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# Dynamic collapse test on eccentric reinforced concrete structures with and without seismic retrofit

Yousok Kim [a,*], Toshimi Kabeyasawa [a], Shunichi Igarashi [b]

[a] Earthquake Research Institute, University of Tokyo, 1-1-1 Yayoi Bunkyo-Ku, Tokyo 113-0032, Japan
[b] Structural Quality Assurance Inc., 2-7-10 Samikicho Chioda-Ku, Tokyo 101-0061, Japan

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ABSTRACT

Reconnaissance reports on structures damaged or collapsed by severe earthquakes have revealed several common characteristics in their structural members and systems, such as insufficient reinforcement details in beam-column joints and transverse confinements, low aspect ratios, soft and or weak stories, and eccentric plans. Dynamic tests were carried out to investigate the collapse process of reinforced concrete structures that had seismically deficient reinforcement details (light transverse reinforcement) and seismic systems (soft/weak stories and eccentric plans). A comparison of collapse behaviors with and without seismic retrofits also verified the effectiveness of the SRF (super reinforced with flexibility) strengthening method, which was developed to prevent the loss of axial load carrying capacity even at excessive lateral deformation. The columns of one specimen were strengthened with polyester fiber belts and its shear walls with polyester fiber sheets, while the members of the other were not. Each specimen was designed following old (1970s) reinforcement detail practice in Japan, and is a one-third-scale reinforced concrete structure with considerable stiffness and strength eccentricity in the first story. The specimens were composed of independent column frame and shear wall frame. Torsional response resulting from the eccentricity in the 1st story induced a displacement concentration on the weak frame, and eventually the independent columns of the RC specimen failed in shear and lost their axial load carrying capacity. On the other hand, the SRF specimen survived not only an identical earthquake load to the one that caused the RC specimen to fail, but also three additional earthquake loads, although significant strength deterioration and considerable lateral and vertical deformation were generated at the end of the test. The following conclusions were drawn from the comparison of the two specimens' responses: axial column collapse cannot be predicted from vertical responses since the vertical behavior of bare RC columns was not discernibly different from that of SRF columns until axial collapse was initiated, and the SRF strengthening method is effective in confining the column and preventing the cracking progress, thus modifying the failure mode of the RC columns from brittle shear failure after flexural yield to flexural dominant behavior.



## 1. Introduction

Collapsing buildings have caused numerous casualties during recent major earthquakes, even in countries with advanced earthquake engineering technologies. Understanding the collapse mechanisms of reinforced concrete (RC) structures subjected to earthquake attack is a crucial aspect of one of the goals of earthquake engineering, which is to protect people's lives and safety, and has been a challenging task in many researches [1–3]. Many RC structures have suffered severe damage in devastating earthquakes in the past, leading to unrecoverable damages and the collapse of structures. Reconnaissance reports describing these damaged or collapsed structures have revealed several common characteristics in their structural members such as insufficient reinforcement details in beam-column joints, transverse confinement designed following old seismic codes, and low aspect ratio (shear span to depth ratio) members that are susceptible to shear failure [4–7]. In addition to these seismic element deficiencies, the unbalanced layout of structural members in elevation or plan (i.e. buildings with soft/weak stories or eccentric plans) caused poor seismic performance leading buildings to collapse.

Although research themes in earthquake engineering are turning to innovative technologies for new structures, it is still important to continue developing economical retrofitting methods for existing buildings that have seismically deficient members and systems in order to reduce injuries and loss of life and property. To perform safely in an earthquake, vertical members (columns and walls) must maintain their gravity load carrying capacity even

* Corresponding author. Tel.: +81 3 5841 5783; fax: +81 3 5841 1765.
*E-mail address:* yskim@eri.u-tokyo.ac.jp (Y. Kim).

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when earthquake intensity exceeds the members' design limits. In some old reinforced concrete buildings, the columns can lose their axial load carrying capacity due to inadequate transverse reinforcement, then the buildings collapse at the weakest story or completely pancake. The development of a simple and economical strengthening method to prevent these brittle columns from gravity load collapse during strong earthquakes would be very beneficial.

