HYSTERETIC DEVICE SYSTEM FOR WALL BEARING MASONRY BUILDINGS

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ABSTRACT

Hysteretic device (HYDE-) systems are designed such that they physically limit the forces in the structure and concentrate deformations in dissipative devices. A lot of energy is released during an earthquake. For a building with certain input energy, the demand on energy dissipation through inelastic deformation can be eliminated by using structural protective systems. As a result of this approach, the building consists of several rigid parts connected by highly dissipative structural fuses. IIn In this study, a 5 storey building with a simple floor plan is taken into consideration. The building is assumed to have a soft story in the ground floor and 4 stories on top. It is considered in two versions: First as conventional wall bearing masonry, second as a HYDE system with a seismic link in the ground floor. Wall openings comply with EC8 regulations. Each structure is modeled with linear shell elements and non-linear hysteretic spring elements are used to model the HYDEs in the seismic links. Crack development in corners of openings is checked by fracture mechanics principles. Non-linear time history analysis is performed with adequate earthquake records (e.g. a Central Asia Earthquake). This study presents relations between force, local stresses, crack development, energy dissipation and maximum top displacement. The results demonstrate again the superior performance and economy of a HYDE system and its capacity to protect wall bearing masonry structures against earthquakes.

KEYWORDS: HYDE system, Passive Control, Masonry, Fracture Mechanics

1. INTRODUCTION

Recent devastating earthquakes around the world have underscored the lack of understanding the way in which civil engineering structures respond to such loading. Earthquakes have demonstrated the vulnerability of many residential buildings. This is mainly due to poor construction practice and the application of insufficient design standards. Many of these buildings are wall bearing masonry buildings or reinforced concrete frames and steel structures with masonry infill that have poor detailing and therefore this results in a collapse in a brittle fashion.

1.1. Masonry material

Un-reinforced masonry buildings are mostly occupied as residential facilities in Germany and in many other countries. In most design codes, a rather low ductility factor is given for un-reinforced (q=1.5) and reinforced (q=3~4) masonry to reduce the design response accelerations in comparison with the linear elastic response values.Masonry buildings are brittle structures and therefore fail suddenly without dissipating considerable amount of energy through ductile mechanisms. Laboratory tests of solid masonry shear walls have shown that their behavior can be described at low force levels by linear homogeneous material models. Their stiffness is reported to be low when compared to that of concrete. (Em=.08~.25 Ec),[1]. These walls are very commonly used in many developing countries.

1.2.Soft storey

Infill walls are built for architectural needs and aesthetical reasons in framed structures. In the ground floor, such walls are missing in some cases such as necessitates of parking or commercial space, resulting in occurrence of soft storey and a rigid body above. Often, walls and openings are placed in an unsymmetric fashion which causes torsion in the building. Recent earthquakes have shown that a lot of buildings fail in the ground floor suffering from maximum base shear. (Figure 1).
Figure 2 gives an example of a structure with soft storey where the first mode shape clearly demonstrates the rigid body motion of the upper floors. The stiffness in fist story is assumed AK, and the stiffness in upper stories are same and K.

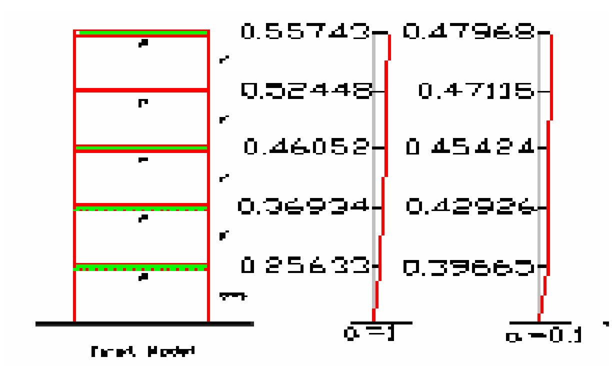


Figure 1. Many buildings failed in their ground floor during the Kashmir earthquake

Figure 2. An example demonstrating rigid body action on a soft ground floor in its 1st mode shape

These results show that;
1- Most displacements are concentrated in the soft story.
2- We can assume a rigid body on top of that soft storey (multiple rigid bodies with multiple soft stories)
3- We can adjust the story stiffness to create such rigid body motions.
4- If the stiffness in the ground floor is half of the other stories, the effective mass of the first mode is more than 95% of the total mass. In this case, only the first mode is needed for dynamic analysis.

