ENHANCING SEISMIC RESILIENCE: VALIDATION OF FRP REPAIR TECHNIQUES THROUGH 6-DOF HYBRID TESTING

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ABSTRACT

This paper highlights the role of 6-DOF hybrid testing as a validation tool for assessing the effectiveness of Fiber Reinforced Polymer (FRP) composite repair and retrofitting techniques in structures undergoing seismic events. By combining physical testing and numerical simulations, the advanced hybrid testing technique accurately replicates complex loading conditions, including axial, lateral, longitudinal, pitch, roll, and yaw forces. This comprehensive evaluation helps optimize the design and implementation of FRP solutions, enhancing the seismic resilience of reinforced-concrete structures. The paper presents some examples emphasizing the importance of hybrid testing in promoting the adoption of FRP composites and advancing seismic retrofitting practices in civil engineering.

KEYWORDS

6-DOF hybrid testing, FRP-repair and retrofit, seismic resilience.
[two lines]

INTRODUCTION

Structural engineers face the daunting challenge of designing buildings to withstand uncertain loads throughout their service life while minimizing the risk of catastrophic damage and enhancing urban infrastructure resilience. Accurately predicting structural responses from linear-elastic behavior to near-collapse conditions remains a significant challenge. Despite advancements in computational models, accurately characterizing member properties is difficult due to simplification assumptions that impact result reliability. Therefore, the experimental validation remains crucial, especially for assessing assumptions made by numerical models under extreme dynamic loads and highly nonlinear elements. Conducting experimental testing on entire structures is complex, expensive, and hazardous. Small-scale models often fail to replicate real structures' behavior accurately. Consequently, alternative large-scale testing methods have been developed. Hybrid simulation, derived from pseudo-dynamic testing, is an innovative cyber-physical technique that combines the flexibility and cost-effectiveness of computer simulation with the realism of experimental testing (Hashemi et al., 2017b). This approach provides a robust and adaptable platform for large-scale testing, effectively assessing structural response behavior and the full range of the seismic performance (Hashemi et al., 2014; Hashemi and Mosqueda, 2014; Hashemi et al., 2016).

Hybrid testing proves invaluable in validating various Fiber Reinforced Polymer (FRP) repair techniques for earthquake-damaged reinforced concrete structures (Hashemi et al., 2017a). Through hybrid simulation, researchers and engineers can replicate the complex forces and interactions experienced during seismic events, comprehensively evaluating the performance and effectiveness of FRP repairs in enhancing the seismic resilience of reinforced-concrete structures. Physical representation of damaged portions combined with numerical models for the remaining parts enables the development of reliable and efficient repair strategies, leading to improved seismic resilience and safe utilization of FRP composites in civil engineering applications.During hybrid testing, the damaged portions of the reinforced concrete structures can be physically represented, while the remaining parts are simulated using numerical models. This approach allows the development of reliable and efficient repair strategies, leading to improved seismic resilience and the safe utilization of FRP composites in civil engineering applications.

