COLLAPSE RISK ASSESSMENT OF CFRP-REPAIRED EARTHQUAKE-DAMAGED RC COLUMNS USING HYBRID SIMULATION

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ABSTRACT: *Hybrid simulation combines computer simulations with experimental testing to provide a powerful platform for large-scale experimental investigation of the seismic response of structures through collapse. This paper presents an application of hybrid simulation for tracing the seismic response of a limited-ductility reinforced-concrete (RC) column through collapse and evaluating the capability of carbon-fibre reinforced polymer (CFRP) repair on rehabilitating the damaged column to its initial collapse resistance capacity. A state-of-the-art hybrid testing facility, referred to as the Multi-Axis Substructure Testing (MAST) system, was used to simulate complex time-varying six-degrees-of-freedom (6-DOF) boundary effects on the physical specimens using mixed load/deformation modes. Based on the experimental results, a comparative collapse risk assessment of the initial and repaired column was conducted, which illustrates the effectiveness of using CFRP-repair to restore and improve the collapse resistance of earthquake-damaged RC structures.*

KEYWORDS: Hybrid simulation, Multi-axial loading, Collapse risk assessment, RC structures, CFRP repair

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1. INTRODUCTION

Hybrid simulation combines numerical and experimental methods for cost-effective large-scale testing of structures under simulated earthquake actions. This is an attractive alternative, particularly for experimental seismic collapse simulation of structures due to the limited capacity of most facilities, as well as the costs and risks associated with a collapsing structure on a shaking table. Hybrid simulation is based on splitting a structure into numerical and physical models. Typically, the physical/experimental substructures are critical elements of the structure, which are difficult to model numerically, while analytical/numerical substructures represent structural components with more predictable behaviour. The combination and interactions of the two substructures form a hybrid model of the complete structure [1; 2].

More recent applications of hybrid simulation have focused on large and complex structural systems, in which the highly nonlinear behaviour of critical elements can be realistically modelled. Such experiments are conducted to accurately capture structural collapse and provide realistic data to fully validate and improve analytical tools in collapse studies [3-6].

This paper presents the implementation of two series of hybrid simulations that aims to investigate the suitability and effectiveness of carbon-fibre-reinforced polymer (CFRP) repair to restore the resisting capacity of earthquake-damaged RC structures against sidesway collapse. In the first series, a typical limited-ductile RC column was tested to collapse under bidirectional ground excitations, while in the second series, the damaged column was repaired using CFRP wraps and retested under the same loading conditions.

In order to consider the influence of biaxial bending and the variation in axial loads, a state-of-the-art hybrid testing facility, referred to as the Multi-Axis Substructure Testing (MAST) system, was utilized because of its capability to simulate complex time-varying 6-DOF boundary effects on large-scale structural components using mixed load/deformation modes. Based on the experimental results, a comparative collapse risk assessment of the initial and repaired column is conducted, which illustrates the effectiveness of using CFRP repair for restoring the initial collapse resistance of earthquake-damaged RC structures.

2. HYBRID SIMULATION AND THE MULTI-AXIS SUBSTRUCTURE TESTING SYSTEM

2.1 CONCEPT OF HYBRID SIMULATION

Hybrid simulation is a cyber-physical procedure that combines classical experimental techniques, with online computer simulation and provides a cost-effective platform for large-scale testing of structures under simulated extreme loads. Hybrid simulation was originated as the computer-actuator online system by Takanashi *et al.* [7] or the pseudo-dynamic testing method [1; 2]. During the late 1970s, 1980s, and early 1990s, efforts in Japan and the United States were undertaken to expand the capabilities and validation of the hybrid simulation. A comprehensive review of the hybrid response simulation method is presented by Saouma and Sivaselvan [8]. According to a report developed by the U.S. earthquake engineering community, hybrid simulation capabilities are a major emphasis of the next generation of earthquake engineering research [9].

Hybrid simulation can be viewed as conventional finite element analysis, where physical models of some portions of the structure are embedded in the numerical model. In such a way, the errors related to the simplification of the theoretical modelling of complex nonlinear structures or subassemblies can be effectively mitigated as the elements are tested physically in the lab [10].

