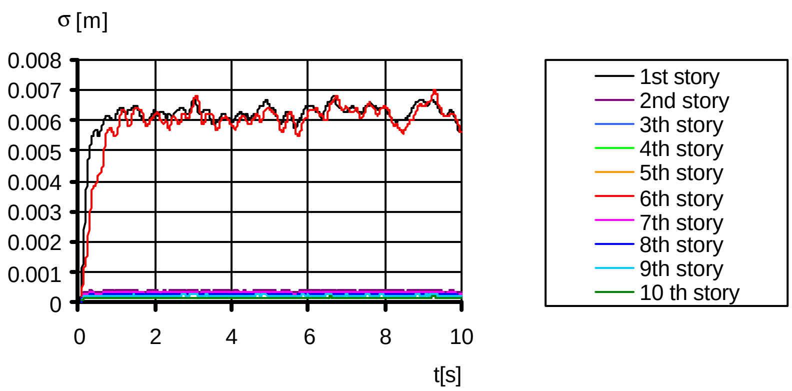

Figure 5: Standard deviations of story drifts over time for 10 story building with SLs in every 5th story.

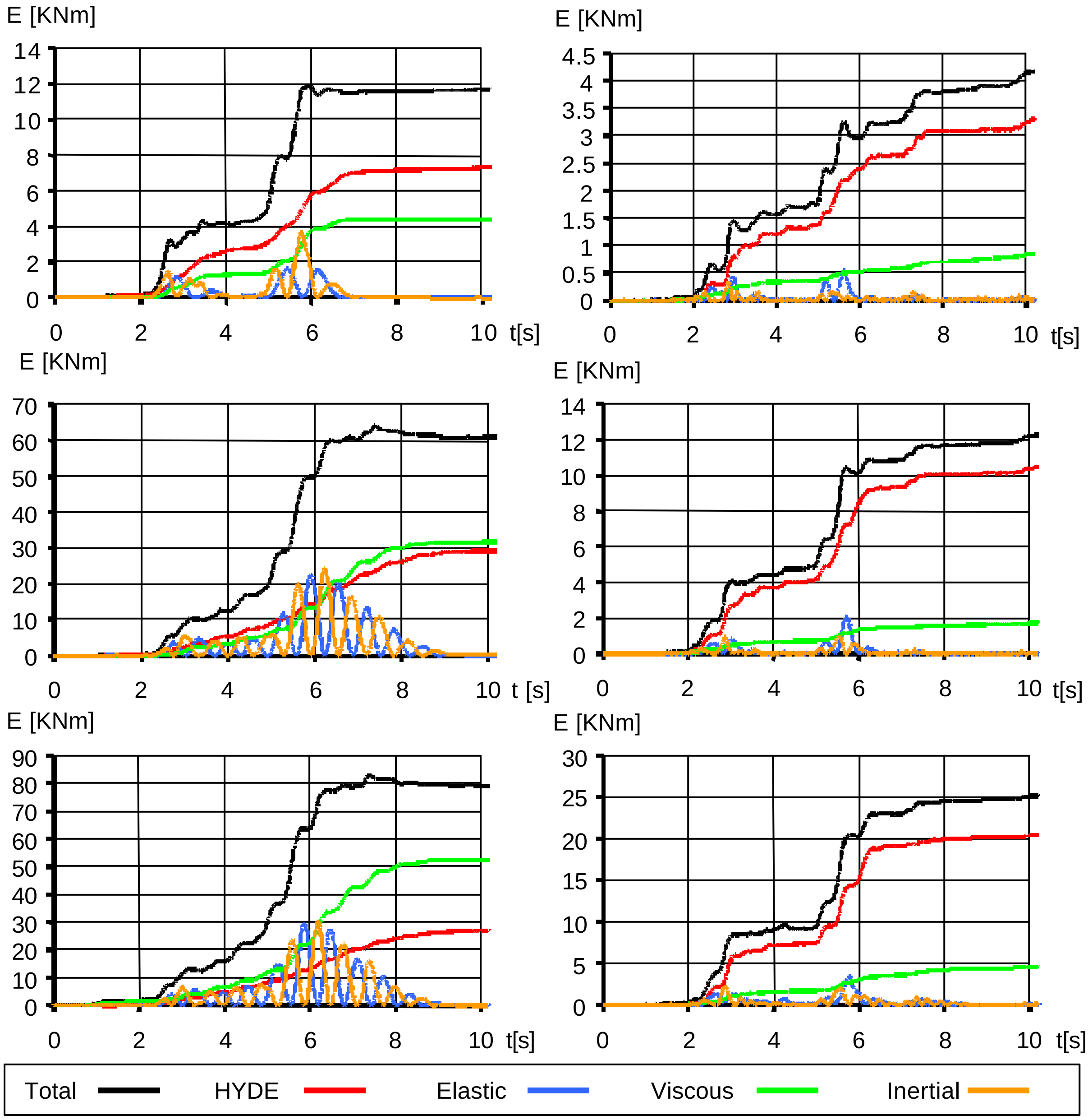

Figure 6: Energies over time in the 5- (above), 10- (middle) and 15 story buildings (below) with SLs in each story (left) and every 5th story (right).

SUMMARY AND CONCLUSIONS

Three typical office buildings with Hyde systems were studied to show the effects of different types of distributions of Hyde forces. In this study, the safety of the buildings is calculated using the β-index concept of modern codes. Taking the elastic story drift limit of the SHS as limit criterion, this translates into the calculation of the standard deviations of the story drifts which can be done by evaluating 500 non-linear time histories statistically. For a 10 story building, this requires about 15 minutes on a high performance PC, including the generation of the Finite Element model and condensation of its system matrices. Thus, this method is suitable for checking the design of practical Hyde system applications. A software module is available for this purpose which can be implemented into various software systems.

The study was performed for an excitation statistically equivalent to the 1995 Kobe earthquake. It showed the importance of the slenderness of the SHS system: The less slender the SHS, the less effective are the Hydes in the seismic links and with them, the whole Hyde system concept.

The study also showed that with typical SHS designs, a seismic link in every 5th story is preferable to a full distribution yielding a smaller total of Hyde forces. With respect to the PHS design, it is important to choose a layout with prominent story shear deformations where the seismic links are to be provided.

Again, it can be seen that the Hyde system concept not only provides considerable performance advantages over other design concepts. Moreover, it yields very economical structures because of the slenderness requirement on the SHS that allows the use of simple connections and small x-sections through most of the structure.

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