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Seismic Resistance Evaluation of Reinforced Concrete (RC) Exterior Beam-Column Joints with and without GFRP under Quasi-static Lateral Cyclic Loading by Adopting Experimental Analysis

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ABSTRACT

The beam-column joint is an important component of Reinforced Concrete (RC) structures because its design and detailing are critical to the safety of these structures under seismic loading. In recent decades, structural behaviour of beam-column joints has been widely explored. To better understand the behaviour of beam-column joints, researchers have conducted experiments and provided analytical and experimental solutions. The seismic behaviour of beam-column joints with and without Glass Fibre Reinforced Polymer (GFRP) when subjected to quasi-static lateral cyclic loading was compared in this research using two specimens. The first specimen is a typical RC exterior beam-column joint without GFRP while the second specimen is RC exterior beam-column joint that is pre-installed with Glass Fibre Reinforced Polymer (GFRP) using Near-Surface Mounted (NSM) technique. The specimens were evaluated to a drift of 2.0% under quasi-static lateral cyclic loading. There were two cycles in each drift. Based on the amplitudes of both specimens, it can be seen that the amplitude of beam-column joint with GFRP is lower than the beam-column joint without GFRP. This suggests that the presence of GFRP reduces the intensity of the loading. This study also discusses the energy dissipation and equivalent viscous damping on both specimens. During the experiment, each crack, void between the concrete, and spalling of concrete fragments were carefully monitored. Visual observation during the experiment shows that severe cracking is evident on the inner part of the structure in both specimens. Therefore, a new location of GFRP-NSM would be suggested for a future experiment.

Keywords: RC Exterior Beam-column joint; Quasi-static lateral cyclic loading; Glass-Fibre Reinforced Polymer (GFRP); Near-Surface Mounted (NSM); Amplitude; Energy dissipation; Equivalent viscous damping

INTRODUCTION

Recent developments in seismic activity have highlighted the consequences of poor performance of beam-column joints. This has been identified as the main reason for frame breakage under seismic loads. The beam-column joints must be able to resist and sustain the load transmitted from the beams and columns with sufficient hardness and strength. Southeast Asian regions such as Thailand, Singapore and Malaysia are also usually considered safe against seismic disasters, the research on this issue has already received more attention (Li et al. 2002 and 2004; Warnichai 2004).

Generally, Malaysia is known as a safe country because it is located outside the Pacific Ring of Fire, but it is not a guarantee that the country does not affect by it. With the location of Malaysia close to the most two seismically active plate boundaries and two earthquake active countries, namely Indonesia and the Philippines, directly caused the country to feel low magnitude vibration when strong scale earthquakes hit both neighbouring countries.

According to the Malaysian Meteorological Department, the earthquake occurred in Ranau, Sabah, Malaysia, on 5th June 2015, with a magnitude of 6.0 on the Richter scale, lasted for 30 seconds. The earthquake was the strongest to hit Malaysia since 1976. The hostel and rest house near the top of Mount Kinabalu was severely damaged. Buildings in Kota Belud and Tuaran were also affected by the earthquake. In the Kundasang and Ranau areas, water supply was disturbed when the most water pipeline broke, and a few plants in both locales were damaged by a spill within the sedimentation tank.

According to Balendra et al. (1999), most of the existing buildings in Malaysia have been designed using the British standard BS 8110 which does not consider the factors or effects of earthquakes in its code provisions. Resident's safety is an important indication in structural building design, therefore analysis of buildings like a hospital in earthquake situations needs to be handled. This is to prevent the important buildings from being badly damaged when an earthquake suddenly occurred in Malaysia. Existing and future buildings in Malaysia must have a structural performance that can be used to evaluate the building's ability to withstand an aftershock.

Several procedures have been employed to repair and increase the structural capability of reinforced concrete frame connections throughout the last few decades. Retrofitting small part of existing structures may offer a workable solution since demolishing and reconstructing RC buildings are expensive. Retrofitting with fibre-reinforced polymer (FRP) materials is a well-known and cost-effective repair approach that is now commonly employed as a seismic retrofitting method throughout the world. There are many available FRP in the market such as Carbon FRP, Glass FRP, Aramid FRP and Basalt FRP.

