Relationship between Seismic Index and Response of RC Structure Retrofitted by ACM Braces

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Abstract

In general, a seismic retrofitting countermeasure of RC building in Japan can be decided by a seismic index value of structure. In this paper, a seismic non-linear response analysis of 3-story RC building structure retrofitted by ACM braces using a strong earthquake motion measured in the 1995 Hyogo-ken Nambu Earthquake was carried out. The relationship between the seismic index value of structure and the seismic response of 3-story retrofitted RC building structure was numerically investigated from a viewpoint of the number of ACM brace.

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Keywords: Seismic retrofitting work, ACM braces, 3-d seismic non-linear response analysis, seismic performance index of structure, fiber element.

1. INTRODUCTION

It is well-known in Japan that a lot of RC story buildings built by some old earthquake resistant design codes before 1981 must be reinforced against a large earthquake as early as possible. In general, both steel brace and RC wall have been typically adapted for the seismic retrofitting countermeasure of RC building structure, and the seismic retrofitting countermeasure of RC building can be decided by a seismic index value of structure, \( I_s \), which is obtained from the floor plan and various investigations of RC building structure and does not require any seismic responses of RC building structure against a large earthquake. However, it is very important for a structural engineer to take account of a seismic response of RC building in the seismic retrofitting design process, because the relationship between the seismic index value, \( I_s \), of structure and the seismic response of RC building structure can play a key role to propose an effective countermeasure in the seismic retrofitting design process.

The author has already proposed a retrofitting work of RC story building using ACM bracing method (Takatani and Ono 2008a; 2008b), which is consist of a carbon fiber reinforced plastic material, steel
sleeves and anchors. The seismic response analysis of RC building structure retrofitted by ACM braces was conducted using 3-D non-linear beam elements (Takatani and Ohfuji 2010). In particular, the effect of ACM braces on the seismic response behavior of RC building structure was discussed. In this paper, the displacement, velocity and acceleration responses were numerically investigated by 3-D elasto-plastic seismic response analysis using fiber elements for RC columns in order to investigate the relationship between the seismic index value, $I_s$, of structure and the seismic response of a retrofitted RC building structure. In a fiber element, the cross section of RC column is divided into a lot of microscopic areas. An element stiffness of RC column can be evaluated using a uni-axial stress-strain relationship for each microscopic area. Therefore, the fiber element can accurately simulate the damage developing process of both reinforcing steel bar and concrete materials (Shirato et al. 2006).

2. SEISMIC RESPONSE ANALYSIS

2.1 3-story RC building structure

Figure 1 shows a floor plan of 3-story RC building structure. Elevation plan is indicated in Figure 2. As this RC building structure was built in 1972 based on an old earthquake resistant design code, there may exist a doubtful problem concerning on the seismic resistant performance against a strong earthquake. Table 1 illustrates the seismic index value, $I_s$, of this RC building structure, and this seismic index value, $I_s$, can be obtained by the criteria established by the Japan building disaster prevention association (2001). The seismic index value, $I_s$, must satisfy a given seismic judgment index value, $I_{so}$. In this case, the seismic judgment index value, $I_{so}$, is 0.7. The seismic index values of structure, $I_s$, of the first and second floors in X direction are smaller than the seismic judgment index value, $I_{so}$ = 0.7. Consequently, it is noted that RC walls of the first and second floors in X direction need some seismic retrofitting countermeasures.

![Figure 1: Floor plan of RC building structure (Second and Third floors).](image1)

![Figure 2: Elevation plan of RC building structure (NS direction, Unit: mm).](image2)
Table 1: Seismic index value $I_s$ of RC building structure ($I_{so}=0.7$)

| Floor | $I_s$ (X direction) | $I_s$ (Y direction) |
|-------|---------------------|---------------------|
| 1     | 0.52 NG             | 1.21 OK             |
| 2     | 0.60 NG             | 1.16 OK             |
| 3     | 0.94 OK             | 1.58 OK             |

2.2 Seismic retrofitting work by ACM braces

In Japan, the steel bracing method shown in Figure 3(a) has been used for the seismic retrofitting work of RC building structure. It is more desirable for a lot of RC building structure owners that a seismic retrofitting work for RC building structure can be conducted as quickly and economically as possible, and also can be done without residents' removal or temporary evacuation. The seismic retrofitting work conducted on the outside of RC building structure shown in Figure 3(b) may be more convenient for both the residents in RC buildings and their owners. A new seismic retrofitting work using ACM brace has been proposed by Takatani and Ono (2008a) in order to aim at both low cost and short construction period in comparison with the steel brace.