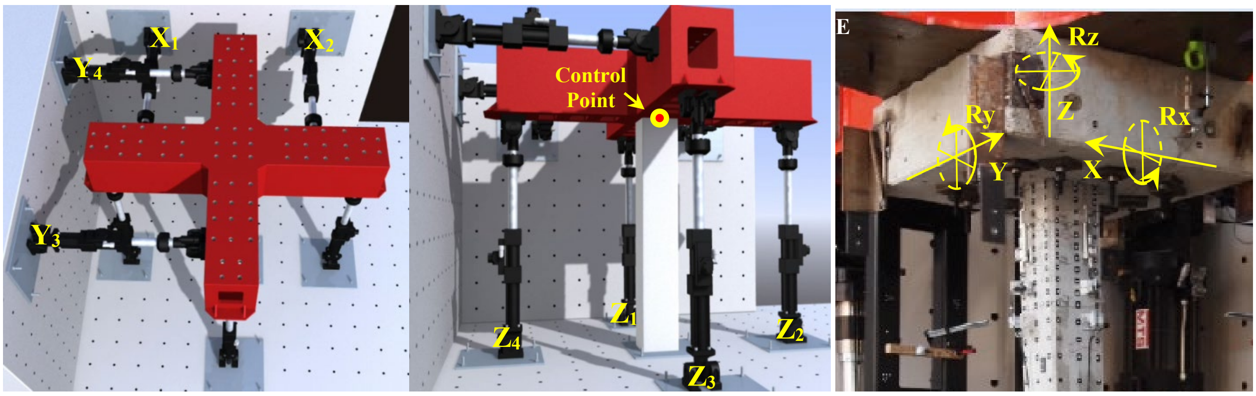
STATE-OF-THE-ART SYSTEM FOR HYBRID SIMULATION AT SWINBURNE

Swinburne University of Technology has developed and validated a state-of-the-art loading system known as the Multi-Axis Substructure Testing (MAST) system (AlMahaidi et al., 2018). This cutting-edge facility significantly enhances the capabilities of hybrid testing by enabling three-dimensional response analysis of structures under extreme loads (Hashemi et al., 2015). The facility is situated within the impressive Smart Structures Laboratory, a unique and comprehensive three-dimensional testing facility designed for large-scale testing of civil, mechanical, aerospace, offshore, and mining engineering components and systems. It is the only facility of its kind available in Australia.

The Smart Structures Laboratory, housed in the architecturally striking Advanced Technologies Centre (ATC), boasts transparent walls that provide a visually captivating view of researchers and scientists at work. The laboratory features a robust 1.0-meter thick strong floor, spanning an expansive area of 20 meters by 8 meters. Two 5-meter tall reaction walls intersect at one corner, ensuring structural stability and enabling various testing configurations. The laboratory is equipped with a comprehensive suite of hydraulic actuators and universal testing machines, offering a wide range of capacities from 10 tonnes to 500 tonnes. Adjacent workshops and a hydraulic pump system located in the basement provide essential support and services to the Smart Structures Laboratory.

The key components of the 6-DOFhybrid testing facility (MAST system) are:

1. The facility is equipped with four vertical hydraulic actuators with a capacity of ±1MN each and two pairs of horizontal actuators with a capacity of ±500kN in orthogonal directions. Supplementary actuators are also available to accommodate additional loading configurations on the specimen (refer to Figure 1 and Table 1).
2. A 9.5-tonne steel crosshead is employed to transfer the six degrees of freedom (6-DOF) forces from the actuators to the specimen. The test area beneath the crosshead spans approximately 3 meters by 3 meters in plan and has a height of 3.25 meters.
3. The facility features a robust reaction system consisting of an L-shaped strong-wall measuring 5 meters in height and 1 meter in thickness, along with a 1-meter thick strong-floor.
4. An advanced servo-hydraulic control system is utilized, capable of imposing simultaneous 6-DOF states of deformation and load using switched/mixed mode control. Moreover, the Centre of Rotation (CoR), which refers to the fixed point around which the 6-DOF movements of the control point occur, can be adjusted by assigning desired values.
5. The facility incorporates an advanced three-loop hybrid simulation architecture. This includes the servo-control loop containing the MTS FlexTest controller (inner-most loop), the predictor-corrector loop operating on the xPC-Target real-time digital signal processor (middle loop), and the integrator loop running on the xPC-Host (outer loop).
6. Additional high-precision draw-wire absolute encoders with a remarkable resolution of 25 microns are available, which can be directly fed back to the controller for enhanced precision and accuracy.



