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Seismic Energy Response of Steel Moment Resisting Frames with Mass Irregularity

질량비정형을 갖는 강 모멘트 저항 골조의 지진에너지 반응

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국문요약

고층의 강 모멘트저항골조에 대한 지진 반응을 살펴보기 위해서 동적해석을 실시하였다. 구조물은 세가지의 다른 설계절차로 의도적으로 설계하였고 그 세가지의 개념은 강도 지배설계, 강기둥-약보 지배설계, 횡변위 지배설계이다. 그렇게 설계한 구조물이 각각 질량비정형이 존재하도록 하여 횡변위, 소성힌지, 이력에너지 입력 및 요구응력에 대해서 토론하였다. 미래에 설계에의 응용을 위해서 최대 지반가속도로 표현한 두 등급의 지진 하중을 이용해서 이력에너지 입력요구 곡선을 제시하였다.

1. Introduction

This research was carried out to investigate the hysteretic energy input characteristics, plastic rotation distributions, and story drift ratios on sixteen story high-rise steel moment resisting frames. The paper covered on the mass and stiffness irregularities using 16-story steel moment-resisting frames.

The paper considers the seismic response of the steel moment resisting frames through examining the vertical mass irregularities under various seismic loadings. The seismic response results in terms of the hysteretic energy inputs, plastic rotations, and story drifts using sixteen story steel moment resisting frames are presented. The stress distribution at the beam-column connection of the first floor was studied to take account for the damage patterns under the same seismic loading using the finite element analysis. Finally, the amount of hysteretic energy input at the two design levels of earthquake ground motions in quantitative manner are considered.

2. Background

A structure is considered to be irregular if it has significant physical discontinuities in its configuration or in its lateral-force resisting system. Many structural codes specify limited values for structural irregularities. According to the 1997 UBC, the following irregularities exist (UBC, 1997).

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Mass irregularity: Mass (weight) irregularity is considered to exist where the effective mass of any story is more than 150% of the effective mass of an adjacent story. A roof that is lighter than the floor below need not be considered.

Stiffness irregularity: A soft story is one in which the lateral stiffness is less than 70% of that of the story above, or less than 80% of the average stiffness of the next three stories above.

Discontinuity in capacity (weak story): A weak story is one in which the story strength is less than 80% of that of the story above. The story strength is the total strength of all seismic-resisting elements that share the story shear for the direction under consideration.

The irregularities can occur as setbacks, mass irregularities, stiffness irregularities, or weak stories. The vertical irregularities in a building may result in a concentration of forces of deflections or in an undesirable load path in the vertical lateral-force-resisting system. In the extreme cases, this can result in serious damage to or collapse of a building, since the lateral system is often integral with the gravity-load-resisting system (FEMA-274, 1997).

To date, the detailed evaluations of the vertical irregularities for tall steel moment resisting frames are not fully carried out on hysteretic energy inputs, plastic rotations, drift ratios, and stress demands. These research points are also easily overlooked in many undeveloped countries.

The hysteretic energy input is a very valuable parameter for investigating the seismic response of steel moment resisting frames subjected to various seismic loadings. The displacement ductility itself does not fully demonstrate the damage pattern of the structure. However, the hysteretic energy input represents the low cycle fatigue and structural damage. Accordingly, the hysteretic energy input parameter was used as one of the main parameters in this essay. Uang and Bertero (1997), Kuwamura and Galambos (1989), and Akiyama (1985) measured the energy input of structures due to various earthquake ground motions. These investigations proved the possibility that the hysteretic energy input is a good parameter for explaining structural demands and damages. Valmundsson et al. (1997) published a paper regarding seismic response of building frames with vertical irregularities. Their paper mainly focused on the ductility demand ratio using multi-degree of freedom (MDOF) systems. However, the hysteretic energy input characteristics and plastic rotations of the MDOF systems with vertical irregularities were not fully covered in their research.

Therefore, it is necessary to study the seismic responses of the vertical irregularities using various parameters.

3. Hysteretic energy input

The various energy terms can be defined by integrating the equation of motion of an inelastic system. The governing equation for an inelastic system is as follows (Chopra, 1995):

$$m\ddot{u}+c\dot{u}+f_S(u,\dot{u})=-m\ddot{u}_g(t) \qquad (1)$$

$$\int_0^u m\ddot{u}(t)du + \int_0^u c\dot{u} + \int_0^u f_S(u,\dot{u}) = -\int_0^u m\ddot{u}_g(t)du \tag{2}$$

The energy dissipated by hysteretic yielding is

$$E_h(t) = \int f_S(u,\dot{u})du - E_S(t) \tag{3}$$

Eventually, the energy should be balanced to keep the stability of the system.

