ULTIMATE ENERGY DISSIPATION CAPACITY AND COLLAPSE BEHAVIOR OF MULTI-STORY STEEL FRAME WITH SHS COLUMN UNDER BIAXIAL EXCITATION

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Abstract

In seismic design, Moment Resisting Frame (MRF) is generally designed to form the overall sway mechanism. However, because of the strain hardening of beams and panel zones and decreasing of the strength of columns caused by bi-directional horizontal external forces, it is possible to form the weak column mechanism. Once weak column mechanism is formed, frames tends to collapse because of deterioration of restoring force caused by local buckling in column and P-Δ effect. In this study, bi-directional response analysis of weak column type steel MRFs using realistic hysteresis model of columns considering local-buckling are conducted. From analytical results, it is clarified that, once columns start to deteriorate, deformation of the story progressed in one direction. Historic dissipation energy until collapse was not much larger than that of monotonic loading due to damage caused by orthogonal excitation.

Keywords: Energy Dissipation Capacity, Moment Resisting Frame, Square Hollow Section Column, Local Buckling, Bi-Axial Ground Motion, Collapse
1 INTRODUCTION

In seismic design, Moment Resisting Frame (MRF) is generally designed to form the overall sway mechanism under severe earthquake. However, it is possible to form the weak column mechanism. That is because strength of beams and panel zones rises due to strain hardening. Also, strength of columns decreases due to the bi-directional horizontal external forces. These effects are considered in the current seismic design method, however due to the uncertainty of the earthquake ground motion etc., the formation of the weak story mechanism cannot be certainly prevented. In the full-scale shaking table test of 4 story steel moment frame conducted at E-defense in 2007 [1,2], specimen building made sway mechanism under design level earthquake. However, under extremely strong ground motion, mechanism changed to weak story type and specimen building was completely collapsed.

The causes to collapse the weak column type frame are strong bi-axial seismic force, P-Δ effect and deterioration of restoring force caused by local buckling in column. Many studies focused on the collapse behavior of multi-story frames under severe earthquake have been conducted. In the studies focused on the influence of P - Δ effect, generally ideal historical behavior was considered to clarify its influence. Analysis taking into consideration the deterioration behavior of members has also been carried out [3]. These studies have taken into consideration the influence of the deterioration behavior of the members in addition to the P - Δ effect, however they are limited to the in-plane behavior considering single horizontal ground motion. These studies have taken into consideration the influence of the deterioration behavior of the members in addition to the P - Δ effect, however they are limited to the in-plane behavior considering single horizontal ground motion. It is because the current hysteresis models of steel members considering the deteriorating behavior [4, 5] are limited to the in-plane behavior.

In this study, at first, by comparing with experimental results it is verified that bi-directional behaviors of Square Hollow Section (SHS) columns including deteriorating range subjected to horizontal bi-directional external force can be reproduced by applying the in-plane hysteresis model of SHS columns to Multiple Shear Springs (MSS). Then, multi-story weak column type steel MRF with SHS columns is modified to the multi-story lumped mass shear model and conducted a series of response analyses considering bi-axial horizontal ground motion. From analytical results, collapse behavior and ultimate energy dissipation capacity of weak column type steel MRFs with SHS columns under bi-axial excitation is clarified.

2 ANALYTICAL MODEL

Lumped mass model with Multiple Shear Spring (MSS) [6] shown in Figure.1, is used to analyze the responses of steel MRF subjected to bi-directional ground motion. MSS consists of the equal shear springs which placed at an equal angle express the behaviors of each stories. The strength $q_s$ and the stiffness $K_s$ of the springs constituting the MSS are given by the equations (1) and (2) from the shear strength $Q_s$ and stiffness $K_s$ of the story.

$$q_s = \sum_{i=1}^{N_s} Q_s |\cos \theta_i|$$

(1)
Where, $N_s$ is the number of the springs in MSS, $\theta_i$ is the direction of each spring. Considering accuracy of calculation, number of shear springs in a story is set 16.