a) Actuator assembly, plan view b) Actuator assembly, side view c) 6-DOF axis

Figure 1. Actuator assemblies of the MAST system

Table 1. Actuators and DOF specifications

MAST Actuator Capacity			
Actuator	**Vertical**	**Horizontal**	**Auxiliary**
Model	MTS 244.51	MTS 244.41	2 (MN) (Qty. 1) 250 (kN) (Qty. 4) 100 (kN) (Qty. 3) 25 (kN) (Qty. 3) 10 (kN) (Qty. 1)
Quantity	4 (Z_1, Z_2, Z_3, Z_4)	4 (X_1, X_2, Y_3, Y_4)	
Force Stall Capacity	± 1,000 (kN)	± 500 (kN)	
Static	± 250 (mm)	± 250 (mm)	
Servo-valve flow	114 (lpm)	57 (lpm)	
MAST DOFs Capacity (non-concurrent)			
DOF	**Load**	**Deformation**	**Specimen Dimension**
X (Lateral)	1 (MN)	± 250 (mm)	3.00 (m)
Y (Longitudinal)	1 (MN)	± 250 (mm)	3.00 (m)
Z (Axial/Vertical)	4 (MN)	± 250 (mm)	3.25 (m)
Rx (Bending/Roll)	4.5 (MN.m)	± 7 (degree)	
Ry (Bending/Pitch)	4.5 (MN.m)	± 7 (degree)	
Rz (Torsion/Yaw)	3.5 (MN.m)	± 7 (degree)	

APPLICATION OF THE MAST SYSTEM FOR PRE- AND POST-EARTHQUAKE FRP-REPAIR AND RETROFITTING SOLUTIONS:

Retrofitting or strengthening existing structures is a highly effective approach to enhance their integrity and prevent sudden collapse under extreme loads. This method ensures that structures can withstand maximum loading responses and remain intact, safeguarding life safety and enabling cost-effective repairs. Similarly, repairing and rehabilitating damaged structures to their original performance can offer a time-saving and economical alternative to complete replacement. Particularly in the aftermath of a catastrophic event, swift repairs are crucial to facilitate emergency response and expedite the recovery process in the affected region.

The use of fiber reinforced polymers (FRP) for rehabilitation and repair of structures damaged in earthquakes is an efficient and cost effective alternative to structural replacement. The suitability of FRP when compared to other materials such as structural steel is largely attributed to their high tensile strength, light weight, resistance to corrosion and ease of application (Al-Mahaidi & Kalfat; 2019). FRP materials are typically applied to the concrete surface as externally bonded reinforcement using high strength epoxy resin after adequate surface preparation of the concrete. Surface preparation may consist of sandblasting, water jetting and the application of a suitable primer. To date, there have been many studies which have proven the effectiveness of using FRP as an effective solution to strengthen RC members for flexure, shear, torsion and axial loading (Al-Ghrery & Al-Mahaidi et al. 2021; Kalfat et al. 2020; Hii & Al-Mahaidi, 2007; Al-Kamaki & Al-Mahaidi, 2015). This has resulted in widespread applications in the strengthening of RC bridges and buildings for increased loadings, design defects, damage due to vehicle impact or earthquake loading. FRP has also proven to be effective predamage strengthening technique to improve the earthquake performance of reinforced concrete (RC) columns and beam-bolumn connections resulting in many researchers reporting enhacements in both strength and ductility without affecting the initial member stiffness (Karayannis and Golias 2022; Allam et al. 2019; Wang et al. 2015; Wei et al. 2009). Various retrofit techniqies for beam-column connections subject to earthquake loading have been explored by researchers with various degrees of effectiveness including: (1) U-shape configurations which involved wrapping the column horizontally using FRP, (2) T-shape configurations which involve applying the FRP in horizontal and vertical directions around the beam-column joint; (3) X-shaped configurations involving applying the FRP in diagonal orientations across the connection and (4) bi-directional or quad-directional FRP around the joint. The effectiveness of the given strengthening technique has been found to vary widely depending on the strengthening arrangement used and while most researchers found a sizable increase in strength compared to unstrengthened joints, most reported that some form of anchorage of the FRP was necessary in order to increase the effectivess of the strengthening technique and avoid premature debonding (Pohoryles et al. 2019). While previous studies have focussed on isolated beam-column connections, no studies have explored the earthquake performance of strengthening RC columns using FRP using hybrid simulation.

