The 2013 World Congress on
Advances in Structural Engineering and Mechanics (ASEM13)
Jeju, Korea, September 8-12, 2013

Research on the reparability of structures based on post-earthquake residual deformation

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Abstract

The post-earthquake reparability of structures serves a crucial role in modern performance-based seismic design. However, due to intrinsic defects, traditional reinforced concrete structures continuously undergo significant residual deformation during earthquakes. As a result, the repair of these structures can be either technically challenging or economically inefficient. This paper contains a state-of-the-art review of post-earthquake residual deformation. Several technical methods to enhance the reparability of new and existing structures, which incorporate unbonded prestressed tendons or FRP materials, are also introduced.

1. INTRODUCTION

Modern and mainstream seismic design codes employed in China, Japan, America and Europe have adopted a design method for strength and ductility, which enables structures to enter an inelastic stage without collapsing in moderate or large earthquakes. This design method, which considers the protection of human life a top priority, is one of the most successful design methods to address the high unpredictability of an earthquake. Although considerable success has been achieved in practice, distinct structural defects remain a concern. Considering strength and ductility in the design of structures can significantly reduce the potential of collapse; however,

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structures continuously undergo substantial residual deformation, which create technical and economic challenges for post-earthquake repair and rehabilitation.

The reparability of structures after an earthquake is controlled by the residual deformation of structural and non-structural elements. Large residual deformation of structural elements, such as columns and beams, may cause the structures unable to restoration to its original position and the structure may require demolition and reconstruction. Large residual deformation of non-structural elements may necessitate significant economic input in the repair process. Thus, the demand for reparability has increased in modern construction. High reparability is especially required for lifeline structures or other major infrastructure because their functioning is vital immediately after an earthquake or because the structural damage may cause secondary disasters.

It is challenging for traditional RC structures to achieve suitable reparability due to intrinsic defects. A hysteresis curve from the results of a column shaking table test, which was conducted by Laplace (1999), are shown in Fig. 1. The column shakes near zero displacement at the beginning of the experiment and experiences a massive impulse-like displacement under the peak acceleration strike; the damage is too large to enable the column to return to its original position. The subsequent displacement response permanently tilts on one side and results in significant residual displacement. This phenomenon is predominantly caused by the steel reinforcement bars, which exhibit limited post-yield stiffness and cannot provide sufficient restoring force; this defect is intrinsic in material that cannot be resolved with the addition of extra reinforcement bars. Therefore, new techniques are required to enhance the reparability of structures.

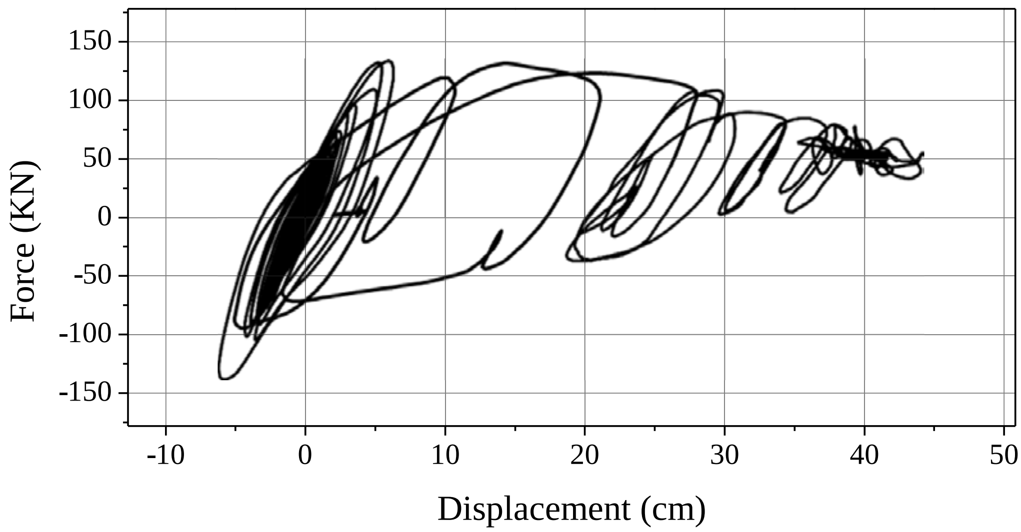

Fig. 1 Results of a shaking table test of a RC column

This paper contains a state-of-the-art review of post-earthquake residual deformation and introduces several techniques for enhancing the reparability of structures. Special attention is focused on the use of FRP composite materials for enhancing the reparability of new and existing structures.