2.STRUCTURAL CONTROL CONCEPTS SUITABLE FOR EARTHQUAKE PROTECTION

Some structural control concepts have emerged over the years which are particularly suitable for earthquake protection because of their utilization of rigid body motion control [8]. These are: Base Isolation (BI), Hyde systems (HS), Tendon Systems (TS), and Pagoda Systems (PS) with their principal mechanisms. (Figure 3)

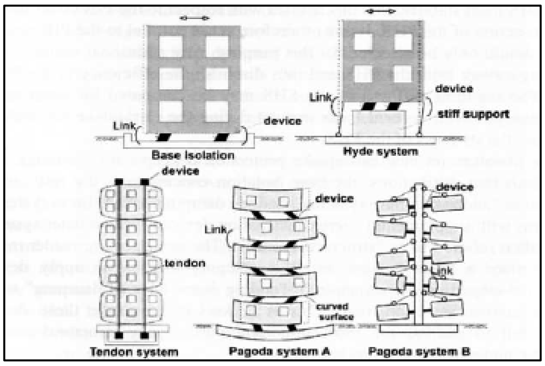


Figure 3. Structural control concepts for earthquake protection based on rigid body motion control.

2.1.The HYDE-System concept

The HYDE system concept was first introduced by Dorka [2]. It consists of two parallel structures; a very stiff **P**rimary **H**orizontal load bearing **S**ystem (**PHS**) with **S**eismic **L**inks (**SLs**) where **HY**steretic **DE**vices (HYDEs) are placed and a conventional soft **S**econdary **H**orizontal load bearing **S**ystem (SHS) (Figure. 4). The Seismic Link (SL) is defined as the gap in the stiff system (PHS) where the devices are placed, including the devices' connections. In some buildings, the PHS has to be amended through the introduction of stiff braces or by the addition of a concrete wall. In others (like large panel prefabricated buildings), an SL can be achieved by simply making a horizontal cut in the walls of the ground floor and introducing vertical gaps at their ends to allow for the SL's movement.

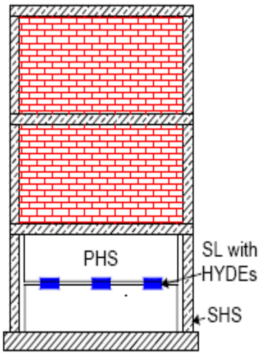


Figure 4. HYDE system with single seismic link (SL) in the ground floor, primary horizontal system (PHS) and secondary horizontal system (SHS)

The PHS must be very stiff in order to concentrate horizontal displacements in its HYDEs in the seismic links. Many inexpensive devices can be used as HYDEs; an overview is given in [2]. To dissipate a large amount of input energy, HYDEs must show almost ideal stiff-elastic-plastic behavior. Then, the SLs can transmit only the maximum HYDE force as storey shear to the adjacent structural members. The conventional part of the PHS,, which remains elastic as part of the HYDE mechanism, is thus protected from overloading.
This unique feature of the HYDE system concept allows the designer to choose a shear force envelope that is suitable for a conventional design of the members. The remaining task is to verify the displacement capabilities of the chosen mechanism, e.g. in the locations of the seismic links. The design limit of the HYDE system is defined by the maximum elastic deformation of the SHS, usually represented by the columns of the story where the SL is placed.
The SHS must stabilize the P-Δ effect that takes place during the activation of the HYDE system. The SHS should be stiff enough to perform this task, but soft enough so as not to diminish the efficiency of the HYDE system. Any additional stiffness of the SHS will draw energy away from the PHS, causing un-necessary stresses.
A correctly conceived HYDE system possesses a clearly defined stiff-ductile mechanism where the kinetic energy (and with it, the potential energy) in the structure is minimized, thus minimizing deformations and stresses. A well-designed HYDE system dissipates approximately 85% of the energy input into the structure. The result is a combination of the advantages of a stiff non-ductile system with those of a soft ductile system, thus achieving a reduction both in terms of forces and displacements. Linear behavior of the conventional part of the structure, even under severe earthquakes, is achieved.