Among composite materials, carbon fibre FRP (CFRP) has historically been a suitable solution for prestressed concrete applications. Nevertheless, the high cost of carbon fibre, along with some technical drawbacks, can hinder widespread use of this technique. Fibre-glass is an economical alternative to carbon fibre for applications that do not require a high level of concrete precompression. By limiting the initial prestress, you can overcome the design feasibility issues identified with CFRP tendons. On the other hand, when the cost of glass is reduced, it becomes a competitive and durable alternative to standard steel strands. (Rossini et al. 2018). GFRP has been chosen in this experiment because when used in composite materials, it is much cheaper and significantly less brittle. This material is a denser, much weaker insulation than glass wool, with little or no air or gas. (Fitzer et al. 2000).

The use of NSM-FRP is increasing primarily due to the high strength and rigidity of composites, non-corrosiveness, and ease of installation (Truong et al. 2017). According to Prota et al. (2002), the combination of FRP laminate and NSM rod can be used to increase the strength of the subassembly and achieve a more desirable failure mode from a global perspective. In addition to a sufficiently detailed control sample, an experimental program conducted by Mahmoud et al. (2013) consists of examining 10 half-scale samples divided into 3 groups covering 3 possible failures. The outcomes of the third group showed that when the joint is strengthened with NSM strip technology, the sample can exceed the structural performance of the control sample, while the joint which has been strengthened with externally bonded FRP strips and plates showed that it did not match the capacity of the reinforced joint. An experiment to compare the strengthening techniques of NSM and externally-bonded FRP is also conducted by Akash and Jayasree (2018). The results of their experimental work showed that the NSM retrofitted specimens with the orientation of 30^o have significantly enhanced the strength, ductility, energy absorption and stiffness degradation of the tested specimens.

The same objective is also been adapted by Wang et al. (2019). They carried out an experimental study on six specimens including one non-seismically designed specimen, one seismic sample and four modified samples using both externally bonded FRP panels and near-surface (NSM) FRP strips as reinforcement options. Test results show that the use of NSM-FRP strips for beams and joints effectively moves the plastic hinges from the joints, resulting in ductile fracture mode (beam bending fracture), and this modified seismic method is effective.

NSM-FRP technology does not require extensive surface treatment work and usually does not require the use of primers and putties, resulting in minimal installation