2. STATE-OF-THE-ART REVIEW OF RESIDUAL DEFORMATION

In 1979, Riddell and Newmark (1979) researched the displacement responses of various hysteretic models subject to earthquakes. In their report, they demonstrated that the restoring force of elastic-plastic models, bilinear models and stiffness degrading models differ after the first yielding and that residual displacements vary greatly within the same earthquake. However, minimal attention was given to this phenomenon and the connection between residual displacement and reparability was overlooked. In 1994, Kowalsky *et al.* (1994) originally suggested that residual deformation may be more important than maximum displacement in the reparability of structures. Kawashima *et al.* (1994) are presumably the first researchers to systematically research the residual displacement of a SDOF system. They examined the influences of earthquake inputs, ductility demand, natural period and post-yield stiffness on residual displacement and proposed a residual deformation spectrum. After the 1995 Hyogo-Ken Nanbu earthquake, numerous bridge columns required demolition and reconstruction due to significant residual deformation, which resulted in substantial financial loss. Based on Kawashima's research, the 1996 revision of the Design Specifications of Highway Bridges (Japan Road Association 1996) introduced residual deformation limits. The residual displacement is calculated by Eq. (1) as

$$\delta_R = c_R\left(\mu_R - 1\right)\left(1 - r\right)\delta_y \tag{1}$$

where δ_R is the residual displacement, r is the post-yield stiffness, μ_R is the ductility factor, c_R is a coefficient related to post-yield stiffness, and δ_y is the yield displacement.

After the pioneering research conducted by Kawashima et al., numerous researchers began to realize the importance of this parameter, which prompted a surge in research. However, the surge was also encouraged by the enthusiasm for the new performance-based seismic design theory, in which residual deformation is recognized as one of the most important parameters in the evaluation of post-earthquake performances of structures. Christopoulos *et al.* (2003) originally proposed a residual deformation damage index and corresponding performance levels by considering structural and non-structural elements. Although specific calculating methods were not established, the index provides a theoretical basis for the extension of the residual deformation to performance-based seismic design methods. They also analyzed the displacement responses of a SDOF system with different hysteretic models and demonstrated that the hysteretic model and earthquake intensity also significantly influence residual deformation. In a companion paper (Pampanin *et al.* 2003), the residual displacement theory of a SDOF system was also extended to a MDOF system by considering P-Δ effects and high-mode effects.

Ruiz-Garcia and Miranda (2006) conducted statistical research on the residual deformation of a SDOF based on numerous numerical calculations. Residual deformation was determined to be more sensitive to different earthquake inputs than maximum deformation, which signifies that the dispersion of residual deformation induced by different earthquake inputs is massive and cannot be neglected during seismic design. A simulating equation was also established for the calculation of the residual displacement of an elastic-plastic system (Eq. (2)) as

$$C_r = \left\lfloor \frac{1}{\theta_1} + \frac{1}{41T^{\theta_2}} \right\rfloor \beta \tag{2}$$

where β can be calculated by Eq(3)

$$\beta = \theta_3 \left\lfloor 1 - \exp\left(-\theta_4 \left(R - 1 \right)^{\theta_5} \right) \right\rfloor \tag{3}$$

In this equation, θ_1, θ_2, θ_3, θ_4, θ_5 are the fitting parameters that correspond to different site conditions.

Recently, Yazgan and Dazio (2011) conducted numerical reproduction analyses of shaking table tests of 12 RC columns using the bilinear model, modified Takeda model and fiber model. The results show that the modified Takeda model and fiber model adequately capture the maximum displacements of the structures, whereas the fiber model adequately captures the residual deformation. Conversely, the bilinear model yields unacceptable accuracy.

The Chinese researcher Ye *et al.* (2009) studied the influence of post-yield stiffness on short-period and long-period structures and discovered that the post-yield stiffness can effectively reduce the residual deformation of a structure and the dispersion of maximum displacement of different earthquake inputs. The post-yield stiffness can also inhibit the damage concentration and local damage of structures under earthquake impacts.

