

## **DESIGN PRACTICE OF FRAMED BUILDING STRUCTURES BASED ON AIJ DESIGN GUIDELINE 2002**

K. KOBAYASHI

*Department of Architecture and Civil Engineering, Fukui University  
3-9-1 Bunkyo, Fukui-city, Fukui 910-8507, Japan*

H. FUKUYAMA

*Department of Structural Engineering, Building Research Institute  
1 Tatehara, Tsukuba-city, Ibaraki 305-0802, Japan*

T. FUJISAKI

*Institute of Technology, Shimizu Corporation  
3-4-17 Etchujima, Koto-ku, Tokyo 135-8530, Japan*

S. FUKAI

*Structural Engineering Department, Nikken Sekkei Ltd  
2-1-3 Koraku, Bunkyo-ku, Tokyo 112-8565, Japan*

T. KANAKUBO

*Institute of Engineering Mechanics and Systems, University of Tsukuba  
1-1-1 Tennohdai, Tsukuba-city, Ibaraki 305-8573, Japan*

Seismic design practices were done using a same design procedure as steel-RC. The response was evaluated using capacity spectrum method that has been added to the Japanese Building Standard Law revised in 2000. The structural detail of member was verified using AIJ guideline in 2002. A possibility of the construction of FRP-RC building in seismic zone was recognized, but at the same time it was proven that the response strongly depends on the expected damping factor. If the seismic response can be reduced, FRP-RC buildings will perform well and have less residual deformation because of the completely elastic behavior of continuous fiber bars. It will realize a reinforced concrete building with high repairable performance after receiving a strong motion.

### **INTRODUCTION**

An Architectural Institute of Japan (AIJ) research committee was organized in the initial stage of FRP-research in 1988-1991. It reviewed the past

research results and studied the evaluation criteria and the evaluation methods of FRP-RC. At the same time the usefulness of FRP was recognized and a Building Research Institute (BRI) project (1988-1993) was organized. The AIJ Committee members fully cooperated with BRI project that compiled the "Design Guidelines of FRP Reinforced Concrete Building Structures" in 1993 and contributed it to the Journal of Composites for Construction, ASCE in 1997<sup>1</sup>.

The research of FRP has shifted to the seismic retrofit using fiber sheet since the Kobe Earthquake in 1995, and a lot of data was accumulated in this field. Then AIJ organized a research committee for FRP again in 1996, and they worked to compile a design and construction guideline. A part of the committee work about fiber sheet wrapping technology was presented at FRPRCS-4.

The structural design of the building is currently shifting to the performance-based design. It is expected that not only fiber sheet but also any fiber material turn into a useful structural material in the future are to meet the required performance. AIJ Committee took this opportunity to compile a design and construction guideline including the evaluation method of material characteristics, fire resistance, durability and FRP-RC using FRP-bars as well as the seismic retrofitting method using fiber sheet, and published it in 2002<sup>2</sup>. The guidelines for FRP-RC using FRP-bars, overlaps vastly with the already published one<sup>1</sup>. However, it has been reconstructed from a viewpoint of the performance-based design to satisfy various demands, both structural and non-structural.

The seismic design concept entails the ensuring of seismic performance by overcoming the ductility deficiency of the continuous fiber material, which shows elastic behaviour up to fracture. The seismic design of building using FRP-bars has therefore been regarded as questionable. However, the elastic behavior of FRP-RC is an advantage to reduce the residual deformation and achieve a repairable structure after a strong earthquake. AIJ guideline<sup>2</sup> includes an example of seismic design of framed building using FRP-bars. It shows that the response of FRP-RC frame can be predicted in a same way as of steel-RC, and FRP-RC building may be constructed in seismic region. This paper introduces this part of the AIJ guideline<sup>2</sup>.

## **STRUCTURAL DESIGN METHOD**

A new option of structural design method was added to the Japanese Building Standard Law in 2000. This is based on the equivalent linearization

method and a way to predict the response to the demand seismic action that is given as a response acceleration spectrum. The response is figured out from the demand and the capacity spectrum characterized by the period corresponding to the equivalent stiffness and the equivalent damping. This method has an advantage that it is applicable to any structural type of building if the load-displacement relation and the equivalent damping are given.

The design procedure is shown in Fig.1. The specific issues for FRP-RC in the capacity spectrum method are mainly: (1) formulation of load-displacement skeleton curve of members; (2) evaluation of equivalent damping; (3) characterized values of sections. These are described in the next section.