$$E_I(t) = E_K(t) + E_D(t) + E_S(t) + E_h(t) \tag{4}$$

Equation (4) implies that total energy equals the sum of damping energy (E_D), kinetic energy (E_K), strain energy (E_S) and hysteretic (E_h). The hysteretic energy demand on the lateral-load resisting elements was further characterized by a factor similar to the displacement ductility demand.

$$\mu_h = \frac{u_{\max}}{u_y} = \frac{E_h}{f_y u_y} + 1 \tag{5}$$

$$E_h = f_y(u_m - u_y) \tag{6}$$

The hysteretic energy ductility demand was defined as one plus total hysteretic energy dissipated by the element during all inelastic cycles divided by twice the energy absorbed at the first yield. Accordingly, in a monotonic loading condition hysteretic energy demand can be acquired as represented in equation six.

On the other hand energy input can be expressed by total energy input divided by the mass of a system. Uang et al. measured the absolute energy input using a six story braced steel frame (Uang et al., 1990). While the relative energy formulation has been used in the majority of the previous investigation, their study shows that the absolute energy equation is physically more meaningful. They presented a formula of energy input for the SDOF system as follows.

$$\frac{E_i^{\max}}{m} = 0.5(1.0 + 0.1t_D)^2 \dot{u}_{go}{}^2 \tag{7}$$

Fajfar et al. proposed the maximum input energy, which is imparted to systems with fundamental periods in the vicinity of the predominant period of the ground motion (Fajfar et al., 1991). They proposed the equation of energy input that can be written in the form as:

$$\frac{E_I}{m} = 0.85\frac{v_g}{a_g}\int \ddot{u}_g{}^2\, dt \tag{8}$$

4. Modeling

4.1 Selection of earthquake level

Two design earthquake levels (DEQL) scaled to 0.3g (DEQL I) and 0.6g (DEQL II) were used in this study. Three earthquake ground motions were used and scaled to the two design earthquake levels.

4.2 Loading Plan

To perform the nonlinear time history analysis, the DRAIN2D+ program was used (Tsai et al., 1994). The Strand7 is also used to evaluate the detailed stress response at the exterior beam-column connection of the first floor for a sixteen story steel moment resisting frame (Strand7, 2002). No rigid zone was considered or beam-column element was used in the DRAIN+ program.

The two nominal strengths of beam and column were assumed to be 2.4 and 2.8 tf/cm^2, respectively. Loads are applied to three major floors: the roof, the middle level floors, and the ground floor, respectively. For the roof, dead and live loads were 350 and 200 kgf/m^2, respectively. For middle level floors, dead load and live load were 500 and 200 kgf/m^2, respectively. For the ground floor, dead load and live load were 540 and 500 kgf/m^2, respectively.

4.3 Design and analysis of steel moment resisting frames

The drift limit of 0.015h was observed in the DRFT-C frame. The LRFD method and 1997 UBC code were used for those designs. To get smoothed design strength over the floor, all designs were made in a way that the interaction of flexure and axial compression to each beam-column connection ranged between 0.85 and 0.95 that are surely smaller than 1.0.

After the design of the three basic systems, the mass of the basic system is artificially changed to create mass irregularities without changing the total mass. With Case 1, the mass at the ground floor was increased by 50% point and the mass at the second-floor was decreased by 50% for three basic designs. Therefore, the vertical mass irregularity of 200% was made in an adjacent story. The value of mass (m) by 3.5469 tf-s^2/cm was used in the design.

The same adjustments were made for cases 2 and 3 to the eight-floor and fifteen-floor, respectively with the three basic systems. However, the total structural mass has not been changed in each case to keep the structural integrity. The selected member sizes of the SD, SCWB and DRFT systems are shown.

The overall analysis was carried out by the following:

(1) The nonlinear push over analysis was carried out for the three basic systems.

(2) The nonlinear time history analysis was performed to evaluate the seismic response including hysteretic energy input, plastic rotation, and drift for the SD system.

(3) Next, the procedure (2) was performed for cases 1, 2, and 3 of the SD system.

(4) The procedures (1), (2), and (3) were repeatedly performed for SCWB and DRFT systems.

(5) Finally, finite element analysis was performed for DRFT system where the 2D plate element was used.

5. Discussions

5.1. Vertical mass irregularities

The vertical mass irregularity of sixteen story steel moment resisting frames was evaluated in this section. The three schedules of mass irregularities were studied. The mass variations were made artificially to investigate the seismic responses. The mass differences were 200% in an adjacent story of 2nd-floor, 8th-floor, and 15th-floor, respectively. The drift ratio and plastic rotation were discussed for the SD and DRFT systems with EQ1, EQ2, and EQ3. The strength and stiffness characteristics of the SCWB system showed a similar pattern to the DRFT system. Thus, the results of the SCWB system were omitted.