This method is based on splitting the structure of interest into two or more substructures and conducting separate analyses on each part, while making sure the interface constraints are continuously verified both in terms of deformation-compatibility and force-equilibrium conditions. The part of the structure that can be reliably modelled numerically, either because they have a simple behaviour or because they are not considered being critical for the analysis conducted, is numerical substructures. The part of most interest that are physically tested, either because they are critical to the safety and performance of the structure or a high degree of nonlinearity is expected, is called the experimental substructure. The combination and interactions of the two substructures form a hybrid model of the complete structure of interest [5; 11].

To illustrate this process for the various types of substructures in hybrid simulation, an example is presented for a multi-story concrete structure. Utilizing the hybrid simulation technique, the first-story corner-column that is typically the critical element can be constructed and physically tested in the lab and the remaining parts of the structure, inertia and damping forces and gravity, dynamic loads and the second order effects can be reliably modelled in the computer (Fig.1).

2.2 MULTI-AXIS SUBSTRUCTURE TESTING (MAST) SYSTEM

Australia's first and only hybrid testing facility [12] is located in the Smart Structures Laboratory at Swinburne University of Technology, Melbourne, Australia. The $15million laboratory is a major three-dimensional testing facility developed for large-scale testing of civil, mechanical, aerospace and mining engineering components and systems and the only one of its type available in Australia. The laboratory includes a 1.0m thick strong floor measuring 20m×8m in-plan with two 5m tall reaction walls meeting at one corner and a suite of hydraulic actuators and universal testing machines varying in capacity from 10tonnes to 500tonnes. The laboratory is serviced by adjacent workshops and a hydraulic pump system located in the basement. The facility is housed in the architecturally striking Advanced Technologies Centre and features transparent walls, allowing passers-by to watch researchers and scientists at work.

The hybrid simulation system at Swinburne consists of several components including software and hardware that allow for hybrid testing in various configurations. Currently, the experimental hybrid procedures include scaled-time hybrid simulation (pseudo-dynamic) with substructuring but can be extended to real-time hybrid simulation and effective force testing methods. An advanced hardware configuration has been set up to ensure a strong coupling and a very high-speed data communication between the servo-controllers and the main computer solving the equation of motion. Hybrid simulation frameworks include:

1. Multi-Axis Substructure Testing (MAST) system for three-dimensional large-scale structural systems and components.
2. 1MN universal testing machine that is suitable for developers and proof-of-concept tests.
3. Generic actuator configuration system for substructure hybrid simulation tests at system level.

The Multi-Axis Substructure Testing (MAST) system at Swinburne University of Technology has been established to provide a state-of-the-art facility for mixed-mode large-scale quasi-static cyclic testing and local/geographically-distributed hybrid simulation experiments (Fig.2). The key components of the 6-DOF testing facility are:

1. Four ±1MN vertical hydraulic actuators and two pairs of ±500kN horizontal actuators in orthogonal directions. Auxiliary actuators are also available for additional loading configurations on the specimen (Fig.3 and Table 1).
2. A 9.5tonne steel crosshead that transfers the 6-DOF forces from the actuators to the specimen. The test area under the crosshead is approximately 3m×3m in-plan and 3.2m high.
3. A reaction system composed of an L-shaped strong-wall (5m tall × 1m thick) and 1m thick strong-floor.
4. An advanced servo-hydraulic control system capable of imposing simultaneous 6-DOF states of deformation and load in switched and mixed mode control. Also, the Center of Rotation (COR) (i.e. the fixed point around which the 6-DOF movements of the control point occurs) can be relocated and/or reoriented by assigning the desired values.
5. An advanced three-loop hybrid simulation architecture including: servo-control loop that contains the MTS FlexTest controller (inner-most loop), the Predictor-Corrector loop running on the xPC-Target real-time digital signal processor (middle-loop) and the Integrator loop running on the xPC-Host (the outer loop).
6. Additional high-precision draw-wire absolute encoders with the resolution of 25microns that can be directly fed back to the controller.