Regarding a capacity spectrum, the acceleration at the reference point is obtained by dividing the base shear by the effective mass for the first mode. The effective mass for the first mode,  $M_{e1}$ , is calculated as follow,

$$M_{e1} = (\sum m_i \cdot \delta_{si}^2) / (\sum m_i \cdot \delta_{si}^2) \tag{1}$$

in which  $\delta_{si}$ =displacement of i-th story, and  $m_i$ =weight of i-th story. The displacement is calculated as follows:

$$\Delta s = (\sum m_i \cdot \delta_{si}^2) / (\sum m_i \cdot \delta_{si}) \tag{2}$$

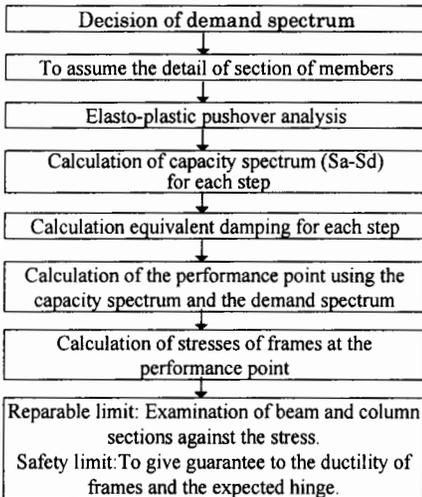


Fig.1. Procedure of seismic design

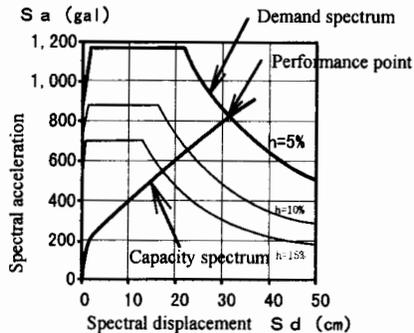


Fig.2. Capacity spectrum and demand spectrum

The demand spectrum ( $S_a-S_d$ ) is made by superimposing  $T-S_a$  relation and the relation of  $S_a=\omega^2 \cdot S_d$ . Here,  $T$  is the period,  $S_a$  is the demand acceleration.  $S_d$  is the demand displacement. The demand acceleration is calculated by multiplying the site amplification factor to the demand acceleration, and on the engineering bedrock. In the Japanese Building Standard Law, the standard value of the demand acceleration spectrum on engineering bedrock to the safety limit state is  $5.12/T$  m/sec<sup>2</sup> on the long-period side with a constant velocity amplitude of 81.5 cm/sec.

The performance point is figured out from the intersection of the capacity spectrum and the demand spectrum, shown in Fig. 2.

### RESTORING FORCE CHARACTERISTICS

#### Hysteretic Loop

Experimental results of beam specimens loaded cyclically are explained in this section. The specimens No.3-8 were tested in Reference 3. CFRP reinforcements (spirally fiber wound type) and AFRP reinforcements (braided type) are utilized as longitudinal bars of specimens No.3-5 and No.6-8, respectively. Shear force versus drift angle curves until 1/33 radian are shown in Fig. 3.

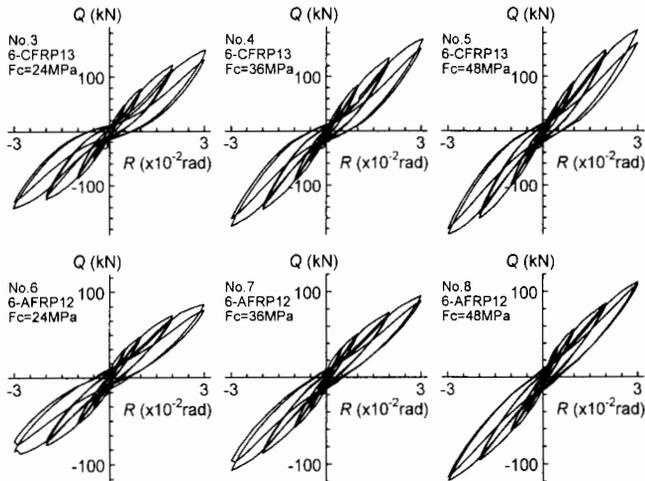


Fig. 3. Shear force versus drift angle curves of beams with FRP main bar

**Skeleton Curve**

Skeleton curves of members with longitudinal FRP-bars are possibly represented by bilinear shape, because FRP bars have no yield phenomenon. The characteristic points, of bilinear shape correspond to elastic part, post-cracking part and ultimate point, as shown in Fig. 4. The elastic stiffness,  $k_e$ , and cracking load,  $Q_{bc}$ , can be estimated similarly with ordinary steel-RC members. In order to predict stiffness after cracking,  $k_2$ , a stiffness reduction coefficient at  $R=1/150$  radian,  $\alpha_{1/150}$ , is newly defined as that corresponding to the yield deformation of ordinary steel-RC members.