The analytical model assumes a weak column type moment resisting frame consist with cold-formed SHS column and H-shaped beam. Since it is a weak column type MRF, its ultimate behavior is dominated by the ultimate behavior of the column. The SHS column has small directionality of the structural performance, it is suitable for applying MSS.

For the shear strength of the first story, it is set as 0.25 times of the total weight of MRF. It corresponds with strength of columns of the 1st story. Furthermore, to form weak 1st story mechanism that is most severe case in earthquake damage, other stories are kept elastic. In addition, P-$\Delta$ effect is considered in the analysis.

![Figure 1 Lumped Mass Model Connected by MSS](image)

### 3 PARAMETERS OF RESPONSE ANALYSIS

Parameters of the analytical model are number of the story $N$ (=4, 8, 12), width-to-thickness ratio of RHS column $D/t$ (=20, 29). The number of the story was set to examine the influence of the difference of fundamental natural period. Regarding the width-to-thickness ratio, the model with $D/t=20$ represents a building with moderate ductility, and the model with $D/t=29$ represents the building without enough ductility. As for the hysteresis model, polyliner hysteresis model of cold-formed SHS column considering deteriorating behavior governed by local buckling [5] is adopted for columns.

In all models, weight of each story $W_i$ is 1,000(kN), height of each story is 3.5(m). In order to make weak 1st story mechanism, all stories except 1st story are kept in elastic range. Fundamental natural period $T_1$, yield shear strength of the first story $Q_{y1}$, and the stiffness distribution $\{K_i\}$ of the analytical models are shown in Table 1.
As input waves, NS and EW components of El-Centro record (1940 Imperial Valley Earthquake), Taft record (1952 Kern County Earthquake), Hachinohe record (1968 Tokachi-oki Earthquake), JMA-Kobe record (1995 Kobe earthquake) and JMA-Sendai record (2011 Tohoku earthquake) were used. In the analysis, amplification factor is multiplied to the acceleration data to change intensity of excitation up to collapse.

Table 1 Characteristics of analysis models

<table>
<thead>
<tr>
<th>Model</th>
<th>$T_1$ (sec)</th>
<th>$W_i$ (Const) (kN)</th>
<th>$h_i$ (Const) (m)</th>
<th>$Q_{y1}$ (kN)</th>
<th>${ K_i } \times 10^3$ kN/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Stories</td>
<td>0.775</td>
<td>1,000</td>
<td>3.5</td>
<td>1,200</td>
<td>68.6, 57.6, 47.4, 31.3</td>
</tr>
<tr>
<td>8 Stories</td>
<td>1.046</td>
<td>1,000</td>
<td>3.5</td>
<td>2,400</td>
<td>137.1, 130.0, 115.2, 104.9, 94.7, 80.3, 62.7, 42.0</td>
</tr>
<tr>
<td>12 Stories</td>
<td>1.262</td>
<td>1,000</td>
<td>3.5</td>
<td>3,600</td>
<td>205.7, 202.2, 187.1, 172.8, 162.0, 152.7, 142.1, 128.4, 112.0, 94.0, 74.5, 48.4</td>
</tr>
</tbody>
</table>

4 COLLAPSE BEHAVIOR OF WEAK STORY TYPE MULTI STORY FRAMES UNDER BI-AXIAL GROUND MOTION

Orbit of the 1st story and hysteresis of the collapsed and its orthogonal directions are shown in Figure 2 (a) – (d). Case A (12 stories, $D/t=20$, Hachinohe) and Case B (4 stories, $D/t=29$, Kobe) represent the cases which the dissipated energy in the collapsed direction, discussed in the next section, were relatively large. Case C (8 stories, $D/t=20$, Taft) and Case D (8 stories, $D/t=29$, Sendai) represent the cases which the dissipated energy in the collapsed direction were relatively small. In the figure, analytical results of collapse level and 75% of collapse level are shown. For the hysteresis, the analysis result of monotonic loading is indicated by a broken line.

