Resilience and recoverability enhancement of concrete structures

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Abstract: This study addresses the importance of enhancing the recoverability of reinforced concrete (RC) structures. A summary of the efforts and achievements done by the research community to improve the recoverability of RC structures is discussed. In addition, the resilience of existing structures designed according to modern codes as well as under designed structures has been evaluated. Finally, the application of fibre reinforced polymer (FRP) composites in existing and modern structures to enhance post-earthquake recoverability and to provide a new controllability-tool is discussed. Recoverability and controllability can be realised using FRP composites.

Keywords: resilience; damage-controllable systems; fibre reinforced polymer; FRP; RC structures.

Reference to this paper should be made as follows: Wu, Z. and Fahmy, M.F.M. (2021) 'Resilience and recoverability enhancement of concrete structures', *Int. J. Sustainable Materials and Structural Systems*, Vol. 5, Nos. 1/2, pp.1–10.

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This paper is a revised and expanded version of a paper entitled 'Resilience and recoverability enhancement of concrete structures' presented at 2nd International Workshop on Resilience 2018 (IWR2018), Nanjing and Shanghai, China, 31 August–2 November 2018.

1 The importance of enhancing recoverability of RC structures

The experienced history of reinforced concrete (RC) structures during the life-cycle time of serviceability and the response to the natural hazards and/or the human-made disasters have invoked the society to consider the construction of sustainable cities. In parallel, the fast growing of economy and the long-time investment in superior infrastructures all over the world are supporting the concept of both sustainability during the serviceability state and the resiliency under the effect of sudden disruptions. Further-more, considering the existing cities, although it would be difficult to start a simultaneous updating to all cities to the required recoverability, enhancing the recoverability of deficient infrastructures to meet the requirements of modern seismic design codes is critical.

2 What are the efforts done all over the world to enhance recoverability of RC structures?

The seismic resilience is the capability of infrastructures or structures to withstand the effects of anticipated interruptions and to recover efficiently the original functionality. Moreover, the time required to restore/recover that functionality, i.e., rapidity to restore the original functionality, is a critical parameter of resilient structures. Hence, the research community has been triggered to define new resilient RC structural systems satisfying the requirements of both limited resilience loss and short time recovery of the original functionality. In Japan, a fundamental plane for national resilience has been established. The basic concept in this plan is the creation of a strong and resilient country. The basic policies included: protection of human lives; avoid fatal damage and maintain important functions of the nation and the society; minimising damage to the property of the citizenry and public facilities; and swift recovery and re-construction. In the USA, the National Earthquake Hazards Reduction Program (NEHRP) recommended seismic provisions, which presents the minimum recommended requirements necessary for the design and construction of new buildings and other structures to resist earthquake ground motions throughout the states. The objectives of these provisions are to provide reasonable assurance of seismic performance that will avoid serious injury and life loss; preserve means of egress; avoid loss of function in critical facilities; and reduce repair costs of structural and non-structural where practicable.

2.1 Modern seismic design codes

The International Organization for Standardization (ISO) developed different standers for performance requirements of concrete structures. Environmental, economic and social aspects have been considered to en-sure green and sustainable material and structure; minimum life-cycle cost; and enhancement of safety and recoverability design. For example (Fahmy et al., 2010a), ISO 15392 and ISO/TS 12720 have been developed for sustainability in building construction, and they present general principals and their application, respectively. Other standards have been developed for the construction works and construction products and services. In addition, ISO 19338 has been established for performance and assessment requirements for design standards on structural concrete. One subsection of ISO 19338 defines the restorability as ability of a structure or structural element to be repaired physically and economically when damaged under the effects of considered actions. In the general requirements, a design standard for structural concrete shall be based on quantitative performance evaluation at the limit states. Design shall consider safety, serviceability, restorability, structural integrity, robustness, environmental adequacy and durability.

In order to promote the concept of recoverability, seismic design codes (JSCE Earthquake Engineering Committee, 2000; AASHTO, 2011; CSA, 2010) have been updated to include the definition of the seismic-performance design for structures and infrastructures considering the importance level of the structure, the type of ground shaking and its return period, and the geotechnical characteristics at the construction site. The Japanese code considers three limit states: structure safety limit, serviceability limit, and the restorability limit. At present, only the restorability (repairability) limit state under earthquake action is defined in the Japanese standards. Other damage deteriorations, such as environmental action, have no specific definition. In the future, it is recommended to consider the restorability limit state under different specific action, such as fatigue, durability, fire. In addition, no specific design guideline has been defined to satisfy the pro-visions of the required resiliency.