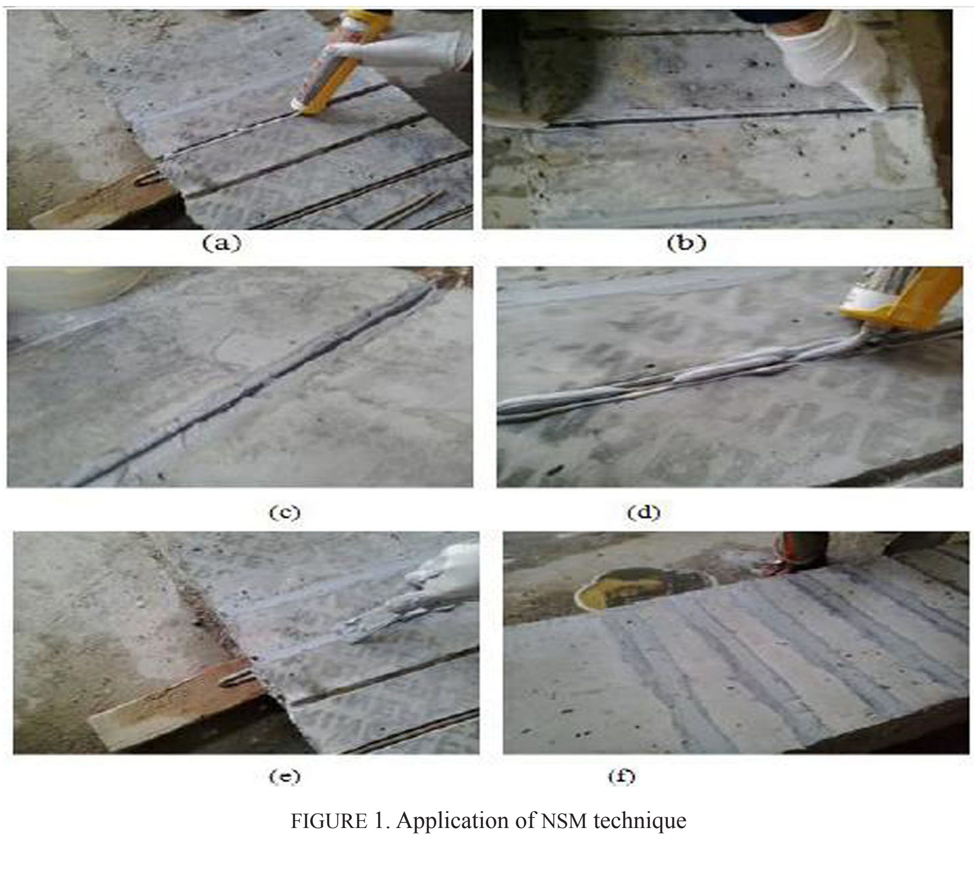


FIGURE 1. Application of NSM technique

time after grooving compared to externally bonded FRP laminates. Figure 1 show the application of the NSM technique from experimental work by Anis Mohamad Ali et al. (2015). The grooves were made using a Hilti diamond saw cutter machine on both sides of specimens with different spacing and different inclination. The grooves were cleaned with water under pressure and the slits were cleaned with compressed air. The epoxy pastes of type Sikadur-30 were then made by using a power mixer to mix the two components (resin and hardener) in a 3:1 volume proportion. The groove was half-filled with paste, then the FRP rod was placed in it and lightly squeezed. This caused the paste to flow around the FRP bar and entirely fill the space between the FRP bar and the groove's sidewalls. The groove was then refilled with paste and the surface smoothed.

EXPERIMENTAL SET-UP

SETTING UP AND LOADING REGIMEN

Two full-scale of RC exterior beam-column joints were designed, constructed and tested in the heavy structural laboratory. The substructure of the test specimens consists of a column with two beams designed in accordance with British Standard BS8110. The test specimens were cast using concrete with a compressive strength of 30 N/mm2. The first specimen is a typical exterior beam-column joint marked as a BCJ without GFRP while the second specimen is an exterior beam-column joint that is pre-installed with Glass Fiber Reinforced Polymer (GFRP) installed using Near-Surface Mounted (NSM) technique. It will be marked as BCJ with GFRP.

Figure 2 shows the set-up of experimental work on the beam-column joint with GFRP. Figure 1(a) shows the epoxy used to install GFRP to the specimen. Figure 1(b) shows the tools that were manually built using plywood to ensure application of 1mm depth of epoxy on GFRP and figure 1(c) shows the location of GFRP installed on the specimen using the NSM technique. Note that during the set-up of the experiment on the beam-column joint with GFRP, there was a malfunction on the machine (the machine keeps on running and fail to stop during adjustment of actuator at the very beginning of the experiment) which causes cracks on the specimen. Therefore, there might be errors in the outcoming results.