$$\alpha_{1/150} = \left\{ 0.043 + 1.64n \cdot p_t + 0.043 \frac{a}{D} + 0.33\eta_0 \right\} \cdot \left\{ \frac{d}{D} \right\}^2 \quad (3)$$

where  $n$  = elastic modulus of FRP / elastic modulus of concrete,  $p_t$  = main bar ratio,  $a$  = shear span length,  $D$  = depth of member,  $\eta_0$  = axial stress / concrete strength, and  $d$  = effective depth of member.

The stiffness reduction coefficient can be calculated by Eq. (3), which has been originally proposed to identify the yielding point of steel-RC members. Fig. 5 shows the correlation between observed stiffness after cracking in experiments and calculated ones. Both values correspond well to each other.

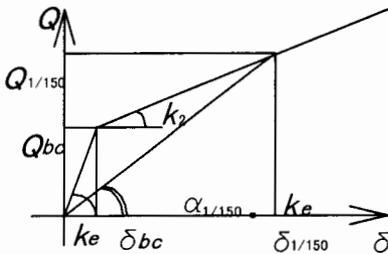


Fig. 4. Bilinear model

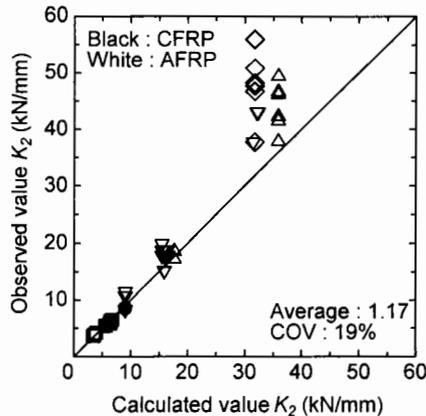


Fig. 5. Comparison of stiffness  $K_2$

### Hysteretic Energy Absorption

The hysteretic energy absorption could be expected even though FRP-bars have no yield phenomenon. Table 1 indicates values of equivalent damping factor,  $h_{eq}$ , obtained for the specimens shown in Fig. 3. The values of  $h_{eq}$  ranged from 3 to 4% in the 2<sup>nd</sup> cycle at the drift angle of 1/200-1/100 radian, and 4 to 6% for 1/50-1/33 radian. There is a room of argument whether this could be accepted in a seismic design. It is a safer consideration to deduce that there is no hysteretic energy absorption.

Table 1. Values of  $h_{eq}$ 

ID	Loading cycle								
	1/200rad.		1/100rad.		1/50rad.		1/33rad.		1/20rad.
	1 <sup>st</sup>	2 <sup>nd</sup>	1 <sup>st</sup>						
No.3	0.079	0.044	0.070	0.044	0.082	0.053	0.081	0.060	0.126
No.4	0.078	0.038	0.067	0.041	0.074	0.047	0.074	0.057	0.110
No.5	0.076	0.038	0.060	0.038	0.070	0.047	0.072	0.058	0.102
No.6	0.093	0.041	0.070	0.043	0.079	0.053	0.092	0.074	0.184
No.7	0.094	0.038	0.065	0.038	0.072	0.045	0.070	0.059	0.199
No.8	0.091	0.041	0.068	0.039	0.068	0.044	0.065	0.049	0.145

### DESIGN PRACTICE-1

The response of a frame structure was figured out, using the horizontal loading test result of a 2.5-story, 2-bay frame<sup>4</sup>. This experiment differs from actual building conditions such as horizontal load distribution. The capacity spectrum was made under the following assumptions.

- (1) The acceleration at the reference point was calculated assuming the effective mass for the first mode is 90% of the total building weight.
- (2) The displacement of the reference point was calculated by multiplying the 2-story height to the measured drift angle at 3<sup>rd</sup> floor level.

Demand spectrum for safety limit had a velocity of 165 cm/sec on the long-period side assuming the normal ground (type II: site amplification factor is 2.025.) and 5% of damping. Demand spectrum for reparable limit was assumed 20% of that for safety limit demand. The relation between the acceleration and displacement at reference point and the demand spectrum are shown in Fig. 6. The response to the demand for reparable limit is about 1/500 in drift angle, and it is less than 1/200 that is generally accepted in the design of Steel-RC frame. The response to the demand for safety limit is

about 32cm (more than 1/25 in drift angle). This performance point is close to the point where the bottom bars of beam ruptured in tension. The displacement response to the safety limit demand will be considered too large to be accepted. Such a large response may be caused due to the assumptions of large seismic design load and only 5% of damping factor.