Hao *et al.* (2013) analyzed the correlation between earthquake intensity and residual deformation. The results indicate that peak velocity significantly influences residual deformation. A residual deformation calculating equation was proposed based on a vast number of numerical calculations (Eqs.(4)–(5)) as

$$\theta_r = \frac{a_{\max}}{0.1}\theta_{r0}e^{-b/c} \tag{4}$$

$$\theta_{r0} = \begin{cases} 6.23T & 0\text{s} \le \text{T}<1.3\text{s} \\ 8.10+\beta\left(T-1.3\right) & 1.3\text{s} \le \text{T}<6\text{s} \end{cases} \tag{5}$$

where θ_r is the residual deformation drift, b is the post-yield stiffness, T is the natural period, and β and c are fitting parameters related to the site condition.

Compared with previous studies on residual deformation, current research is primarily based on the SDOF system; minimal attention has been given to the MDOF system. Post-yield stiffness and unloading stiffness are considered factors that predominantly influence residual deformation.

3. TECHNOLOGY FOR ENHANCING THE REPARABILITY OF STRUCTURES

Because the post-yield stiffness and unloading stiffness, especially the former parameter, are parameters that primarily influence residual deformation, substantial effort has been made to enhance the reparability of structures by adjusting the post-yield stiffness and unloading stiffness. The most common techniques include the unbonded (prestressing) technique and the use of FRP composite material.

3.1. Unbonded (prestressing) technique

Unbonded prestressing was originally introduced by the American engineer E. Freyssinet; however, it was not employed in practice until the 1950s. The application of this technique began to thrive in the 1960s. The use of prestressing to enhance reparability began in the 1990s and was promoted by the occurrence of several large earthquakes in America and Japan. Ikeda *et al.* (1998) and Zatar and Mutsuyoshi (2002) discovered that the residual deformation of traditional RC columns can be significantly reduced by the application of unbonded prestressed tendons.

The major principle of unbonded prestressed tendons in columns to reduce residual deformation is based on the notion that prestressed tendons remain elastic during earthquakes and provide columns with additional self-centering forces. The hysteretic curve of an unbonded prestressed RC column is shown in Fig. 2. Prior to the yielding of the prestressed tendon, the unloading residual displacement is extremely small. Note that the use of unbonded prestressed tendons introduces several side effects. Although the prestressed tendons provide extra self-centering force in the structures, they also cause a pinching effect in the hysteretic curve and affect the energy dissipation in structures; thus, the maximum displacement demand of the structures is greater than expected. Prestressing in the structure may cause early crushing in the plastic hinge region during an earthquake.

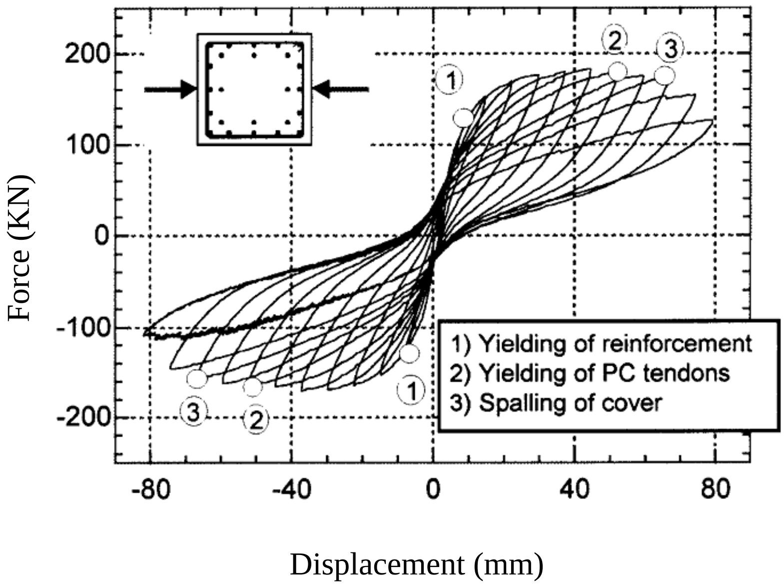

Fig. 2 Hysteresis of an unbonded prestressed concrete column

Lemura *et al.* (2004) also proposed an unbonded bar reinforced concrete (UBRC) by applying high-strength elastic materials (unbonded bars) in traditional RC columns. The elastic materials produce steady post-yield stiffness in the structures. To ensure that the elastic materials adequately function during large earthquakes, they will not begin to operate until the traditional steel bars begin to yield, as shown in Fig. 3.