3 What is the situation of current RC structures?

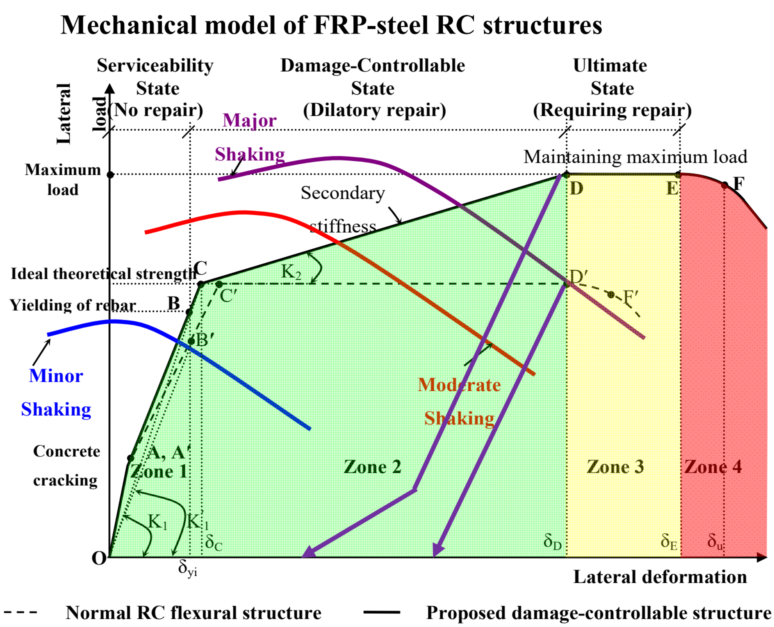
The concerning the new seismic design philosophies of structures, the existing structures should sustain the expected maximum lateral force, under the effect of a strong earthquake, in the inelastic stage with limited damages, which means quick recoverability. Fahmy (2010) studied four groups of rectangular RC bridge columns available from literature and designed according to the available seismic design codes to investigate their recoverability from experimentally simulated seismic forces. Results showed that the current provisions for reinforcement details of RC structures can ensure a respectable resisting system with reasonable deformability; however recoverability cannot be achieved after a drift of 2%. In addition, Fahmy (2010) showed that aged and under-designed structures need an exceptional concern to introduce reasonable retrofitting systems to face the requirements of the current codes. Generally, the existing communities/cities all over the world should be updated for the required recoverability.

4 Application of FRP composites to enhance recoverability of RC structures

There is a call for the development of structural systems which realise supreme seismic performance without or with very slight increase of cost compared with those required in ordinary structures. Hence, the key concept in this part is to introduce rational structure systems for modern structures and retrofitting techniques, which suffer controlled damage from simulated seismic forces meanwhile substantial increase in cost is not required, to enhance but succeed the advantages of conventional structures.

Since the advantages of advanced composite materials, i.e., fibre reinforced polymers (FRPs), include: light weight, high strength or stiffness-to-weight ratios, corrosion resistance, and, in particular, the elastic performance; strengthening of existing structures and reinforcement of modern structures with FRP have drawn increased attention

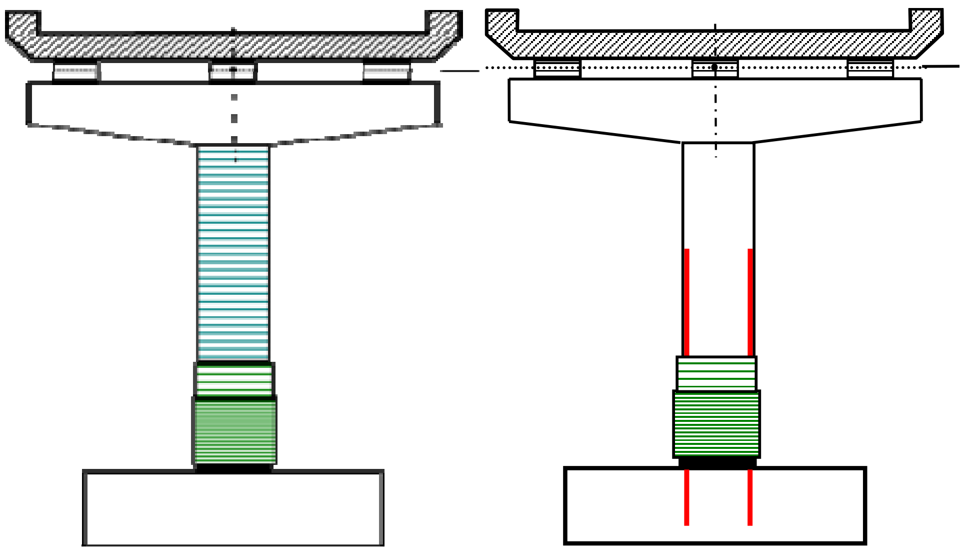
Figure 1 Idealised load-deformation behaviour of the proposed FRP-steel damage controlled structures (see online version for colours)