3. FRACTURE MECHANICS

In this section the basic principles and methods applied in fracture mechanics which are useful for the understanding of fracture mechanisms in masonry buildings are discussed.
Fracture mechanics problems have been classified into linear-elastic fracture mechanics (LEFM), elastic-plastic fracture mechanics (EPFM), and time-dependent fracture mechanics (TDFM) regimes. These classifications are based on the dominant deformation modes in the cracks. When the stress-strain behavior is linear, LEFM can be

used and the relevant crack tip parameter is the stress intensity factor K. In this regime, the plastic zone is small in comparison with the crack size and other pertinent dimensions of the cracked body.
For elastic-plastic problems, the features of the J integral and its use for predicting crack initiation, stable and instable crack growth are discussed, with some words on CTOD. Short reviews of fracture testing and of micro structural aspects follow.

3.1.Mathematical relations in fracture mechanics

3.1.1. Strain energy release rate

For the simple case of a thin rectangular plate with crack perpendicular to the load, Griffith's theory yields:

$$G = \frac{\pi\sigma^2 a}{E}$$

Where G is the strain energy release rate, σ is the applied stress, a is half the crack length and E is Young's modulus. The strain release rate is understood as: *the rate at which energy is absorbed through growth of the crack.* We also have:

$$G_f = \frac{\pi\sigma_f^2 a}{E}$$

If G>= G_c, the crack will begin to propagate.

3.1.2. J integral

The J-integral was defined as a contour integral by Rice

$$J = \int_\Gamma (W dx_2 - T_i \frac{\partial u_i}{\partial x_1} ds)$$

Where Γ is a path surrounding the crack tip , starting and ending at the lower and upper flat crack surface , respectively, and W is the strain energy density;

$$W = W(\varepsilon) = \int_0^\varepsilon \sigma_{ij} d\varepsilon_{ij}$$

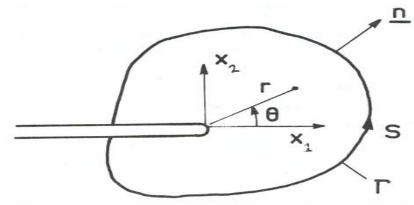


Figure 5. Definition of the J-integral path

In the absence of body forces, Rice has shown that J is identical to the potential energy release rate;

$$J = dU/da$$

Where **U** is the potential energy of the body and **da** the infinitesimal change of the crack length. The definition of the energy release rate G is utilized together with **ΔA= B Δa.**

$$G=J/B$$

3.1.3. Reduction of module elasticity

In the region (near the crack), it is assumed that the boundary condition is not changed during the propagation of crack. In this case we assumed that the length of crack is constant but module of elasticity is changed. Than;

$$\frac{\partial U}{\partial E}=\frac{\partial U}{\partial a}\frac{\partial a}{\partial E}$$

$$E=\frac{\pi\sigma^2 a}{G}\Rightarrow\frac{\partial a}{\partial E}=\frac{G}{\pi\sigma^2 a}$$

$$1{,}2{,}3\Rightarrow\frac{\partial U}{\partial E}=G\frac{G}{\pi\sigma^2 a}=\frac{G^2}{\pi\sigma^2 a}$$