This study evaluates the suitability of using FRP horizonally applied full wrapping to restore the load-bearing capacity of earthquake-damaged reinforced concrete (RC) structures. The study utilized a half-scale symmetrical 5-story, 5×5 bay RC ordinary moment frame building located in Melbourne, Australia (refer to Figure 2). Physical specimens were employed to represent the critical first-story corner-column, while the remaining structural elements, inertial and damping forces, gravity and dynamic loads, and second-order effects were modeled numerically.

The damaged column was repaired using CFRP wraps and subsequently retested under identical loading conditions (see Figure 3). The repair methodology involved: (1) removal of all spalled and fractured concrete; (2) epoxy injection of any cracks wider than 0.3 mm; (3) reinstatement of damaged concrete with a suitable repair mortar; and (4) wrapping of the column with CFRP (Hashemi et al, 2017a). The buckled, ruptured or yielded reinforcement bars were not repaired or replaced as part of the repair process. Prior to conducting the patch repair of the concrete, fractured and loose concrete was removed by light tapping. All cracks were then injected and a polymer-modified structural repair mortar (MasterEmaco S 5300) was used to replace the damaged concrete. CFRP wrapping was applied over a 600-mm length at each end of the column in regions corresponding to the maximum moment, three days after the crack injection was performed. The concrete in these regions was confined using three layers of BASF MBrace CF130 unidirectional carbon fiber sheet. The CFRP was expected to provide a passive confinement pressure, thereby increasing the compressive strength of concrete. Further, the orientation of the fibers was arranged parallel to the existing steel stirrups and was expected to significantly increase the shear capacity at the column ends. The test results demonstrated that the repaired column exhibited enhanced safety and a reduced probability of collapse compared to the brand-new initial column, given a certain ground motion intensity level. Furthermore, from a financial standpoint, the total repair cost for the columns amounted to approximately 30% of the total replacement cost, making it a more cost-effective solution. Further, the collected experimental data can then be used for resilience and sustainability assessments. For example, Figure 4 shows how the experimental tests using the MAST system can be used in a framework for resilience and sustainability assessment of two scenarios of the ‘total replacement’ and ‘carbon-fiber reinforced polymers (CFRP) repair’ as post-earthquake solutions following the collapse of an RC columns (Hashemi et al., 2019).

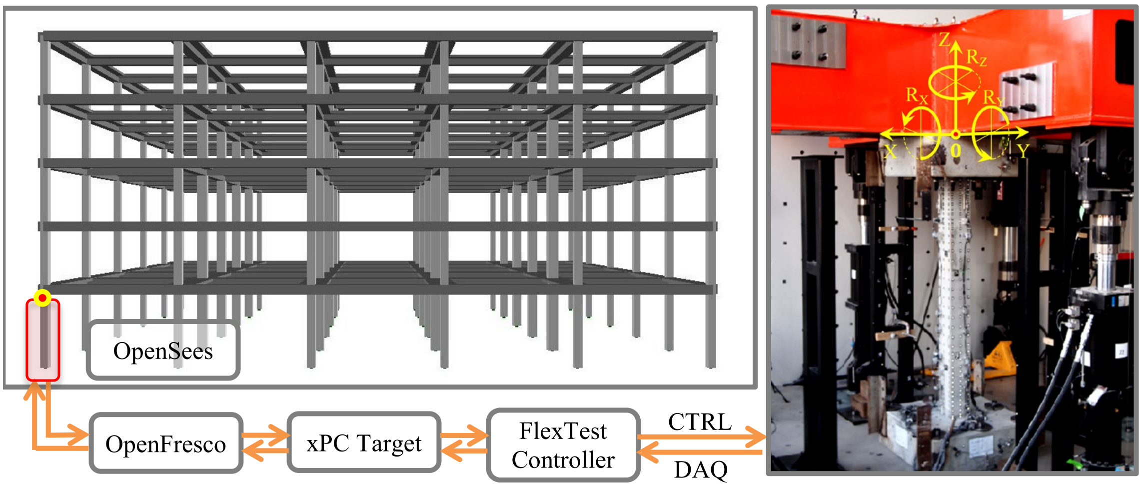
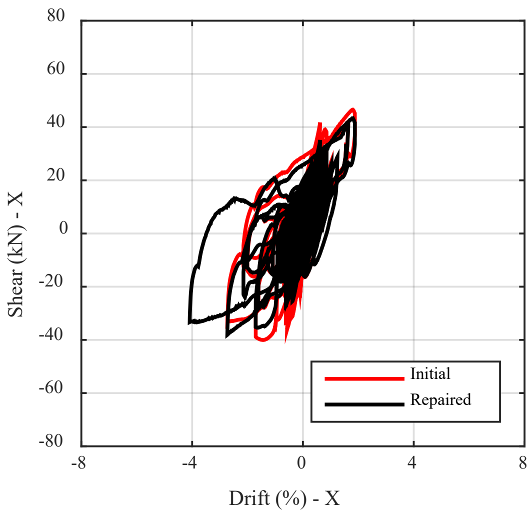