Source: Wu et al. (2009)

According to the mechanical behaviour shown in Figure 1, the load-deformation of the proposed FRP-steel damage controlled structure can be divided into four main zones; zone 1: from point O to B; zone 2: from point B to D; zone 3: from point D to E; and zone 4: after point E. Zone 1 corresponds to a stage of no damage or concrete cracking. Under a small earthquake, the mechanical behaviour should be controlled in this zone, and the original function of the structure can be maintained without any repair and displacement of elements. Zone 2 corresponds to the hardening behaviour after the yielding of steel reinforcements, where a distinct secondary stiffness is demonstrated and the dramatic deformation can be effectively controlled. Under a medium or strong earthquake, the mechanical behaviour of the proposed structure should be within zone 2. Thus, damage can be effectively controlled by the secondary stiffness. The original function of the structures can be quickly recovered through repairs after a medium or large earthquake. Zone 3 corresponds to ductile behaviour after hardening, where favourable ductility is demonstrated under a large earthquake. The proposed structure can be kept in place for a relatively long time without collapse during a large earthquake, though severe damage may occur. The original function of the structures may be recovered through the replacement of some elements. During a severe earthquake, the mechanical behaviour may enter zone 4 with collapse.

Figure 2 Proposed retrofitting techniques for existing structures using FRP, (a) FRP confinement (b) NSM FRP bars + FRP confinement (see online version for colours)



(s) (b)

4.1 *Recoverability of existing structures using FRP*

A comprehensive evaluation for the recoverability of existing bridge columns retrofitted with external FRP confinement was done by Fahmy et al. (2009). The enhancement in the post-yielding stage was mainly dependent on the improvement of the local axial stress-strain compression behaviour of the concrete and/or the enhancement of the bond strength between the lap-spliced steel reinforcement [Figure 2(a)] (Fahmy et al., 2010a). Furthermore, application of bond-based near-surface mounted (NSM) retrofitting technique using FRP bars was proposed and experimentally evaluated by Fahmy and Wu (2012, 2016). In this technique, the post-yielding stiffness can be directly con-trolled through the amount and type of FRP bars used as flexural reinforcements and the concrete compression behaviour is enhanced through the external confinement with FRP sheets [Figure 2(b)].

Figure 3 Residual deformations of a large database of FRP-confined RC columns and recoverable and irrecoverable states of damage controlled FRP-RC columns (see online version for colours)