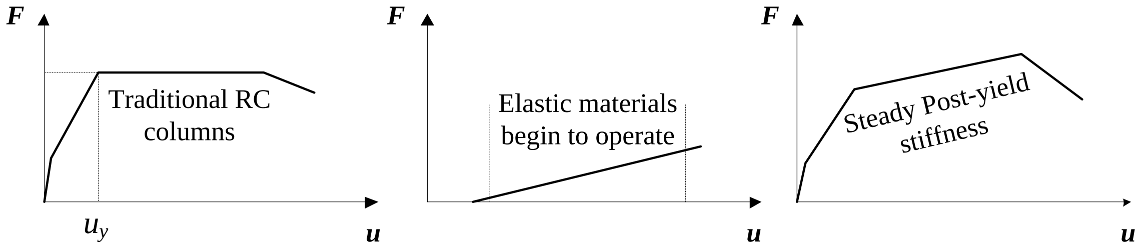

Fig. 3. Schematic of UBRC Iemura *et al.* (2004)

3.2. Enhance the reparability of a new building using steel-FRP composite bars

The invention of fiber reinforced polymer in the beginning of the 20th century initiated a revolutionary development in the aviation and construction industries. Compared with steel, FRP is an elastic material with lighter weight and higher strength.

The Chinese scholar Wu *et al.* (2010) invented a new type of steel-FRP composite bars (SFCB) by wrapping transverse and longitudinal FRP on the outside of steel bars. The configuration details and the tensioning force-deformation relation are shown in Fig. 4. The results of the tensioning tests indicate that the wrapping with FRP can be performed in coordination with the steel core and that both materials provide the initial stiffness (E_{I} in Fig. 4). The FPR can also generate steady post-yield stiffness (E_{II} in Fig. 4) in the composite bars after the first yielding of the steel core and prior to the rupture of the wrapping with FRP. The steel core is capable of bearing forces until fracture. The value of the post-yield stiffness can be easily controlled by adjusting the quantities of the FRP and steel. The results of the cyclic loading test of SFCB-reinforced RC columns, which were conducted by Sun *et al.* (2011), reveal smaller unloading residual displacements than for the residual displacements of traditional RC columns.

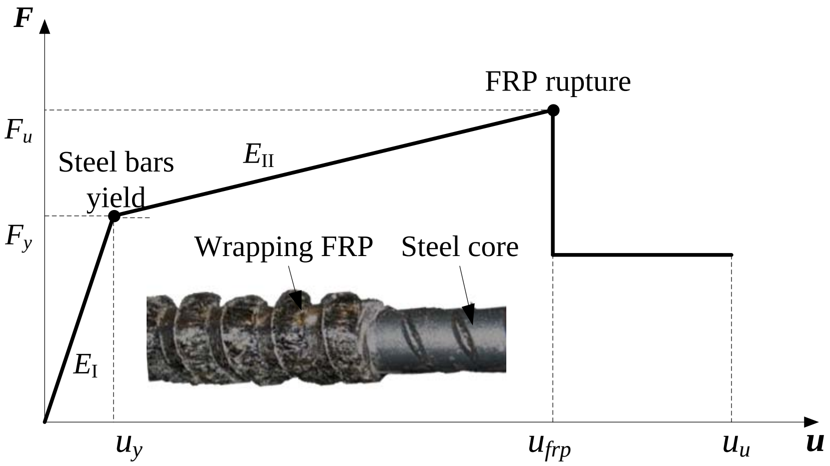

Fig. 4 Configuration and schematic of SFCB

3.3. Enhance the reparability of existing buildings through combinational strengthening

To enhance the reparability of existing structures, especially damaged bridge columns, Yang (2011) proposed a new repairing method by combinational strengthening using FRP bars and FRP sheets. This new method primarily includes near-surface-mounted (NSM) FRP bars and the wrapping of FRP sheets in the plastic hinge region. Combinational strengthening simultaneously addressing the problems of bearing capacity demand, ductility demand and durability demand, which cannot be accomplished by traditional strengthening methods.