When damping is 5%, the displacement response becomes large. Then it may be possible to control the response by introducing some damping mechanisms. The response is shown in Fig. 7 when the damping factor increases up to 10%. The response is successfully reduced to 21cm by adding more 5% of damping and that is 2/3 of the response when the damping is 5%. This suggests the effectiveness of addition of some damping mechanisms.

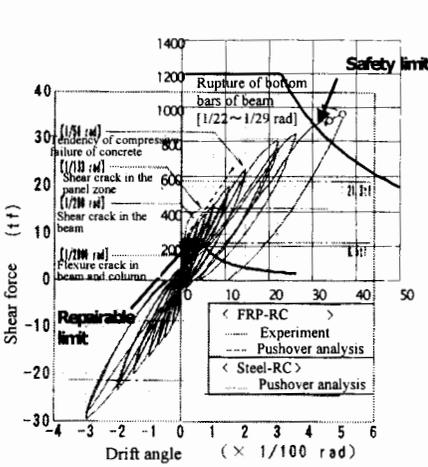


Fig. 6. Response (Normal ground, 5% damping)

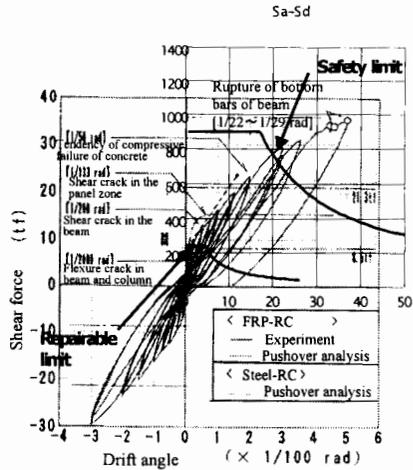


Fig. 7. Response (Normal ground, 10% damping)

## DESIGN PRACTICE-2

Capacity spectrum is made from the result of pushover analysis, and the response of the building is predicted by the capacity spectrum method. The design aims that FRP-bars should rupture neither in tension nor in compression before reaching the performance point.

The analyzed building on hard soil ground (type I) is shown in Fig.8. It is a unit frame building that was taken out of a nine-story building. The specified concrete strength is 30MPa. The longitudinal FRP-bars are

aramid braided bars of which the nominal diameter is 15mm. The sectional area, elastic modulus and design tensile strength are  $180\text{mm}^2$ ,  $68,650\text{ N/mm}^2$  and  $931.6\text{ N/mm}^2$ , respectively. The detail of typical column and beam sections is shown in Fig. 9.

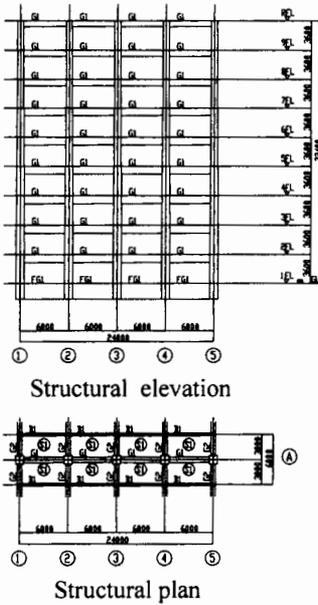


Fig. 8. Analyzed building

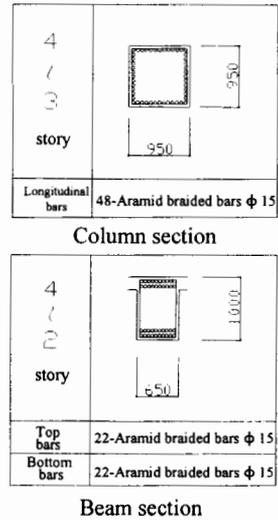


Fig. 9. Typical detail of sections

The response to the safety limit demand is discussed. The demand spectrum was set up to have a velocity of  $110\text{cm/sec}$  (site amplification factor is 1.5 for type I ground) on the long period side and 5% of damping. In the pushover analysis, the horizontal load distribution was decided on the basis of the description in the Japanese Building Standard Law. The horizontal load distribution at  $C_B=0.2$  is shown in Table 2. Pushover analysis was stopped when the first member reached the flexural capacity. The relation between story-shear force and story-drift is shown in Fig. 10. The demand spectrum and the capacity spectrum are shown in Fig. 11, which was calculated on the basis of the analytical result shown in Fig. 10.