3.2 Fracture mechanics in masonry buildings

Brick masonry failures have been extensively investigated through uniaxial and biaxial loading conditions [9-10]. Crack evolution (from micro cracking to macro fracture) can be analyzed by means of recently established experimental techniques [11]. When dissipative phenomena play an important role (as is the case in masonry structures under seismic actions) energy criteria is more useful to analyze fracture than the classical stress criteria. The application of fracture mechanics is extended to brick masonry [7]. There, it was demonstrated how the theoretical results fit with the experimental ones. Further investigations are encouraged with the following objectives:
(i) to characterize the different brick masonry materials
(ii) to simulate numerically the mechanical and fracture behavior of brick masonry structures of complex
The problem of Mode I (opening) fracture in brick masonry is discussed in [7]. Structural elements working in compression often undergo this mode of failure. The fracture energy G_F were evaluated for three-point bending specimens, directly drilled from historical bricks. Theoretical and experimental load-deflection curves were reported to exhibit very similar softening branches. A softening branch with positive slope was revealed experimentally by controlling the crack mouth opening displacement, and numerically by controlling the crack length. It was concluded that both such quantities are thus monotonically increasing with time.
The fracture energy G_f obtained from the load-deflection curves, taking into account the area under the curve divided by the ligament area. Specimens' information and G_f values from are given in Table 2.

Table 2. Experimental results from [7]

Specimen	**size LxHxB**	**Notch depth**	**Notch Thickness**	**Density**	**Young's modulus**	**Tensile strength**	G_f
	cm	cm	cm	kg m^{-3}	Mpa	Mpa	N m^{-1}
A1	20x4x2	0.4	0.1	1718	1900	2.2	52.2
B2	20x4x1.9	1.1	0.1	1750	1880	1.5	37.2
C3	20x4x2	1.9	0.1	1809	4900	10	52.1

4.NUMERICAL MODELLING

4.1 Numerical model

First, a detailed (usually 3D) numerical model is generated for the conventional structure using only linear elements for columns, beams, bracings (beam element), floors and walls (shell elements). This follows the structural principle of the HYDE-System, where all structural members other than the HYDEs remain elastic. Then, static condensation is **applied.** The choice on the number of condensed degrees-of-freedom (DOF) is a trade-off between accuracy and calculation time. With typical building structures, 3DOFs per floor (2 horizontal, one in-plane rotational) are usually sufficient for accuracy and allow very fast simulations.
To describe the behavior of the seismic links with their HYDEs, a Bouc-Wen type hysteresis law was used to describe the shear force transmitted through each SL. This law is numerically stable, an essential requirement when analyzing stiff-ductile systems.

The hysteretic law and its parameters are shown in Figure 6. The model is described by four input variables: initial stiffness KI , yielding and plastic displacement dy and dp and secondary stiffness kE. To model the SL, a nonlinear spring element was used.

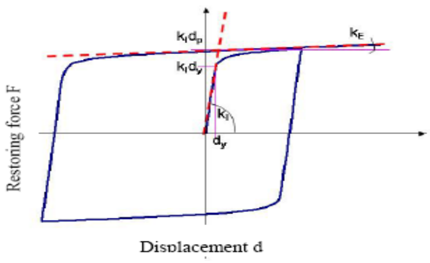


Figure 6. Stiff-ductile Hysteresis Loop for an SL with HYDE's

The concept of the J-integral is useful to estimate the energy released during crack growth. Four potential cracks are assumed around every wall opening. A time-history analysis is performed under earthquake loading and at the end of every time step, the J-integral is calculated for every crack region. If G > G_f, in a region, crack growth takes place and depends on the energy released (J- J_f). Then, the modulus of elasticity E is reduced in this region using the relationship in last energy equation above for the next time step. This will reduce the overall stiffness of the PHS and thus helps to analyze the effect of cracking on the HYDE system performance.