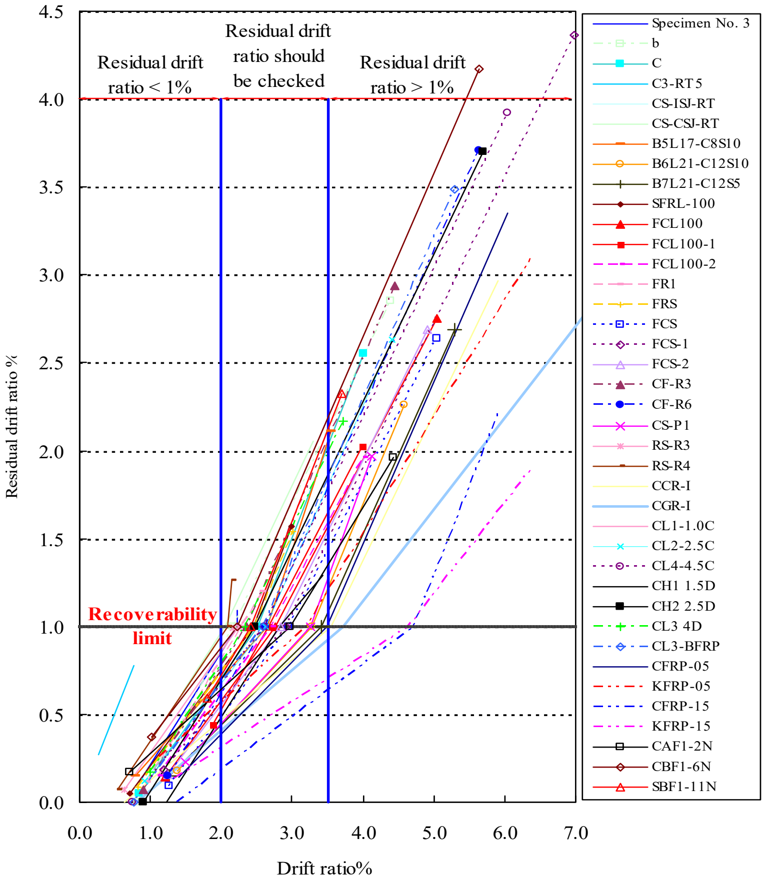


Figure 4 Dynamic results of FRP-confined RC column and another retrofitted with booth NSM FRP bars and FRP confinement (see online version for colours)

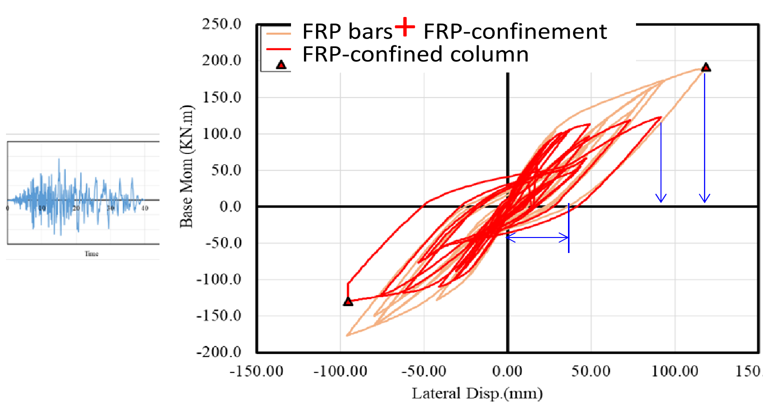
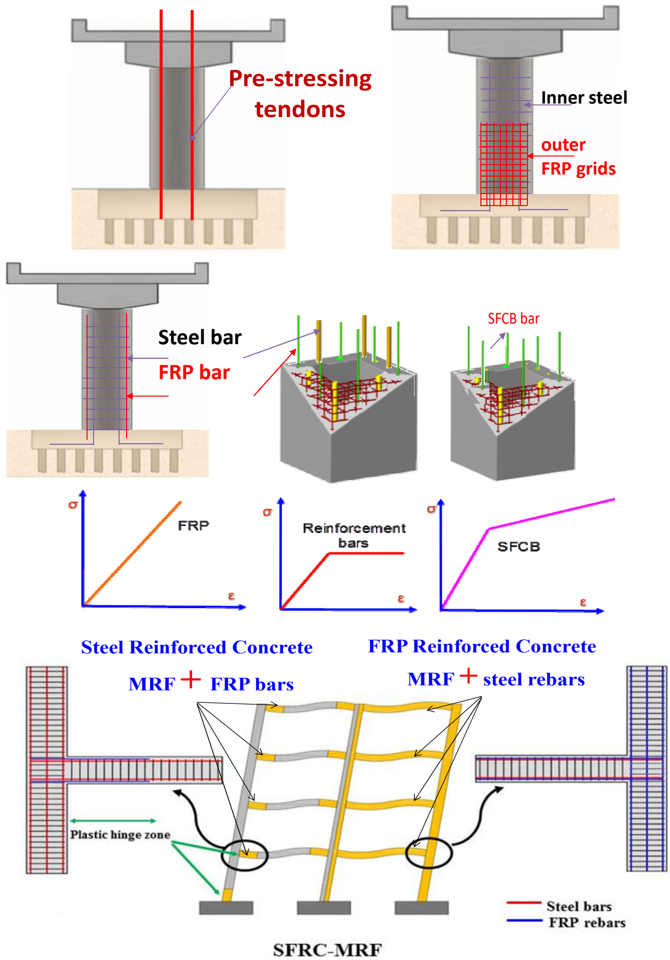


Figure 3 shows a classification for the limit states of FRP-confined bridge columns based on the experimental results for more than 30 RC columns. Figure 4 shows the dynamic results for the response of a bridge columns retrofitted with both techniques, i.e., FRP confinement and NSM + FRP confinement.