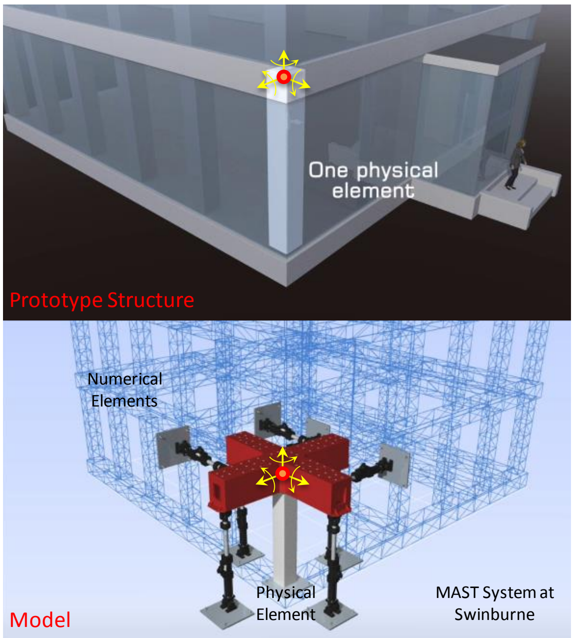


Figure 1: *Hybrid simulation technique*

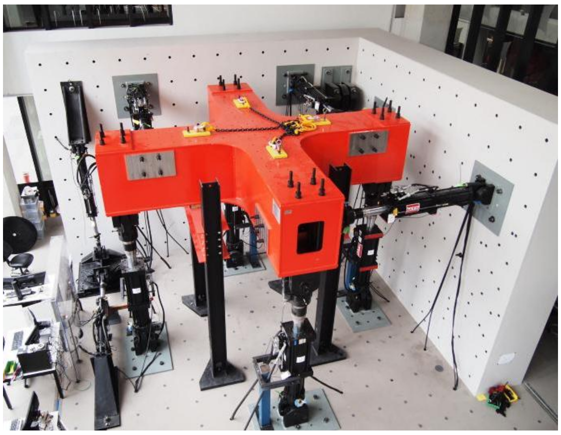
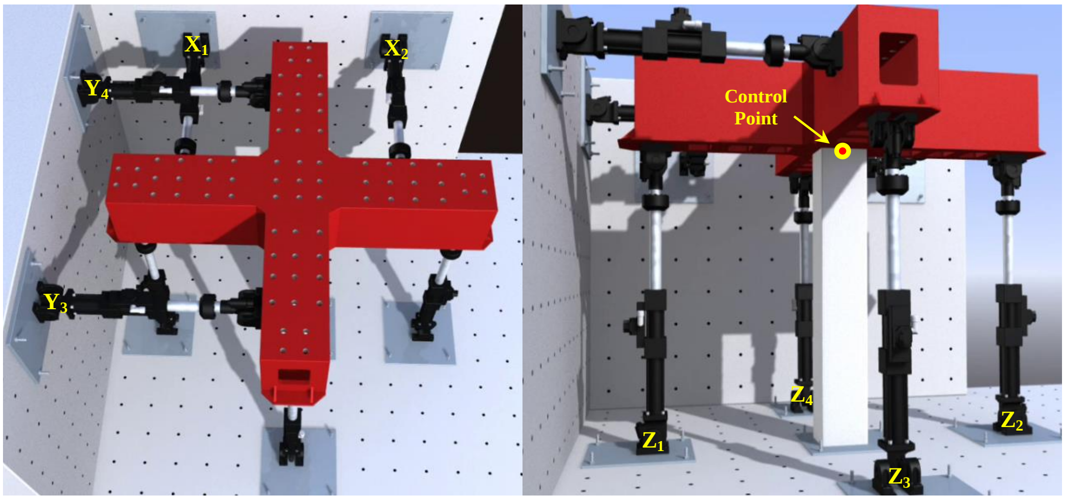