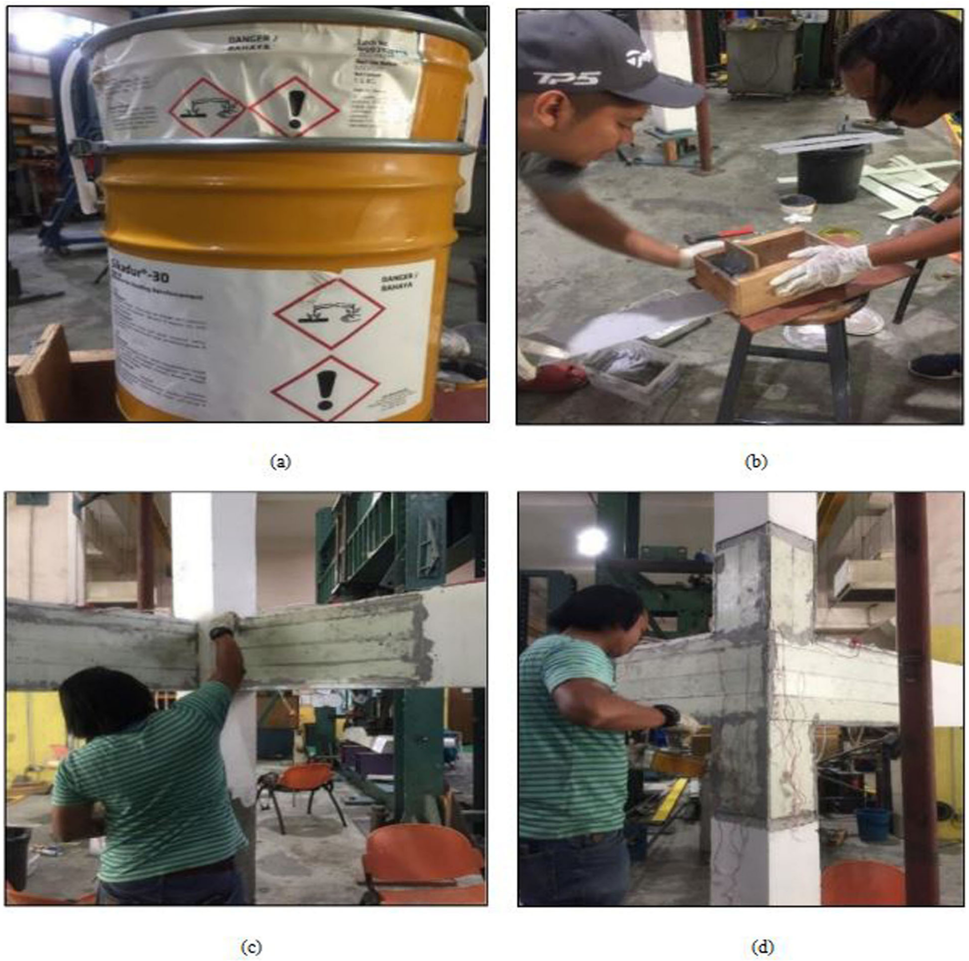


FIGURE 2. Set-up of experimental work on the specimen - BCJ with GFRP

Figure 3 shows side elevation A and B of the substructure and the location of twenty-eight (28) strain gauges that were attached to the rebars for both specimens. The cross-section of the column is 225mm x 225mm with 3m height, while Beam One and Beam Two are 400mm x 150mm with 2.25m length from the center of the column.

The specimen stands on strong ground, the column and beams being clamped on the strong ground. The free ends of the beams were designed as counter-bending points for the beams and the column within the test setup. Finally, eight (8) LVDTs were installed in particular locations on both specimens, as illustrated in the schematic drawing CAD in Figure 4.

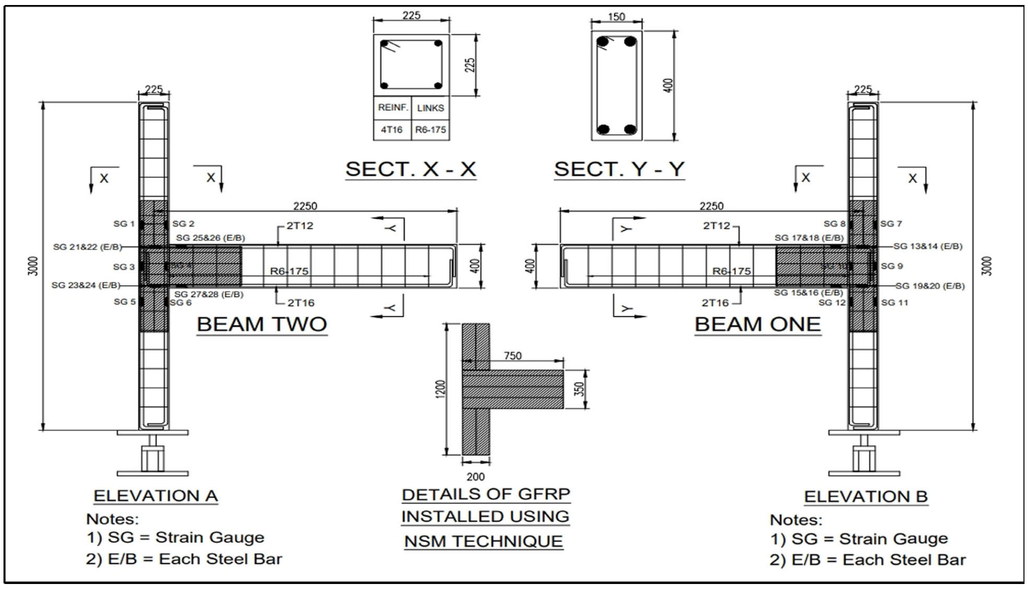


FIGURE 3. Side elevation A and B of the substructure and location of 28 strain gauges. (All measurements are in mm)