4.2 Design Approach

To find the required HYDE system parameters, in particular the yield force and stiffness of the SLs, a large initial stiffness is first selected. It is known from many studies that, if the initial stiffness k1 is "stiff enough", it has no effect on the storey drift in the SL.
By means of time history analysis, maximum link displacements are calculated for selected link yield forces and the results are plotted in a diagram as shown in Figure 7, where the design point and the corresponding link force are defined based on the displacement limit of the SL, as explained before.

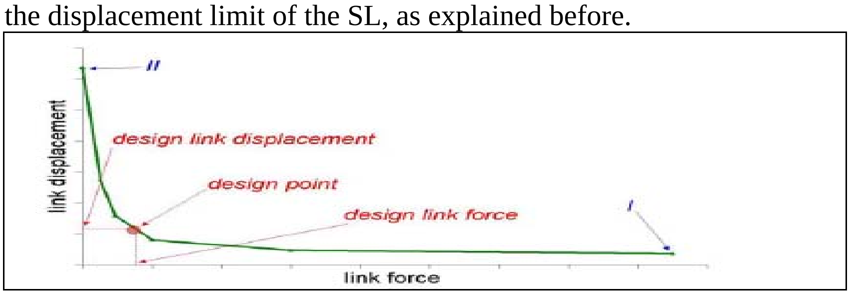


Figure 7. Design Curve fo HYDE System

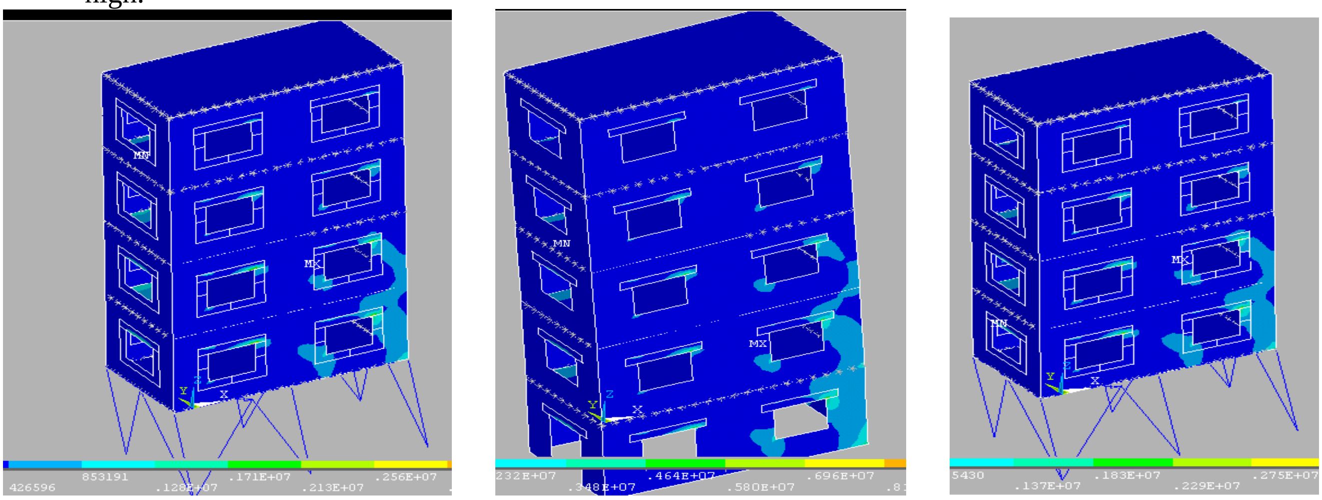
The design curve is limited by two elastic systems, marked as I and II in Fig. 7. System I is characterized by stiff elastic behavior of the SL (no inelastic HYDE action), resulting in maximum forces and minimum displacements. System II is characterized by the absence of HYDEs in the SL, resulting in minimum forces (the SHS is practically acting alone in the SL), but exaggerated displacements (response of the unprotected soft story structure). The location of the design point gives an idea of the efficiency of the selected system in terms of reducing forces and displacements.
After the design link force is selected, a parametric analysis on the stiffness of the link is performed in order to determine its lower stiffness limit (what is “stiff enough”) and obtain a cost effective system for the PHS.