Figure 2. Hybrid simulation components including numerical and experimental substructures

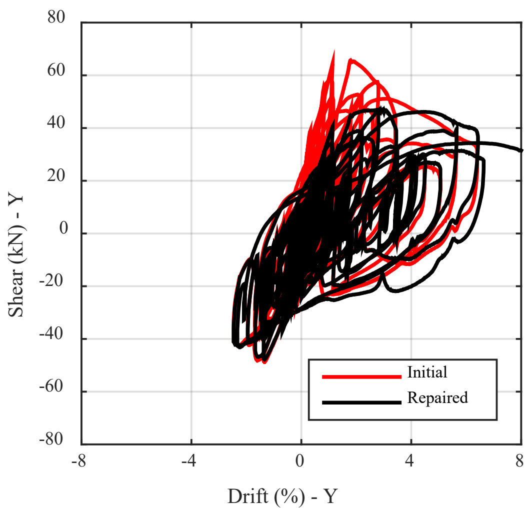

a) Repair of the initial column (Top)


b) Repair of the initial column (Base)


c) CFRP-Repaired column



(a) Comparison of lateral force-deformation – X axis



(b) Comparison of lateral force-deformation – Y axis

Figure 3. CFRP-repair of the earthquake-damaged RC column

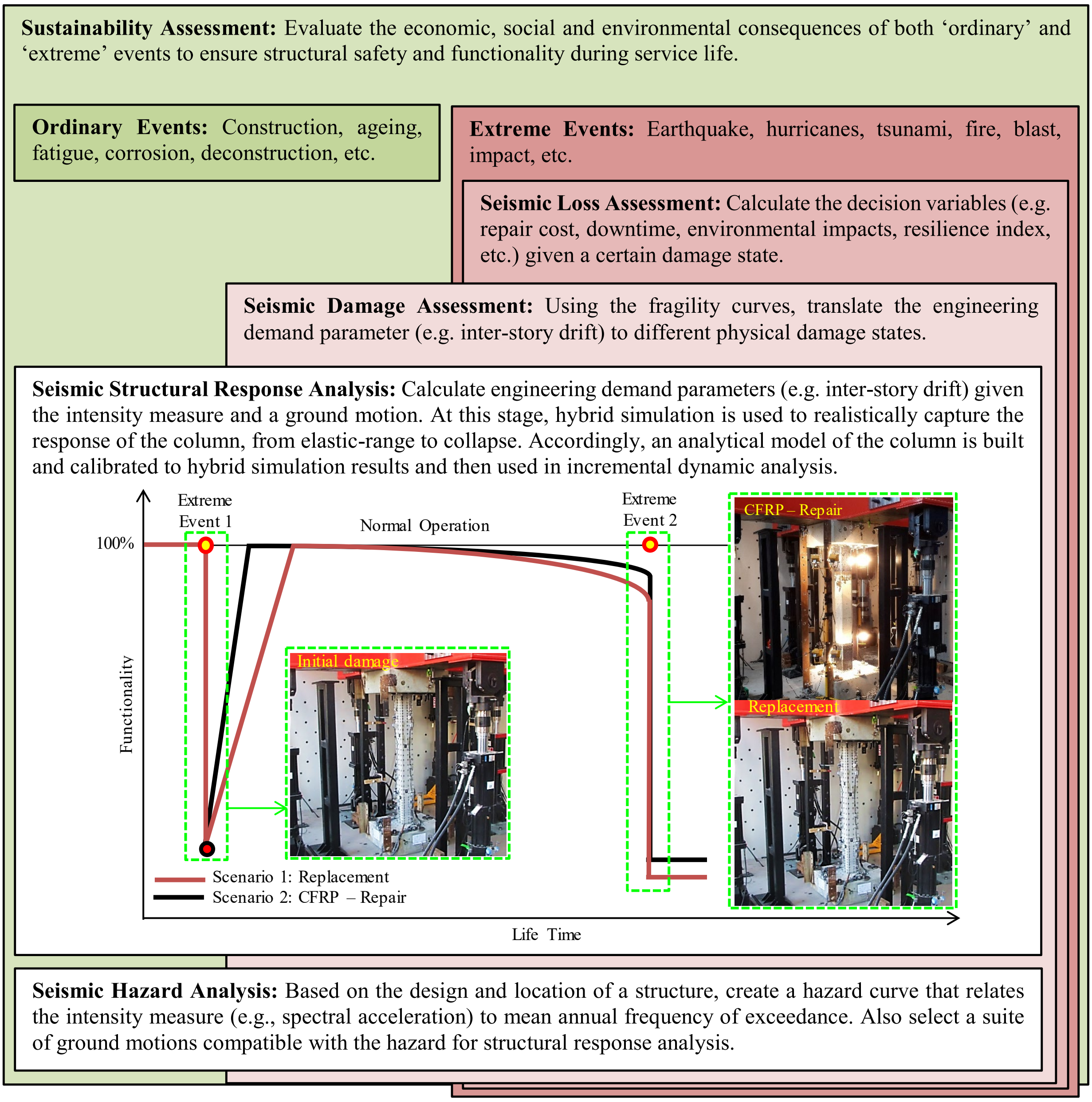


Figure 4. Application of the MAST system for resilience and sustainability assessment (case of earthquake)

CONCLUSIONS

Hybrid testing emerges as a frontier technology and a powerful validation tool in assessing repair and retrofitting techniques using FRP composites for earthquake-damaged reinforced concrete structures. The combination of computational simulation and experimental testing offered by hybrid testing provides a comprehensive understanding of structural behavior under complex loading conditions. This approach enables researchers and engineers to evaluate the effectiveness and performance of FRP repair techniques in enhancing the seismic resilience of buildings and bridges. The advanced capabilities of the hybrid testing facility, such as the 6-DOF hybrid testing system and the Multi-Axis Substructure Testing (MAST) system, offer the means to replicate realistic loading scenarios and assess the structural response accurately. By incorporating physical specimens and numerical models, hybrid testing provides a cost-effective and efficient method for studying the behavior of structures subjected to extreme dynamic forces. Furthermore, the research showcased the suitability of carbon-fiber reinforced polymer (CFRP) as an innovative repair material for earthquake-damaged reinforced concrete structures. The experimental study demonstrated that CFRP wraps effectively restored the load-bearing capacity of a damaged column, resulting in improved structural safety and a reduced probability of collapse.

REFERENCES

Al-Ghrery, K, Al-Mahaidi, R, Kalfat, R, Oukaili, N and Al-Mosawe, A (2021). "Experimental Investigation of Curved-Soffit RC Bridge Girders Strengthened in Flexure Using CFRP Composites." Journal of Bridge Engineering 26(4), doi.org/10.1061/(ASCE)BE.1943-5592.0001691.