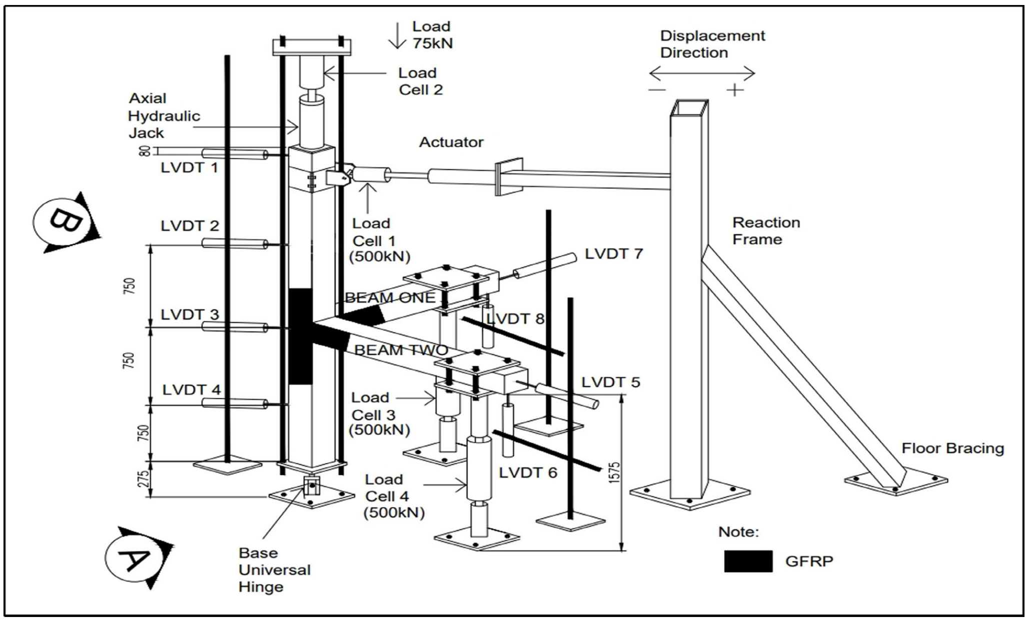
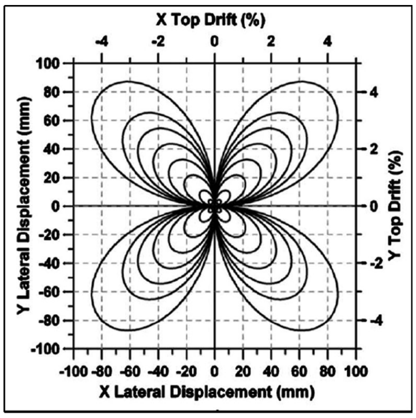


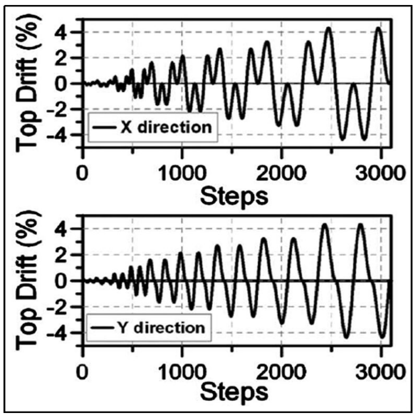
FIGURE 4. Schematic drawing CAD of the experimental set-up with the location of eight (8) LVDTs

Under quasi-static, reversible, cyclic lateral loading, the substructure of beam-column joints was investigated. The response frame was fitted with a double actuator and a 500kN load cell. The goal displacement is regulated in the form of percentage drift in this test, which is known as the displacement control method. The drift is calculated by multiplying the lateral displacement by one hundred percent of the column height. In this study, twelve (12) sets of historical drifts of 0.01%, 0.10%, 0.15%, 0.20%, 0.25%, 0.50%, 0.75%, 1.00%, 1.25%, 1.50%, 1.75%, and 2.00% were applied to the top of the column.

The loading scheme used in this experiment is shown in Figure 5. Two cycles were performed for each drift level. The sample was loaded to drift. The damages to the specimen were visually observed and recorded.



(a) Loading pattern



(b) Displacement components

FIGURE 5. Loading regimen applied in this experiment (Akguzel and Pampanin, 2010)

According to Akguzel and Pampanin (2010), the 2D loading protocol was extended to the 3D dimensions by choosing a cloverleaf-shaped loading path in the 3D configuration tests. At each chosen drift level, a complete cycle of the cloverleaf shape was circumscribed. During each complete cloverleaf cycle, the 3D specimens were subjected to a total of two deflections in the positive and negative directions in the x-axis and y-axis. However, in this experiment, only one actuator is used, which is located at the edge of the outer side of the column, which means it is in the middle of the x-axis and the y-axis direction. Therefore, in this experiment, it is assumed that there would be a combination of the loading pattern and the displacement components of the x-axis and y-axis.

VISUAL OBSERVATION DURING THE EXPERIMENT

DAMAGES OCCURRED DUE TO MACHINE MALFUNCTION

During the experimental work on BCJ with GFRP specimen, there is an error occurred due to a malfunction on the machine (the machine keeps on running and fail to stop during the process to adjust the set-up of actuator at the very beginning of the experiment) which causes cracks on the specimen. Within the inelastic region, major cracks occurred at ±0.10% drift, leading to a fracture of a thin layer of gypsum covering the GFRP as shown in Figure 6.