Figure 2: *Multi-Axis Substructure Testing (MAST) system in Smart Structures Laboratory at Swinburne University of Technology*



***a)** Actuator assembly: plan-view* *__b)__ Actuator assembly: side-view*

***Figure 3:** Actuator assemblies in the MAST system*

***Table 1:** MAST system specifications*

MAST Actuators Capacity				
Actuator	Vertical	Horizontal	Auxiliary	
Model	MTS 244.51	MTS 244.41	2 (MN)	(Qty. 1)
Quantity	4 (Z_1, Z_2, Z_3, Z_4)	4 (X_1, X_2, Y_3, Y_4)	250 (kN)	(Qty. 4)
Force Stall Capacity	± 1,000 (kN)	± 500 (kN)	100 (kN)	(Qty. 3)
Static	± 250 (mm)	± 250 (mm)	25 (kN)	(Qty. 3)
Servo-valve flow	114 (lpm)	57 (lpm)	10 (kN)	(Qty. 1)
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)		

3. SEISMIC ASSESSMENT OF CFRP-REPAIRED RC COLUMN

Strengthening of existing reinforced concrete (RC) structures can be necessary in order to increase the capacity of structural elements to sustain higher load levels or to reinstate the strength of damaged members. Structural members may be damaged through long-term environmental degradation, overloading, blast, impact and exposure to natural hazards such as: fire, flood or earthquake. In particular, earthquakes are a source of extensive damage to existing infrastructure and especially older structures that lack sufficient reinforcement detailing to ensure adequate ductility and internal steel stirrups in beam-column joints. The identification and strengthening of seismically vulnerable elements is necessary to avoid the potential collapse of structures in an earthquake, which could result in significant human and economic loss. Research on the repair and strengthening of beam-column joints has consisted of epoxy repair, removal and replacement, reinforced or pre-stressed concrete jacketing, concrete masonry unit jacketing or partial masonry infills, steel jacketing and/or addition of external steel elements, and fiber-reinforced polymer (FRP) composite applications [13]. New materials such as FRP have been increasingly used to strengthen and rehabilitate existing RC structures to improve or reinstate their respective capacities. FRP's have significant advantages over traditional strengthening materials due to their light weight, resistance to corrosion, high tensile strength, durability and ease of application. The shear failure of beam-column joints has been noted as the most common cause for collapse of buildings subjected to seismic excitations and the majority of research into seismic rehabilitation using FRP has focussed on increasing the shear resistance of beam-column joints by the use of various FRP wrapping schemes. Several research studies have demonstrated the effectiveness of FRP in improving the seismic behaviour of damaged RC beam-column joints [14-17]. The use of FRP has been found to eliminate some of the problems with other strengthening methods such as increases in member sizes, difficulty of construction and high cost. The outcomes of research on FRP strengthened beam-column joints indicate substantial enhancements due to FRP in terms of strength, ductility, and energy dissipation [18]. However, the majority of tests focused on strengthening undamaged joints and were loaded using unidirectional pseudo-static configurations and did not account for bidirectional horizontal loads and moments at the joints. The experimental study presented here investigates the seismic performance of a previously-damaged column that was repaired using carbon-fibre reinforced polymer (CFRP).

3.1 EXPERIMENTAL TEST PROGRAM

A single RC column was designed to simulate a corner column in an RC ordinary multi-story moment resistant frame (OMRF). The column was constructed as half scale and had a cross-section of 250mm×250mm and a height of 2.5m. The longitudinal column reinforcement consisted of four normal ductility 16-mm diameter bars with a yield strength of 634 MPa. These bars were lapped over a length of 800mm just above the bottom of the joint to represent typical construction practices. The column contained transverse reinforcement throughout the entire column length consisting of R6 closed stirrups at 175mm spacing with a yield strength of 430 MPa. The stirrups were anchored using 135° bent hooks with a development length of 75 mm. The column was cast using a single batch of ready mixed concrete and cured for a total of 28 days prior to testing of the specimen. The mean concrete compressive strength (fcm) was found to be 39 MPa and was obtained from tests on six 100mm diameter cylinders constructed and tested according to AS 1012.1:2014. All cylinders were cast at the same time and cured together with the column.