In Case 1, the drift ratio was increased by 48% compared with the Control frame at the first floor for the SD system. The drift ratio was also increased by 31% point compared with Control frame at the 8-floor at the Case 2. The drift ratio for the Case 3 was increase by 80% compared with the control system under EQ2 scaled to 0.6g in PGA. The drift ratio reached 4.87% in Case 3.

The drift response was evaluated for the DRFT systems with the vertical mass irregularities at the three places for three earthquakes at 0.3g and 0.6g. The drift ratio increased by 25% in Case 1 with EQ2, 0.6g. The drift ratio increased slightly by 10% for the Case 2 under EQ2, 0.6g. The drift ratio increased by 117% in Case 3. For the SD systems, the large plastic hinges occurred at the upper floors in the Case 3. The plastic rotation results showed that the vertical mass irregularity of Case 2 was not significant while the other two cases showed large plastic rotation response under the EQ2, 0.6g. For the DRFT system, the size of plastic rotations decreased due to the design characteristics which are apparent from the drift limit and strong column-weak beam conditions (UBC, 1997). Generally, the plastic rotations increased at the upper floors in the Case 3.

The results showed that the drift ratio could increase significantly while plastic hinge rotations are not a major problem in the structure. The results also showed the drift ratio increment ranged from 10% to 117%. In all cases, the drift ratio increased where vertical mass irregularity has occurred in all cases. Among the three cases, the mass irregularity effect in Case 1 and Case 3 were more significant than Case 2 where the vertical mass irregularity was artificially made. The mass irregularity effect using the Case 2 was minor compared with the other two frames. The mass variation at the first floor and upper floors can cause serious drift ratio increment as shown in Case 1 and Case 3. The plastic hinge rotation distributions for the DRFT frame were not significant: about 1.0% radian for high-rise steel moment resisting frames. Also, plastic hinges tend to concentrate at areas where mass irregularities are made. If a mass (weight) irregularity exists in any story mentioned above, a drift ratio response is critical, rather than plastic hinge rotations for this type of high-rise steel moment resisting frames.

If a mass irregularity more than 200% of an adjacent story exists, the drift ratio response is more important than the plastic rotation response. Thus, the research reassured that the drift ratio could reach more than 5% radian under the guideline value of 200% of vertical mass irregularity of UBC from the studied Case 3 model.

The average drift ratio of the Control frames was 1.55% under three earthquakes at 0.3g. The average drift ratio of the Control frames was 2.10% under three earthquakes at 0.6g. The results showed the most severe case of vertical mass irregularity was caused by the change in mass at the upper floors, as in Case 3. Then, the next severe case caused by mass variation at the lower stories, as in Case 1. The drift increase ratio in average was 28% and 199% at 0.3g and 0.6g, respectively in Case 3. The drift ratio for Case 1 increased up to 23% and 32% at 0.3g and 0.6g, respectively on average. Therefore, it is more dangerous if vertical mass irregularities occur at the lower or upper floors, then if they occur in the center levels of the structure.

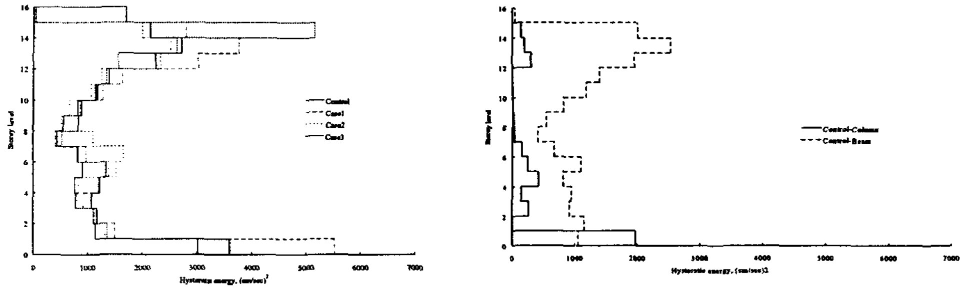

Figure 1. Hysteretic energy with vertical mass irregularity effect; (a)total response (b)beam-column response

5.2 Hysteretic energy input of systems

The hysteretic energy inputs of the DRFT system are studied to identify the vertical mass irregularity at the EQ2. The hysteretic energy distribution showed a good distribution pattern over the height in the DRFT system. In Case 1 the hysteretic energy increased by 80% at the first floor. The hysteretic energy input increased by 51% in Case 2. Also, the hysteretic energy showed 46% increment in Case 3. As we have seen, the greater increment of the hysteretic energy input demand occurred in the order of Case 3, Case 1, and Case 2, respectively.

The hysteretic energy input demands of the beams and columns are shown in Figure 1. The figure considered as a reasonable output because the DRFT system was designed by observing the strong column-beam column conditions of 1997 UBC. The hysteretic energy input demands on the beams at the upper floors were higher than the demands of the middle and lower floors. The similar hysteretic energy input patterns resulted in other earthquakes, too.