Table 2 shows the seismic index values of structure, $I_s$, of 3-story RC building structure after seismic retrofitting work by ACM braces. The seismic index values of structure, $I_s$, in both 2 and 4 sets of ACM brace cannot satisfy the seismic judgment index value, $I_{so}=0.7$. It can be noted from Table 2 that seismic retrofitting work by ACM braces for this RC building structure needs more than 6 sets of ACM brace to satisfy the seismic judgment index value, $I_{so}$.

![Figure 3: Sketch for seismic retrofitting works using steel and ACM bracing methods.](image)

Table 2: Seismic index value $I_s$ of RC building structure after seismic retrofitting work

| Set Number of ACM brace | Floor | $I_s$ (X direction) | $I_s$ (Y direction) |
|-------------------------|-------|---------------------|---------------------|
| 2                       | 1     | 0.64 NG             | 1.21 OK             |
|                         | 2     | 0.62 NG             | 1.16 OK             |
|                         | 3     | 1.00 OK             | 1.58 OK             |
| 4                       | 1     | 0.68 NG             | 1.21 OK             |
|                         | 2     | 0.67 NG             | 1.16 OK             |
|                         | 3     | 1.08 OK             | 1.58 OK             |
| 6                       | 1     | 0.73 OK             | 1.21 OK             |
|                         | 2     | 0.71 OK             | 1.16 OK             |
|                         | 3     | 1.13 OK             | 1.58 OK             |
| 8                       | 1     | 0.77 OK             | 1.21 OK             |
|                         | 2     | 0.76 OK             | 1.16 OK             |
|                         | 3     | 1.18 OK             | 1.58 OK             |
3. **SEISMIC RESPONSE**

Figure 4 illustrates 3-D frame models with ACM braces for 3-story RC building structure shown in Figures 1 and 2, and also the installation position of ACM braces are indicated in Figure 4. In this paper, the seismic responses at five nodal points shown in Figure 4 are numerically investigated by 3-D non-linear seismic response analysis using the 1995 Hyogo-ken Nambu Earthquake.

Table 3 shows the material properties for RC columns modeled by the fiber element used in this seismic response analysis. These parameters shown in Table 3 represent the stress-strain relationship for both cover concrete and core concrete materials shown in Figure 5. On the other hand, the stress-strain relationship of the reinforcing steel bar in RC column is assumed to be bi-linear.

![Figure 4: 3-D frame model of 3-story RC building structure retrofitted by ACM braces.](image)

**Table 3: Material properties for RC column**

| Cover concrete |  |
|----------------|----------------|
| $E_{C0}$ (N/mm²) | $\sigma_{CC}$ (N/mm²) | $\sigma_U$ | $\varepsilon_{CC}$ | $\varepsilon_U$ | $\varepsilon_L$ | $\sigma_f$ (N/mm²) |
| $2.94 \times 10^4$ | -28.6 | 0.8108 | -0.00200 | -0.00400 | -0.01110 | 2.28 |

| Core concrete |  |
|----------------|----------------|
| $E_{C0}$ (N/mm²) | $\sigma_{CC}$ (N/mm²) | $\sigma_U$ | $\varepsilon_{CC}$ | $\varepsilon_U$ | $\varepsilon_L$ | $\sigma_f$ (N/mm²) |
| $2.94 \times 10^4$ | -35.0 | 0.7127 | -0.00425 | -0.02126 | -0.11912 | 2.28 |

| Reinforcing steel bar (axial direction) |  |
|----------------|----------------|
| $E_{C0}$ (N/mm²) | $\sigma_f$ (N/mm²) |
| $1.85 \times 10^7$ | 351 |

| Hoop lateral tie |  |
|----------------|----------------|
| $E_{C0}$ (N/mm²) | $\sigma_f$ (N/mm²) |
| $2.25 \times 10^7$ | 396 |

Figure 6 shows mode shapes for natural frequencies for three models, “No ACM brace”, “4 sets of ACM brace” and “8 sets of ACM brace”. RC floor slab is assumed to be rigid or not rigid. The mode shape changes with the increase of ACM brace, and those in “8 sets of ACM brace” are different from those in “No ACM brace” and “4 sets of ACM brace”. Figure 7 illustrates seismic responses at the nodal point.
“D” shown in Figure 4. Both displacement and velocity responses decrease with the increase of ACM brace, while the acceleration response increases with ACM braces. Tables 4 and 5 indicate the maximum response values at five nodal points “A”, “B”, “C”, “D” and “E”. It should be noted from these tables that both displacement and velocity responses are more sensitive to the set number of ACM brace in comparison with the acceleration response.

Figure 5: Skeleton curves of concrete material (Shirato et al. 2006).