The column was tested using a pseudo-dynamic testing technique also known by hybrid simulation to failure using the Imperial Valley 10/15/79 2316, EL CENTRO ground acceleration records. The effect of multi-dimensional earthquake excitation in the two horizontal orthogonal directions was imposed through using the Multi-Axis Substructure Testing (MAST) system by providing 6-DOF states of force or deformation

3.2 REPAIR METHODOLOGY OF DAMAGED COLUMN

The damaged column contained localized zones of spalled and fractured concrete, horizontal and inclined cracking and bent longitudinal reinforcement at each end of the column. The repair methodology involved:

(1) removal of all spalled and fractured concrete.

(2) crack injection of any cracks greater than 0.3mm.

(3) reinstatement of damaged concrete with a suitable repair mortar.

(4) wrapping of the column with FRP.

Replacement of the damaged (i.e. yielded, buckled or fractured) rebars was not included in the repairing process. Visual inspection and light tapping using a rubber hammer was used to identify and remove fractured concrete. Cracks that required injection were identified and labelled. Epoxy injection ports were drilled into the concrete directly over the crack and bonded to the surface with epoxy resin. The surface of the crack was sealed and the injection carried out using Sikadur® 52 high-strength adhesive. After hardening of the Sikadur 52, the injection ports were cut and a repair mortar was used to replace the damaged concrete. BASF MasterEmaco® S 5300 which is a polymer modified structural repair mortar was used for this purpose. The average compressive strength of the repair mortar at the test date was based on the results of three 50×50mm cubes was 41.9 MPa. The mortar was tested in accordance with ASTM C109.

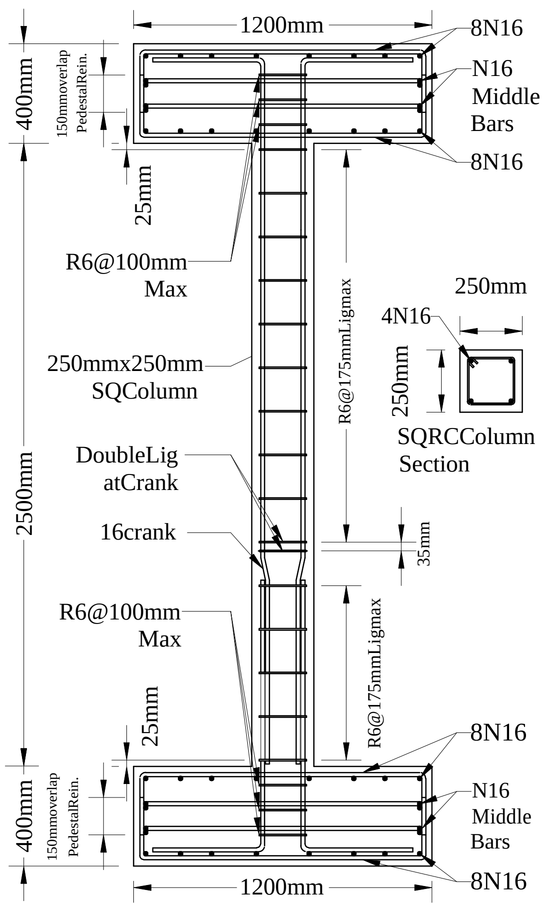


Figure 4: *Design details of the specimen*

The CFRP wrapping was applied over a 600mm 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 MBrace CF130 unidirectional carbon fibre sheet. The CFRP was expected to provide a passive confinement pressure, thereby increasing the compressive strength of concrete with applied load. Furthermore, the orientation of the fibres was parallel to the existing steel stirrups and was expected to significantly increase the shear capacity at the column ends. The total increase in axial and shear capacity of the column as a result of the FRP was estimated as 35% and 250% respectively when calculated in accordance with ACI440.2R-08.