Under the relatively low input level that model does not reach its maximum strength, such as 75% of collapsed level excitations of Cases C and D, deformation of the story did not progress in one direction. However, under the relatively high input level that stiffness of the story becomes negative according to the deterioration caused by local buckling, such as collapsed level excitations of all cases, displacement progresses to one direction after deterioration of the stiffness is observed.

Comparing the hysteresis of each cases in collapsed direction, in the cases of A and B, stable behavior is appeared until story reaches its maximum strength. On the other hand, in the cases of C and D, displacement progresses to one direction without obvious cyclic behavior under collapse level excitation.
(a) Case A Model; 12 stories, D/t=20 Input Wave; Hachinohe

(b) Case B Model; 4 stories, D/t=29 Input Wave; Kobe
Figure 2 Orbit of the 1st story and hysteresis of the 1st story in collapsed and its orthogonal directions

(c) Case C Model; 8Stories, D/t=20 Input Wave; Taft

(d) Case D Model; 8stories, D/t=29 Input Wave; Sendai

Figure 2 Orbit of the 1st story and hysteresis of the 1st story in collapsed and its orthogonal directions
5 DISSIPATED ENERGY BY WEAK STORY TYPE MULTI-STORY FRAMES UNTIL COLLAPSE UNDER BI-AXIAL GROUND MOTION

In this chapter, seismic performance of model is discussed with hysteretic dissipated energy $E_p^{\nu}$ calculated by equation (3). Here, $Q_i$ is restoring force of the story, $W_i$ is weight of the story, $h_i$ is the story height, $\Delta \theta_i$ is increment of story drift, $N$ is the total number of story and $t_0$ is the duration of input wave. In $E_p^{\nu}$, loss of the energy dissipation capacity due to P-δ effect is considered.

$$E_p = \int_0^{t_0} \sum_{i=1}^{N} \left[ \{Q_i - (\sum_{j=1}^{N} W_j)/h_i\} \cdot \Delta \theta_i \right] dt \quad (3)$$

Hysteretic dissipated energy in the collapse direction under collapsed level excitations $E_{pu}^{\nu}$ are divided by the dissipated energy under monotonic loading $E_{gm}$ and shown in Figure 3. In most of the cases, the ratio of $E_{pu}^{\nu}$ to $E_{gm}$ is around 1.0 to 1.5 regardless of the deformation capacity (width-to-thickness ratio $D/t$) of the column. In some cases, i.e. cases C and D etc., the ratio falls below 1.0. In those cases, the energy dissipation capacity was reduced due to the influence of damage caused by the response in the orthogonal direction.

![Figure 3 Hysteretic dissipated energy in the collapsed direction under collapsed level excitations](image)

6 CONCLUSIONS

A series of response analyses of weak column type multi-story steel frames under bi-axial ground motion are carried out. Hysteresis model used in analysis is based on the realistic behavior of column including the deterioration range governed by local buckling. From analytical results, following conclusions are obtained.

1. Focusing on the orbit of the 1st story, under the relatively low input level that model does not reach its maximum strength, deformation of the story did not progressed in one direction. However, under the relatively high input level that stiffness of the story becomes
negative according to the deterioration caused by local buckling, displacement progresses to one direction after deterioration is observed.

2. In many cases, hysteretic dissipated energy in the collapse direction under collapsed level excitation $E_{pc}$ became 1.0 to 1.5 times of the hysteretic dissipated energy under monotonic loading $E_{pm}$ regardless of the deformation capacity (width-to-thickness ratio $D/t$) of the column. However, in some cases, $E_{pc}$ became slightly lower than to $E_{pm}$ due to the influence of damage caused by response in the orthogonal direction.

REFERENCES