In the study, the hysteretic energy input demand of SCWB and DRFT frames was smaller than that of SD frames. The hysteretic energy input demand did not vary under the mass irregularity effect. However, we have to note that hysteretic energy input demand can increase without much variation of total hysteretic energy input demand at the certain floor where the vertical mass irregularity is created. Until now the vertical mass irregularity effect has been studied with parameters such as drifts, plastic rotations, and input energies. The stress response at the beam-column connection was included in this essay to explain the stress demand using finite element analysis. To examine the stress demand for Case 1, DRFT frame, the same condition of load and vertical mass irregularity were used to simulate the mass irregularity effects. The maximum stress near the connection area was about 92 kgf/cm with EQ 3, 0.6g. The stress demand showed that the maximum stress occurred in the top flange of the beam and propagated into the panel zone. In that case the stress demand at the lower flange of the beam and panel zone was minor.

The simulated stress results showed that the damage mainly occurred at the upper beam flange and upper panel zone. Then, the energy demand propagated to the lower flange of the beam column connection areas.

Finally an empirical curve of the hysteretic energy input demand is presented in Figure 2. This curve is well accorded in the results of former researcher (Choi et al., 2001). In Figure 2, the hysteretic energy input was illuminated by the variation of natural period by adding current results to the ones of Choi et al.. The empirical equation can be drawn using interpolation from the results:

$$E_h/m = -2092 \cdot \ln(T) + 3332, \qquad 0.5 \le T < 5.0 \text{ and } PGA \le 0.3g$$

$$E_h/m = -8334 \cdot \ln(T) + 15865, \quad 0.5 \le T < 5.0 \text{ and } 0.3g < PGA \le 0.6g.$$

Here E_h/m is the normalized hysteretic energy input demand and T is the target period of structures. The results have two important implications. First, the hysteretic energy of systems decreases with increasing period. In the same fashion, the hysteretic energy of structures increases with increasing base shear coefficient (V/W). Secondly, the mean hysteretic energy input of MDOF systems can be approximated.

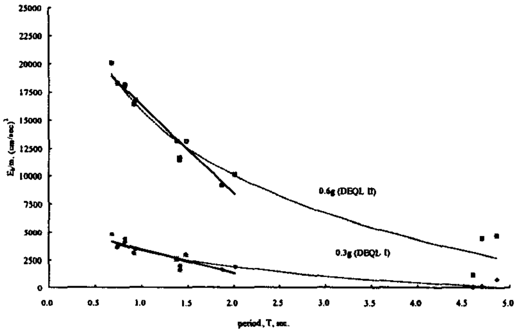

Figure 2. Empirical hysteretic energy for steel moment resisting frames

The presented curve represented that hysteretic energy input demand gradually decreased with the increase of the natural period of vibration. The empirical equation was valid only in limited regions. The hysteretic energy input demand can be estimated with a known T. Therefore, the empirical curve of the energy input demand is valuable as a design tool that uses an energy approach for steel moment resisting frames.

6. Conclusions

Mass irregularity is one of the important factors affecting structural responses under seismic loadings. This paper presented the seismic responses of structures with the vertical mass irregularities using high-rise steel moment-resisting frames. The drift ratio, plastic rotation, energy distribution, and stress in element level were investigated. Based on the research, the following conclusions can be drawn.

The more a structure is strengthened and stiffened, the less the drift ratio will occur. As far as structures are designed by keeping one of the regulations such as strong column-weak beam and drift limitation in the high-rise steel moment-resisting frames, the plastic hinge and drift ratios are of small values in seismic intensity up to 0.3g in PGA.

The results showed the most severe cause of vertical mass irregularity was to change the mass at the upper floors as in Case 3. Then, the next severe case was to change mass at the lower stories as in Case 1. The drift increase ratio on average was 28% and 199% at 0.3g and 0.6g, respectively in Case 3

The hysteretic energy input demands were increased at a higher rate than the one of the drift ratios. For instance, the hysteretic energy of 80% was increased by the vertical mass irregularity of the first floor, Case 1. As far as the structure is designed in satisfaction of the strong column-weak beam condition, larger hysteretic energy demand occurred in the beams than the columns, except with the first floors. This proposed curve was acquired empirically by the compiling of various multi-degrees of freedom systems. Thus, an empirical curve of the hysteretic energy input demands could be used for the energy designs and applications.

Even though the hysteretic energy study has been carried, there still exists many unknowns. In the future, the vertical mass irregularity needs to be compared in various structural systems such as braced frames and shear wall frames. Future studies may include other structural systems and more seismic records to provide more appropriate information about the hysteretic energy input of the regular and irregular structures.

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