A summary of the material properties of the FRP and adhesives used in the repair are summarized in Tables 2 and 3. Prior to application of the FRP to the concrete surface, the corners of the column were rounded to achieve a minimum radius of 25mm. A mechanical abrasion technique was used to remove the weak layer of cement laitance adhering to the surface of the concrete and achieve a surface roughness similar to 60grit sandpaper. The surface was cleaned to remove any dust prior to application of the FRP. The FRP was applied using a wet-lay-up technique where each layer was thoroughly impregnated with resin prior to application to the column. The retrofitting was performed while the column was still under the MAST system and subjected and supporting an axial load corresponding to 130kN. The CFRP was cured at 50°C for 7 days using heat lamps prior to testing.

Table 2: *Summary of FRP material properties*

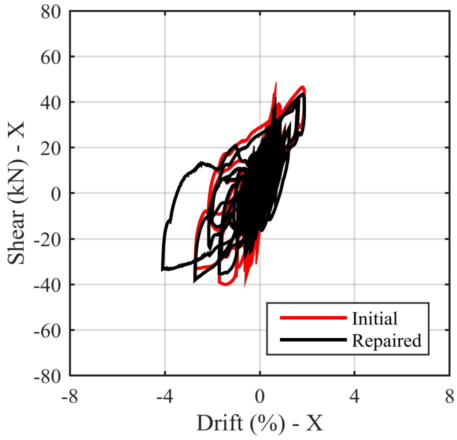
Properties	MBrace CF230	Units
Tensile Strength	4900	MPa
Tensile Modulus	230	GPa
Ult. Elongation	2.1	%
Thickness	0.227	mm

Table 3: *Summary of saturant and primer material properties*

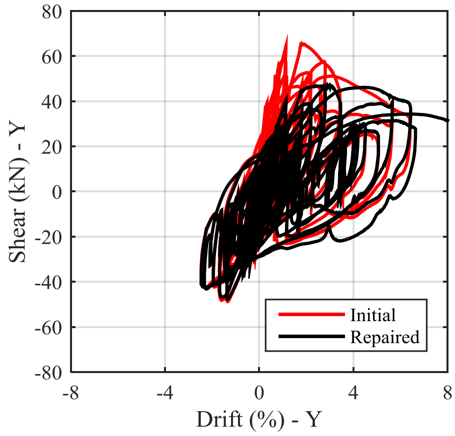
Properties	Saturant	Primer	Units
Resin Type	Epoxy	Epoxy	-
Specific Gravity	1.12	1.08	-
Modulus of Elasticity	>3.0	0.7	GPa
Tensile Strength	>40	>12	MPa
Compressive Strength	>80	-	MPa