FIGURE 6. Exposure of GFRP sheet and cracks occurred on the specimen due to machine malfunction before the experiment of BCJ with GFRP

BCJ WITHOUT GFRP

With repeated cycles, the sample response remained elastic from 0.01% to 0.5% drifts. During the experimental work, hairline cracks on the inside of the beam-column joint were discovered at 0.5% drift. Larger cracks appeared in the inelastic range with drifts of 0.75% and 1.0%. Shear cracks appear on the face of the column as a result of the loading and unloading of the actuator.

Figure 7 displays the visual observation of the BCJ without GFRP throughout the experimental work. Figure 7(a) shows crack at ±1.25% drift. More significant cracking and damage occurred at 1.5% drift as shown in Figure 7(b), leading to concrete spalling along the face of the column, which meets with the lower part of Beam One. Major spalling occurred as shown in figure 7(c) at the same place after a 1.75% drift, exposing the rebar. At 2.0% drift, the experiment's final drift, more significant cracking was detected. The scenario resembled that of a weak column supported by a strong beam. The damage was caused by a lack of rebar in the column and poor detailing of the beam-column joint. The capacity design technique, according to seismic design philosophy, advises that the structure should have strong columns and weak beams in order to have good ductility and a favourable collapse process (Swamy et al. 2015). The structural steel members within the column were not capable of handling a bigger strain, particularly a lateral force from an earthquake, due to their wide spacing of 159 mm centre to centre which is shown in Figure 8. Despite the fact that the BS8110 minimum reinforcing percentage (0.4%) was met, this joint is not designed to withstand lateral loads.