Figure 5 Different applications of FRP reinforcement in modern bridges and buildings (see online version for colours)



4.2 Modern recoverable FRP-steel reinforced structures

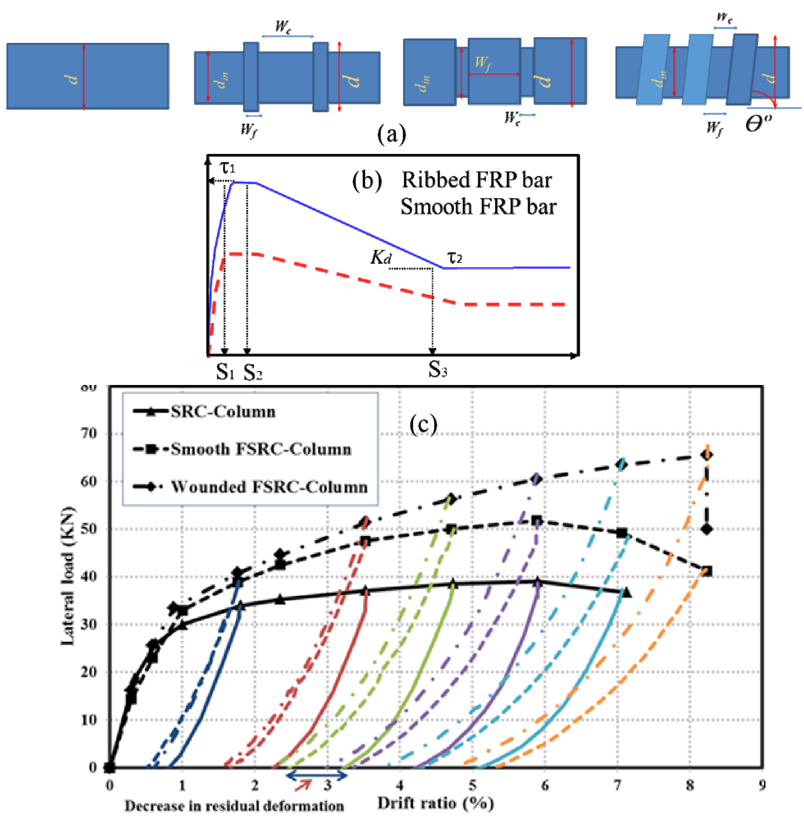
4.2.1 Innovative steel fibre composite bars

For modern structures, innovative hybrid reinforcement, steel fibre composite bars (SFCBs), was proposed as alternative reinforcement for columns in place of the traditional steel reinforcement. Experimental and numerical studies were carried out to evaluate the performance of bridge columns reinforced with the SFCBs (Fahmy et al., 2010b). The innovative bar is composed of inner steel core and outer longitudinal fibres, so it com-bines the mechanical characteristics of both the elastic fibre and the ductile steel as shown in Figure 5. This method would enhance the inelastic response through immediate commencing of strain-hardening behaviour after steel rebar yielding, and the value of the slope of the hardening stage could also be controlled depending on the type and amount of FRP used. Moreover, the permanent deformations would also be further reduced due to the elastic performance of FRPs, which is characterised by approximately zero residual deformations, leading to a smaller unloading stiffness than the elastic stiffness.

4.2.2 Bond-controlled FRP bars as longitudinal reinforcement + steel reinforcement

Furthermore, recently, a novel reinforcement details using both FRP bars and steel reinforcement was proposed for modern RC bridges and buildings (FSRC) (Ibrahim et al., 2015, 2016, 2018). Texture of the FRP bars was applied as a design parameter to control the performance of the FSRC elements. Experimental and 3D finite studies were carried out to evaluate the effect of several potentially influential parameters. The results showed the bond-controlled FRP bars can control the recoverability indices (post-yield stiffness and residual deformations) of modern FSRC structural elements (Figure 6).

Figure 6 (a) Textures of FRP bars (b) Bond behaviour of smooth and rough FRP bars (c) Lateral response of bond-controlled reinforcement of FRP + steel reinforced columns (see online version for colours)



5 Conclusions

Structural recoverability should be one key index of the structural resilience which is an index of the structural sustainability. Combination of FRP and steel can be used to realise damage-controllable and restorable seismic structures with durable, smart and green behaviour. Innovative systems combining modern construction techniques with the application of FRP reinforcement present a new resilient system for modern sustainable structures.

Acknowledgements

The sorting of the main body of authors is with respect to their contributions to the flow of the content of Sections 2 to 6.

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