Figure 6: Mode shapes for natural frequencies.
Figure 7: Seismic response at nodal point “D” (X direction, “Rigid Floor Slab” assumption).

Table 4: Maximum value at three nodal points (X direction, “Rigid Floor Slab”)

| Set Number of ACM brace | Nodal Point A | Nodal Point B | Nodal Point C |
|-------------------------|---------------|---------------|---------------|
|                         | Disp. (cm)    | Vel. (kine)   | Acc. (Gal)    | Disp. (cm)    | Vel. (kine)   | Acc. (Gal)    |
| 0                       | 16.22         | 111.62        | 711.0         | 16.26         | 111.49        | 716.2         | 16.16         | 111.82        | 706.4         |
| 2                       | 18.93         | 104.65        | 926.1         | 19.04         | 105.14        | 940.4         | 18.77         | 103.95        | 905.4         |
| 4                       | 12.28         | 91.69         | 920.6         | 12.31         | 91.65         | 916.5         | 12.24         | 91.75         | 926.5         |
| 6                       | 6.15          | 81.60         | 1,042.2       | 6.18          | 81.69         | 1,047.9       | 6.11          | 81.47         | 1,033.9       |
| 8                       | 4.84          | 60.81         | 1,047.4       | 4.76          | 60.39         | 1,038.1       | 4.96          | 61.43         | 1,060.8       |

Table 5: Maximum value at two nodal points (X direction, “Rigid Floor Slab”)

| Set Number of ACM brace | Nodal Point D | Nodal Point E |
|-------------------------|---------------|---------------|
|                         | Disp. (cm)    | Vel. (kine)   | Acc. (Gal)    | Disp. (cm)    | Vel. (kine)   | Acc. (Gal)    |
| 0                       | 10.66         | 76.31         | 471.0         | 4.23          | 31.50         | 571.2         |
| 2                       | 8.37          | 50.14         | 673.5         | 0.68          | 8.16          | 815.2         |
| 4                       | 5.56          | 39.46         | 696.5         | 0.19          | 4.08          | 850.6         |
| 6                       | 1.88          | 28.65         | 985.5         | 0.33          | 5.69          | 837.3         |
| 8                       | 1.21          | 15.85         | 764.4         | 0.38          | 5.26          | 822.1         |
Figure 8: Relationship between $I_s$ value and maximum response at nodal point “A”.

Figure 8 shows the relationship between the seismic index of structure, $I_s$, and the maximum response value at the nodal point “A” in both “No Rigid Floor Slab” and “Rigid Floor Slab” assumptions. Both displacement and velocity responses in “Rigid Floor Slab” assumption have a tendency to linearly decrease with the increase of ACM brace in comparison with “No Rigid Floor Slab” assumption. The interrelation between seismic index value, $I_s$, and seismic response for “Rigid Floor Slab” assumption is more remarkable than that for “No Rigid Floor Slab” assumption.

The relationship between the seismic index of structure, $I_s$, and the maximum response value at three nodal points “B”, “D” and “E” is indicated in Figure 9. It can be observed from Figure 9 that both displacement and velocity responses more greatly decrease when the position of nodal point moves from higher floor to lower one. This implies that seismic index value, $I_s$, and both displacement and velocity responses are mutually related.
4. CONCLUSIONS

The seismic non-linear response analysis of 3-story RC building structure retrofitted by ACM braces using fiber elements for RC column was carried out in this paper. The acceleration wave records measured in the 1995 Hyogo-ken Nambu Earthquake were used as an input strong earthquake ground motion. The effect of seismic retrofitting countermeasure using ACM brace on the seismic response of 3-story RC building structure was investigated from a viewpoint of the number of ACM brace. The displacement, velocity and acceleration responses were numerically obtained by 3-D elasto-plastic seismic response analysis in order to investigate the relationship between the seismic index value, $I_s$, of structure and seismic response of 3-story retrofitted RC building structure.

The summary obtained in this paper is as follows.

1. Mode shapes for natural frequencies of 3-story RC building structure retrofitted by ACM braces...
changes with the increase of ACM brace.

(2) Displacement and velocity responses of the retrofitted RC building structure may be more sensitive to the seismic retrofitting work in comparison with the acceleration response.

(3) The seismic index value, $I_s$, of structure and seismic response of 3-story retrofitted RC building structure are mutually related in both displacement and velocity responses.

(4) The interrelation between seismic index value, $I_s$, and seismic response of 3-story retrofitted RC building structure for “Rigid Floor Slab” assumption are more remarkable than that for “No Rigid Floor Slab” assumption.

Although the bending moment-curvature response of RC column was not illustrated due to the limited space, it is necessary for an intensive study on the effect of ACM brace on the bending moment-curvature response of RC column.

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