3.3 HYBRID SIMULATION WITH THE CFRP-REPAIRED COLUMN

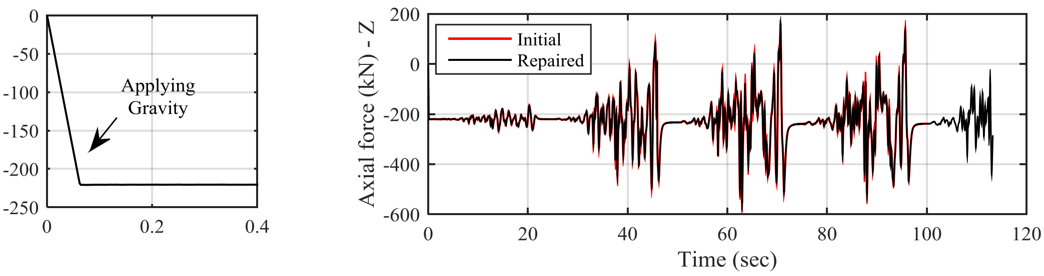
The repaired column was tested as the first-story corner-column of the undamaged RC building experiencing the same loading conditions as the previous hybrid test with the initial column. This allows studying the seismic behaviour of the repaired column as if it is used as a new undamaged RC column and hence provides a fair comparison between the hysteretic response of the initial and repaired columns. The intensity levels in hybrid simulation included the same previous four scale factors of 0.6, 4.0, 8.0, 9.0, as well as an additional scale factor of 10.0, in order to push the structure to ~0.25% (elastic), 2.0%, 4%, 6% and 8% maximum inter-story drift ratio, respectively. Hybrid simulation was completed with no rupture observed in the CFRP sheets. A detailed comparison of hybrid simulation test results for the initial and repaired column is presented in Fig.5. The results include the hysteretic response in X and Y axes and the axial force time history in Z-axis. Fig.6(a) shows a closer view of the hysteretic response of the initial and repaired columns in Y axis, along which the column experienced maximum deformation. Two main significant changes can be observed in the behaviour of the repaired column: 1) the CFRP repair was not able to restore the flexural strength of the initial column, as the maximum resisting force was 32% less in the repaired column. This is mainly due to the fact that the repair process did not include replacement of the yielded, buckled or ruptured rebars, and as a result the loss of strength could not be fully compensated. 2) the repaired column showed significant improvement in ductility due to the confinement effects of the CFRP wraps. As observed in Fig.6(a), the hardening branch of the plastic deformation response of the repaired column is extended to much larger drifts compared to the initial column. Specifically, while applying the maximum compressive axial load on the initial column (552.6kN = 23.35% ultimate capacity), a rapid drop occurred immediately after reaching the peak resisting force. However, the repaired column remained in the hardening region while being subjected to the same level of axial load. This is also evident by comparisons of other corresponding cycles from the two experiments. For instance, Fig. 6(b) shows, respectively, the capping-points ‘A’ and ‘B’ for the initial and repaired column from the same corresponding cycles. The initial column shows stiffness hardening up to 3% drift (point ‘A’), while this value has been extended to 4.5% drift (point ‘B’) for the repaired column. In addition, by comparing the behaviour of the RC columns after point ‘C’, which is located on the same corresponding cycle and at the same level of drift, it is observed that the initial column entered the post-capping negative stiffness region, while the repaired column was still in the stiffness hardening region.



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

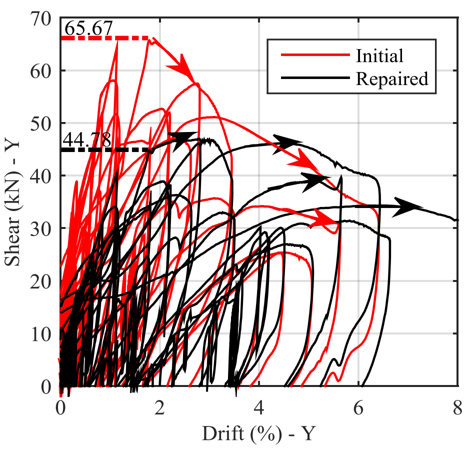


(b) *Comparison of lateral force-deformation – Y axis*

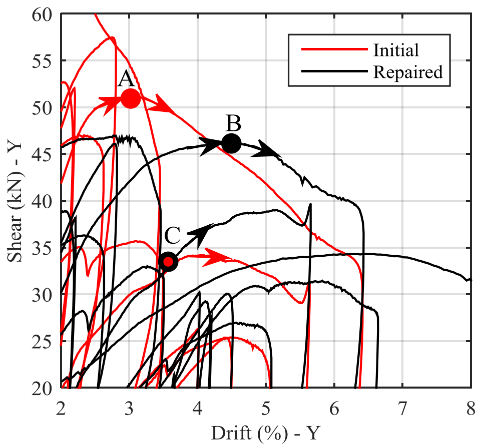


(c) *Comparison of axial load – Z axis*

Figure 5: *Comparison of hybrid simulation test results between initial and repaired RC column*



(a) *Close view 1*



(b) *Close view 2*

Figure 6: *Comparison of the hysteretic response of the initial and repaired column in Y axis*

4. COMPARATIVE COLLAPSE RISK ASSESSMENT

While the CFRP repair significantly improved the ductility of the damaged RC column, it was not able to fully compensate the loss of strength. In order to investigate the influence of these changes on the collapse resistance of the repaired column, a comparative collapse fragility analysis was performed using the results of the two hybrid simulation experiments.