A new strengthening method for RC columns called the super reinforced with flexibility method (SRF) focuses particularly on maintaining the columns' axial load carrying capacity even under excessive lateral deformation. It was developed and has been demonstrated using static tests on columns with a variety of cross-sections under different loading patterns [8–11]. In the first phase of this testing, eight specimens were tested, with 14 in a second phase. The specimens were constructed to simulate reinforced concrete columns in old buildings in Japan or Turkey with light transverse reinforcement and relatively low member aspect ratios. Test results showed that the columns strengthened by the SRF method could maintain relatively high gravity loads through drift ratios of more than ten percent, while the bare specimens failed in shear at small drift ratios, simultaneously losing axial load carrying capacity. Through such testing, the retrofit scheme has been improved to be effective in preventing loss of capacity against not only axial loads but lateral load reversals as well. In the shake table test presented in this paper, we simultaneously tested two eccentric wall-frame specimens with identical section details and material properties. One specimen was strengthened using the SRF method while the other was not.

This study investigates several characteristics of structures that suffer from severe damage or collapse during earthquakes, including: (1) the lack of sufficient shear strength in RC columns designed following 1970s Japanese reinforcement detail practice, which leads to shear failure after flexural yielding and the loss of axial load carrying capacity; (2) irregular layout along the height (i.e. soft/weak first stories); and (3) asymmetric 1st story plans composed of independent column and wall frames that generate considerable stiffness and strength eccentricity. In addition, another aim of this experimental program is to confirm the effectiveness of SRF strengthening under dynamic loading conditions to support static tests that have demonstrated its value.

The primary objectives of this experiment, therefore, are to investigate and understand the collapse process of reinforced concrete structures with both seismically deficient sections (poor transverse reinforcement) and structural member layout (soft/weak stories and eccentric plans) and to confirm the effectiveness of the proposed SRF retrofit scheme by comparing the seismic behaviors and collapse modes of two specimens that are identical except for being strengthened or not. We also investigate the influence of stiffness and strength eccentricity on elastic and inelastic earthquake responses under severe earthquake loads by observing the seismic behaviors of the two specimens.

## 2. Shake table test description

### 2.1. SRF strengthening method

The polyester fiber reinforcing method used here was originally developed to improve vertical members' ability to sustain axial loads under large lateral deformation and to prevent the collapse of structures in severe earthquake loadings. The important characteristics of the SRF material are its toughness, durability, heat-resistance and flexibility.

The results of tensile tests on SRF sheets and belts are given in Fig. 1 and the average material properties obtained from three tensile tests are summarized in Table 1. These results show an almost linear relationship between stress and strain until the sheet and belt fail at very large strains of 16% and 35%, respectively. The tensile strength of belt is almost twice as high as that of sheet, while the Young's moduli are almost same in both materials and lower than that of concrete. Much higher tensile force is expected from belt (3 mm thick) than sheet (0.9 mm thick).

Externally bonded steel or fiber reinforced polymer (FRP) are also very effective in strengthening the structural members of existing buildings which cannot satisfy the current design demands [12,13]. FRP strengthening method, of which advantages over steel plate bonding method are easy installation due to the light weight, chemical resistance and lower labor cost, was proposed to overcome the shortcomings of steel plate bonding method. In special, CFRP (carbon fiber reinforced polymer) retrofit method enhanced both stiffness/strength and ductility of structural members. Improved structural behaviors are resulted from the high strength and stiffness of CFRP materials. Furthermore, adhesive which is essential in the external plating/wrapping method is also stiffer and stronger than concrete. However, some experimental researches have also revealed that peeling off and shear cracks at the plate ends resulted in premature, brittle failure of RC members externally bonded with FRP plates [14–16]. Therefore, it has been recommended that in strengthening applications, the external FRP should fail in tension after yielding the internal steel

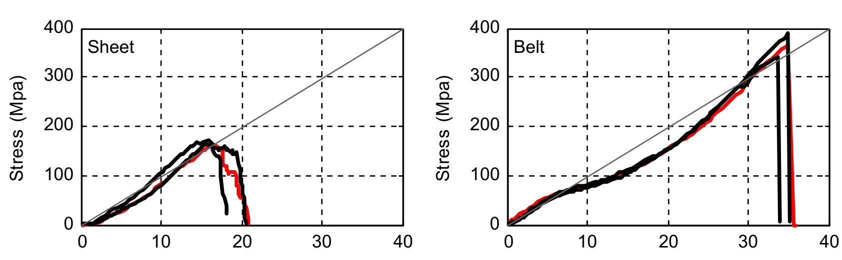


**Fig. 1.** Tensile test results of SRF materials.

**Table 1**
Material properties of SRF belt and sheet.

| | Thickness (mm) | Width (mm) | Tensile strength (MPa) | Strain at max. strength (%) | Elasticity modulus (MPa) |
|---|---|---|---|---|---|
| Belt | 3 | 50 | 358.1 | 34.42 | $0.85 \times 10^3$ |
| Sheet | 0.9 | | 169.7 | 16.17 | $0.76 \times 10^3$ |