The response to the safety limit demand is obtained as a point where the capacity spectrum meets the demand spectrum. The response acceleration of reference point is figured out as  $465\text{gal}$ , and  $26.2\text{cm}$  for the response displacement. At this time, the equivalent period is 1.49 second. The ratio

of the effective mass for the first mode to the total building weight is 0.752. The base shear coefficient is 0.375. The maximum story drift is 51mm (drift angle: 1/71).

The end of curves in Fig. 10 is the end of pushover analysis where the beam-ends in 2<sup>nd</sup> and 3<sup>rd</sup> story reached the flexural capacity. The response remains before reaching these points, so FRP-bars do not rupture in tension. The strain at compressive fiber is 0.138% at maximum and the neutral axis ratio is 0.185, so the strain of FRP-bars in compression side is less than 0.1% and it is proven that they do not rupture in compression.

Table 2. Static horizontal load distribution at  $C_B=0.2$

Story	Weight (kN)	$\Sigma W$ (kN)	$\alpha_i$	$A_i$	$C_i$	Story Shear (kN)
9F	1648	1648	0.103	2.325	0.464	765
8F	1630	3277	0.205	1.881	0.376	1232
7F	1657	4935	0.309	1.656	0.331	1632
6F	1723	6658	0.417	1.498	0.299	1992
5F	1788	8445	0.529	1.372	0.274	2314
4F	1813	10259	0.643	1.266	0.253	2595
3F	1885	12144	0.761	1.170	0.234	2837
2F	1899	14042	0.880	1.082	0.216	3035
1F	1918	15960	1.000	1.000	0.200	3188

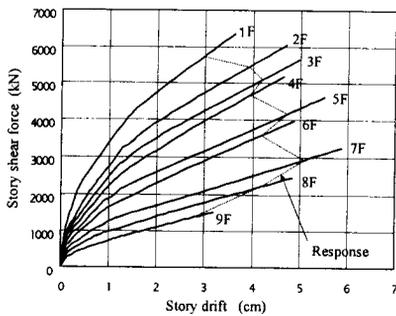


Fig. 10. Story-shear force and story-drift relation

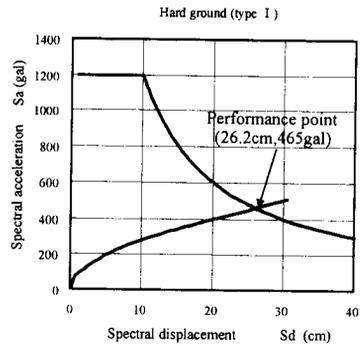


Fig. 11. Capacity spectrum and demand spectrum

## CONCLUSIONS

- (a) In the design practices, the responses remained within the safety limit demand before the tensile or compressive fracture of FRP-bar. It was shown that FRP-RC framed structure may possibly be designed in high seismic region and the seismic design procedure for steel-RC is applicable to FRP-RC.
- (b) It is critical how much damping factor is expected. There is about 4-5% of the hysteretic damping after the occurrence of flexural crack. However, it is not acceptable to take into account this damping effect in seismic design. The combination with some vibration control device/material may be one solution to realize FRP-RC buildings in the high seismic region.
- (c) The almost elastic behavior of FRP-RC is an advantage to realize a structure that has less residual deformation after strong earthquake and has high repairable performance.

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## REFERENCES

1. Sonobe, Y., Fukuyama, H., et al., "Design Guidelines of FRP Reinforced Concrete Building Structures", *ASCE Journal of Composites for Construction*, Vol.1, No.3, 1997, pp.90-115.
2. "Design and Construction Guideline of Continuous Fiber Reinforced Concrete", AIJ, March 2002 (in Japanese).
3. Sonobe, Y., Fujisawa, M., et al., "Flexural Performance of Concrete Beams Reinforced with FRP Bars under Anti-symmetric Cyclic Loading", *Summaries of Technical Papers of AIJ Annual Meeting, Structures-II*, August 1992, pp. 141-144 (in Japanese).
4. Fukuyama, H., Masuda, Y., Sonobe, Y. and Tanigaki, M., "Structural Performances of Concrete Frame Reinforced with FRP Reinforcement, 2<sup>nd</sup> International Symposium on Non-metallic (FRP) Reinforcement for Concrete Structures (FRPRCS-2), Belgium, August 1995, pp.275-286.