Probabilistic collapse assessment of the initial and repaired column was conducted using incremental dynamic analysis [19]. The numerical model selected for this purpose includes only the first-story corner-column and the overhead mass portion of the upper 5 floors, which is equivalent to a single-degree-of-freedom (SDOF) system. This allows the study of the response of the column, purely based on experimental results. The hybrid test results were used to calibrate the SDOF numerical model.

Incremental dynamic analyses (IDA) were performed using the calibrated numerical models in order to capture a range of probable dynamic response behaviours due to record-to-record variability in ground motion characteristics. For this purpose, three earthquake scenarios including M6.0R28, M6.5R40 and M7.0R90 (M and R stand for magnitude and source-site distance, respectively) were considered. A suite of 20 recorded ground motions was selected from the PEER database [20].

Each unidirectional ground motion was individually applied to the calibrated SDOF models. The ground motions were increasingly scaled according to the value of spectral acceleration at the fundamental natural period of the SDOF numerical model ($S_a(T_1)$ and T_1=0.6sec for the SDOF model) until the collapse state of the building was reached. The simulation was based on 5% mass-proportional damping and restricted to sidesway-only collapse with a drift limit of 7%, based on the experimental results. The outcome of this assessment is a structural collapse fragility function for the initial and repaired column respectively, which is a lognormal distribution relating the structure's probability of collapse to the ground-motion intensity, in terms of $S_a(0.6)$.

Fig. 7 presents the fragility curves for the initial and repaired RC column.

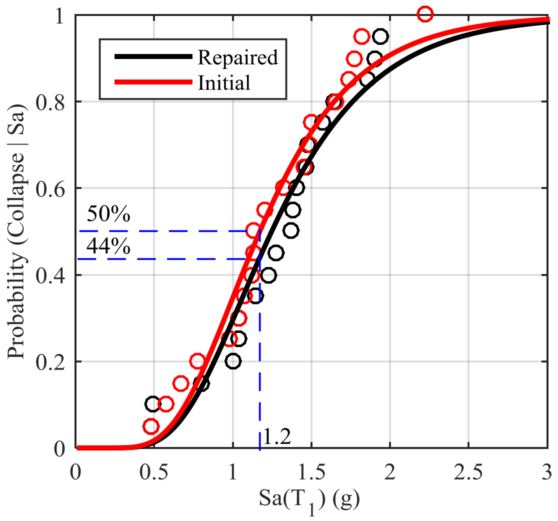


Figure 7: *Comparison of fragility curves for the initial and repaired RC columns*

It is observed that at an intensity level (S_a) of 1.2g, the probability of collapse for the initial columns is 50%, while this value for the repaired column is 44%. This shows that CFRP repair can effectively restore the capacity of the column and slightly improve the resistance of the column against sidesway collapse.

5. CONCLUSIONS

This paper reports the use of hybrid simulation to assist the evaluation of the effectiveness of CFRP repair on restoring the resistance capacity of earthquake-damaged RC structures against collapse. For this purpose, a limited-ductile RC column was tested using a three-dimensional hybrid simulation with a focus on flexural failure and sidesway-only collapse. The specimen was then repaired using CFRP wraps and retested under the same loading conditions. A state-of-the-art loading system, referred to as the Multi-Axis Substructure Testing (MAST) system that is capable of controlling all 6-DOF boundary conditions in mixed load and deformation modes, was used for the hybrid simulations. From the comparison of experimental results, significant enhancement of ductility was observed for the repaired column, while the strength was not fully recovered as the yielded, buckled or ruptured rebars of the damaged column were not replaced in the repair process. A comparative collapse risk assessment of the initial and repaired RC columns was performed using SDOF numerical models calibrated to the experimental results. The fragility curves obtained from these simulations show that the collapse risk of the CFRP-repaired column is slightly lower than that of the initial column.

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