Allam, K, Mosallam, A.S, Salama. (2019). Experimental evaluation of seismic performance of interior RC beam-column joints strengthened with FRP composites, Engineering Structures, Volume 196, ISSN 0141-0296.

Al-Kamaki YSS, Al-Mahaidi R. (2015). Bennetts I. Experimental and numerical study of the behaviour of heat-damaged RC circular columns confined with CFRP fabric. Composite Structures 2015;133:679–90.

Al-Mahaidi R, Hashemi J, Kalfat R, et al. (2018) Multi-Axis Substructure Testing System for Hybrid Simulation. Multi-Axis Substructure Testing System for Hybrid Simulation. DOI: 10.1007/978-981-10-5867-7. 1-81.

Al-Mahaidi, R, Kalfat, R. (2018). Rehabilitation of Concrete Structures with Fiber- Reinforced Polymer, Butterworth-Heinemann.

Hashemi MJ, Al-Attraqchi AY, Kalfat R, et al. (2019) Linking seismic resilience into sustainability assessment of limited-ductility RC buildings. Engineering Structures 188: 121-136.

Hashemi MJ, Al-Mahaidi R, Kalfat R, et al. (2015) Development and validation of multi-axis substructure testing system for full-scale experiments. Australian Journal of Structural Engineering 16(4): 302-315.

Hashemi MJ, Al-Ogaidi Y, Al-Mahaidi R, et al. (2017a) Application of Hybrid Simulation for Collapse Assessment of Post-Earthquake CFRP-Repaired RC Columns. Journal of Structural Engineering 143(1).

Hashemi MJ, Masroor A and Mosqueda G (2014) Implementation of online model updating in hybrid simulation. Earthquake Engineering & Structural Dynamics 43(3): 395-412.

Hashemi MJ and Mosqueda G (2014) Innovative substructuring technique for hybrid simulation of multistory buildings through collapse. Earthquake Engineering & Structural Dynamics 43(14): 2059-2074.

Hashemi MJ, Mosqueda G, Lignos DG, et al. (2016) Assessment of Numerical and Experimental Errors in Hybrid Simulation of Framed Structural Systems through Collapse. Journal of Earthquake Engineering 20(6): 885-909.

Hashemi MJ, Tsang HH, Al-Ogaidi Y, et al. (2017b) Collapse Assessment of Reinforced Concrete Building Columns through Multi-Axis Hybrid Simulation. ACI Structural Journal 114(2).

Hii, A.K, Al-Mahaidi, R. (2007). Torsional capacity of CFRP strengthened reinforced concrete beams, J. Compos. Constr. 11 (1) 71–80.

Kalfat, R, Jumaah, R, Al-Mahaidi, R, Abdouka, K, Hashemi, J. (2020). Post-tensioned concrete beams strengthened in shear using fiber-reinforced polymer laminates and patch anchors, J. Compos. Constr. 24 (2) (2020) 04019065, https://doi.org/ 10.1061/(ASCE)CC.1943-5614.0000989.

Karayannis, C.G, Golias, E. (2022). Full-scale experimental testing of RC beam-column joints strengthened using CFRP ropes as external reinforcement, Engineering Structures, Volume 250, ISSN 0141-0296.

Pohoryles, D.A.; Melo, J.; Rossetto, T.; Varum, H.; Bisby, L. (2019). Seismic Retrofit Schemes with FRP for Deficient RC Beam-Column Joints: State-of-the-Art Review. J. Compos. Constr, 23, 03119001.

Wang NY and Ellingwood BR. (2015). Limit state design criteria for FRP strengthening of RC bridge components. Structural Safety, 56: p. 1-8.

Wei, H., Wu, Z. M., Guo, X., and Yi, F. M. (2009). Experimental study on partially deteriorated strength concrete columns confined with CFRP. Engineering Structures, 31(10): p. 2495-2505.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest associated with the work presented in this paper.

DATA AVAILABILITY

Data on which this paper is based is available from the authors upon reasonable request.