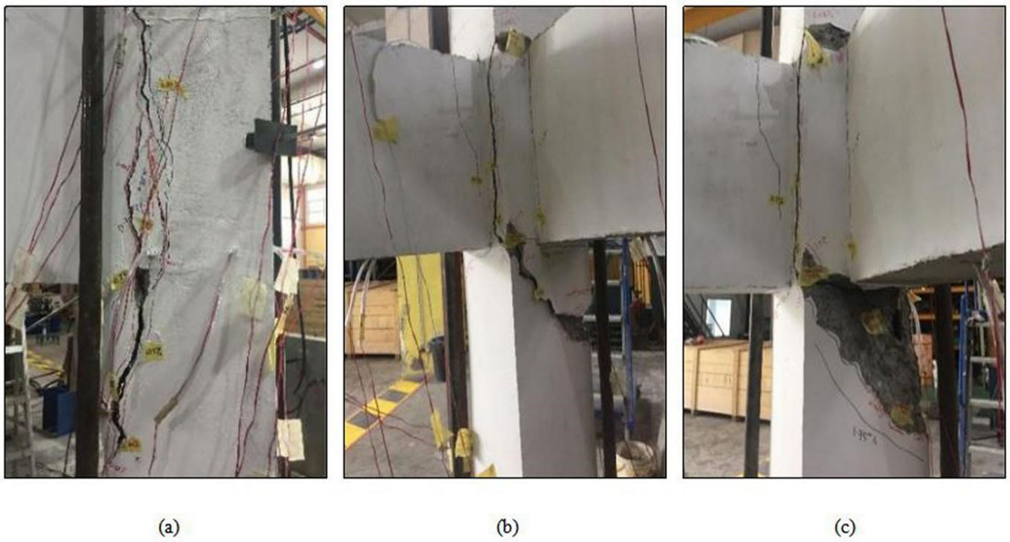


FIGURE 7. Visual observation during the experimental work of BCJ without GFRP

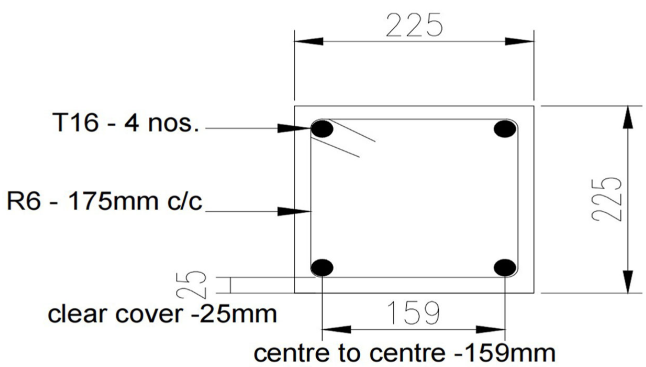


FIGURE 8. Detailing of column reinforcements

BCJ WITH GFRP

Figure 9 exhibits the visual observation of BCJ with GFRP during the experimental work. During the experiment, at a drift of ±0.50%, cracks formed in the upper part of Beam One and Beam Two around the junction area. At a drift of ±0.75%, the GFRP at the edge of the column started to de-bonding causing a void of approximately one inch as shown in Figure 9(a). Figure 9(b) shows cracks formed at the bottom of the intersection of Beam One, and concrete spalling also occurred at the face of the column at the intersection of the column and upper part of Beam One at ±1.25% drifts. At a drift of ±1.50%, a larger void formed, approximately half an inch in size, at the location where the previous de-bonded GFRP. More significant cracking and damage occurred at 1.75% and 2.00% drifts as shown in Figure 9(c), resulting in concrete spalling at the inner area of the joint.

RESULTS AND DISCUSSION

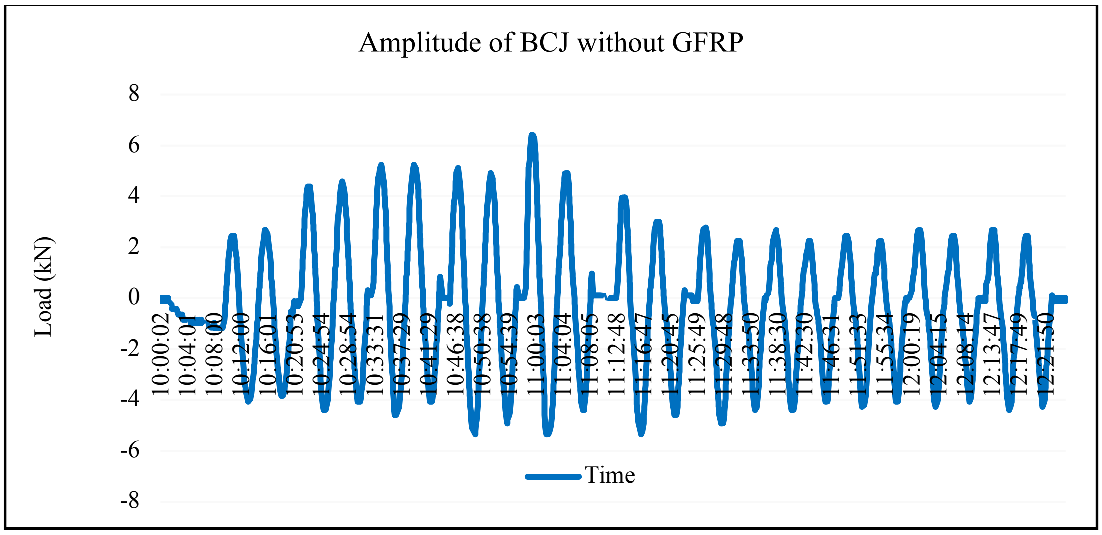
There are three parameters that will be discussed in this paper, which are amplitude, energy dissipation, and equivalent viscous damping.

AMPLITUDE

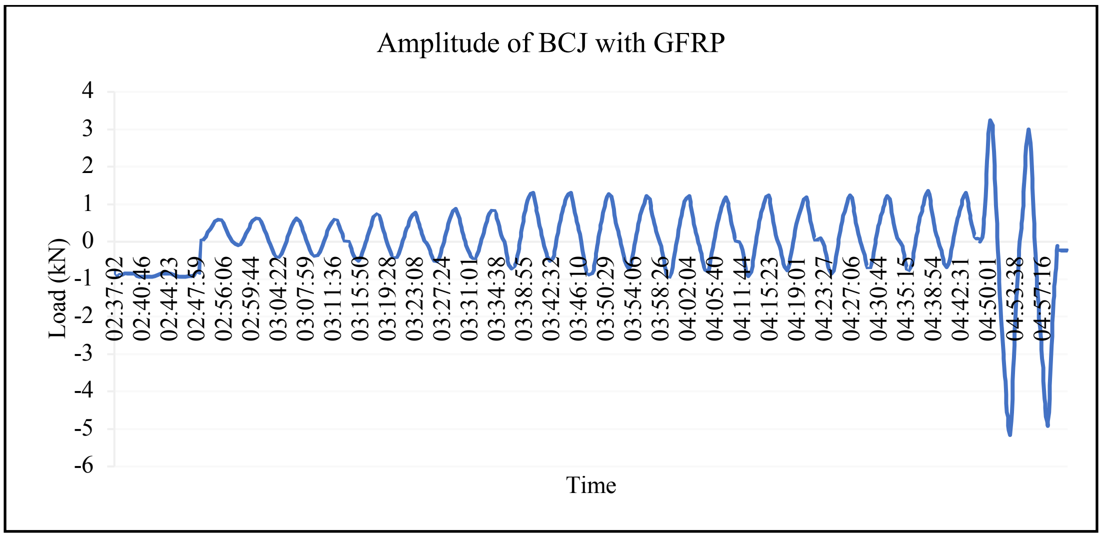
Amplitude is the key to all seismic interpretation objectives other than structure. During the tests, the local deformations of the connection plate zone and the strain values in the steel reinforcement were measured. The maximum amplitude value and frequency component have been regarded as the most important indicators of seismic engineering among the various indicators of seismic motion. (Shoji et al. 2004). The graphs of amplitudes for beam-column joints with and without GFRP are shown in Figures 10(a) and 10(b). The load value for the BCJ without GFRP for the first cycle in the positive (compressive) direction is highest at 0.75% drift with a value of 6.4kN, while the lowest value for the negative (tensile) direction is -5.34kN. For the load value of the BCJ with GFRP, the first cycle in the positive (compressive) direction is highest at ±2.00% drift with a value of 3.12kN, while the lowest value for the negative (tensile) direction is -5.16kN. The amount of energy carried by a wave is proportional to its amplitude. A significant amount of energy is carried by high-amplitude waves and a small amount of energy is carried by low-amplitude waves. From the amplitudes of the two samples, it can be seen that the amplitude of BCJ with GFRP is lower than BCJ without GFRP. This indicates that the presence of GFRP lowers the loading's intensity.