5. ANALYSIS RESULTS

Model is a very simple building with 5 stories. First story is steel frame with bracing as SHS. Model is symmetric and is loaded under Kobe Earthquake record. The 1~5 stories are wall bearing masonry, resistance of which agents dead load and lateral loadings. After time history analyses, design curve is given and design points which are the static limit of column are defined. (Figure 8)

If the results for building in 3 case are compared, it is obviously seen that:

1- The HYDE system is more tolerant to increased earthquake demand and thus comprises a more sustainable structure.
2- HYDE system displacement is higher than the other, because of the stiff feature of masonry building.
3- The masonry buildings are brittle structures. In this case, they loss resistance very fast.
4- The cracks also dissipated energy; however, it is assumed that the numbers of the cracks are not very high.



HYDE system with crack element
Dmax= .11 m
max.Sress=.384e7 N/m^2

Model without HYDE system
Dmax= .03 m
max.Sress=1.5e8 N/m^2

HYDE system without crack element
Dmax= .09 m
max.Sress=.42e7 N/m^2

Figure 8. Model in 3 case and displacement and max. stress for same dynamic loading

The input energy is divided to Potential, Kinetic and Viscous energy. The link (SL) in building with HYDE system dissipates most of the energy. Figure 9 shows the energy division in the model.

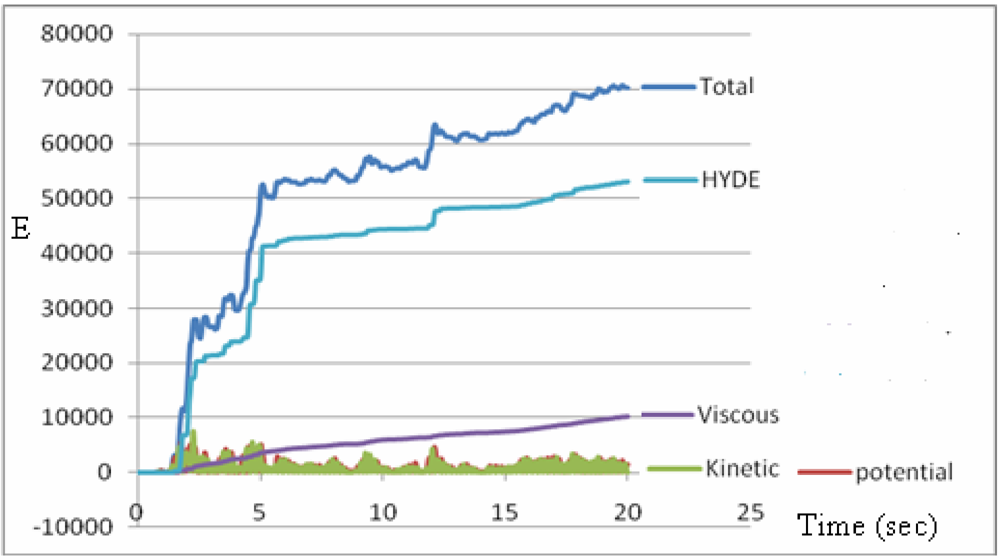


Figure 9. Several Energy Division in Model

6. SUMMARY AND CONCLUSIONS

This paper discusses the application of the HYDE system, a particular kind of seismic control concept fpr wall bearing masonry buildings.Designing residential or mixed commercial- residential buildings as HYDE systems provides a more economic and sustainable structure in an earthquake environment. This seismic control concept needs only inexpensive devices like shear panels to control a rigid body mechanism and can be used to retrofit soft story buildings with little effort and negligible interference with tenant activities.
Fracture mechanics principles are introduced in this research to evaluate the limit states of the masonry walls when they are a part of the PHS of a Hyde system. Crack growth from corners in wall openings can be estimated using the J-integral and thus integrity and required stiffness of the PHS can be checked.

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