The main principle of the combinational strengthening method is shown in Fig. 5. The traditional RC columns exhibit zero post-yield stiffness after the first yield, which is usually negative if the P-Δ effect is considered. The combinatorially strengthened RC columns exhibit higher bearing capacity due to the existence of the FRP bars. The FRP sheets that are wrapped outside the plastic hinge area also delay the crushing of concrete and buckling of reinforcing bars during large deformations. The concrete is in a three-dimensional pressure state and the ductility of the column is improved. The unloading stiffness of the combinatorially strengthened column is smaller than the unloading stiffness of traditional columns due to the existence of the FRP bars and FRP sheets.

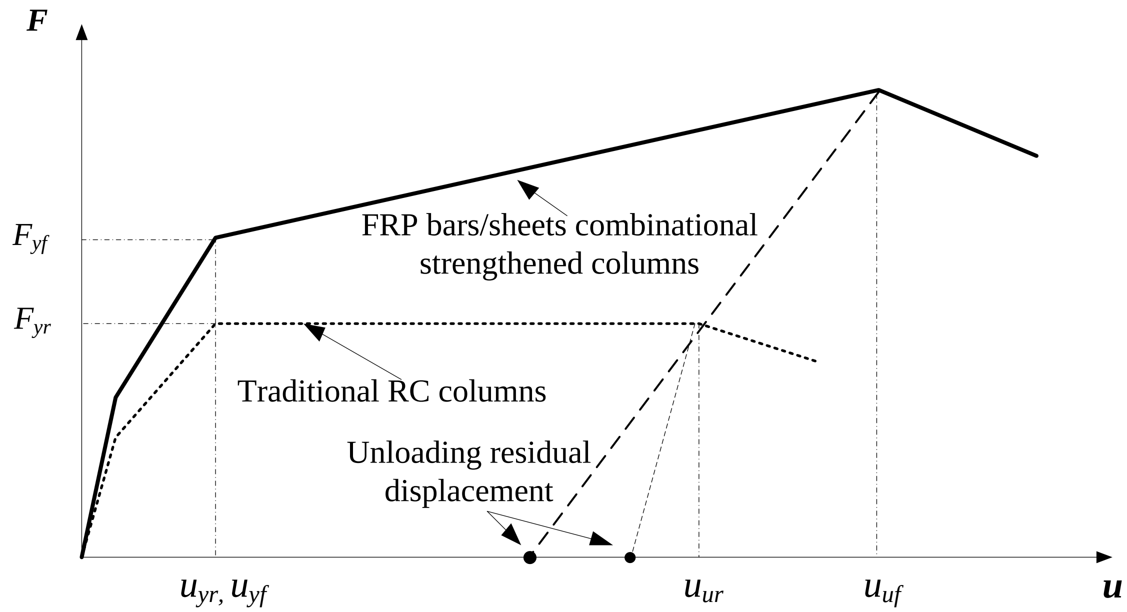

Fig. 5 Schematic of combinational strengthening

4. CONCLUSIONS

This paper contains a state-of-the-art review of the residual deformation of structures during an earthquake. The residual deformation can be reduced by establishing a steady post-yield stiffness in structures or by controlling the unloading stiffness of structures.

The application of unbonded prestressed tendons reduces residual deformation by creating a self-centering force in structures. However, the UBRC is primarily controlled through its post-yield stiffness. The SFCB and combinational strengthening method enhance the post-earthquake reparability of structures by reducing the unloading stiffness and increasing the post-yield stiffness.

Additional methods can be developed by researchers and practitioners to enhance the reparability of structures by adjusting the post-yield stiffness and unloading stiffness of structures.

5. ACKNOWLEDGMENTS

The authors acknowledge the financial support provided by the National Basic Research Program of China (973 Program) (No. 2007CB714200), the National Science Foundation of China (No. 51178099), the Strategic Japanese-Chinese Cooperative Program on “Earthquake Disaster Mitigation” (2012DFG20510) and the Scientific Innovation Research Program of College Graduates in Jangsu Province (CXLX_0128)

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