(a) (b) (c)

FIGURE 9. Visual observation during the experimental work of BCJ with GFRP



(a) Amplitude of beam-column connection without GFRP



(b) Amplitude of beam-column connection with GFRP

FIGURE 10. Graph of Amplitudes of the beam-column connections with and without GFRP

ENERGY DISSIPATION AND EQUIVALENT VISCOUS DAMPING

According to Yuping and Dingwei (2012), the two most important factors affecting a building's seismic performance are energy dissipation and equivalent viscous damping. The response of a system to a harmonic force at an exciting frequency is measured by equivalent viscous damping. The bigger the value of the equivalent viscous damping factor, the better the building's seismic performance. The equivalent viscous system can be used to calculate the energy dissipated in one vibration cycle of the structure. Equation 1 can be used to compute the equivalent viscous damping, ζeq.

$$\xi eq = \frac{1}{4\pi} x \frac{E_D}{E_{SO}} x100\% \quad (1)$$

E_{SO} is the strain energy reflecting the area under the equivalent linear hysteresis curve, and E_D is the loss energy indicating the area under a hysteresis loop.

Table 1 shows the values of equivalent viscous damping, ζeq of the beam-column joints with and without GFRP obtained using Equation 1 for the first and second cycles. From the values obtained in Table 1, the graphs of equivalent viscous damping, ζeq versus the drifts of the beam-column joints with and without GFRP are plotted as shown in Figure 11.

Because the first cycle requires more energy to withstand the strength of the beam-column joint than the second cycle, the equivalent viscous damping, ζeq of both specimens is larger for the first cycle than for the second cycle. Furthermore, the first cycle's energy absorption results in a decreased included area of the hysteresis loop in the second cycle.

The second cycle of beam-column joint without GFRP, however, has a larger value of equivalent viscous damping than the first cycle at a 1.25 % drift. This indicates that if the drift is 1.25 %, the specimen will absorb more energy in the second cycle and suffer more damage than in the first. The first cycle usually refers to the earthquake's first shock, whereas the second cycle refers to the earthquake's aftershocks. The same can be said for the GFRP beam-column joint, which experienced a similar condition at 0.50% drift.

TABLE 1. The values of equivalent viscous damping, ζeq of the beam-column joints with and without GFRP

Top Drifts (%)	BCJ without GFRP		BCJ with GFRP	
	1st cycle	2nd cycle	1st cycle	2nd cycle
0.01	0.00	0.00	0.00	0.00
0.10	5.30	5.02	13.48	9.37
0.15	5.45	5.35	5.76	5.52
0.20	6.32	6.05	7.68	7.59
0.25	7.62	7.09	7.25	7.07
0.50	7.31	7.24	7.52	7.54

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0.75	8.29	7.37	3.56	3.61
1.00	7.37	7.34	7.55	7.70
1.25	7.62	7.85	7.47	8.29
1.50	12.52	14.12	8.48	7.40
1.75	10.44	13.45	7.84	8.16
2.00	8.46	55.89	3.13	5.22

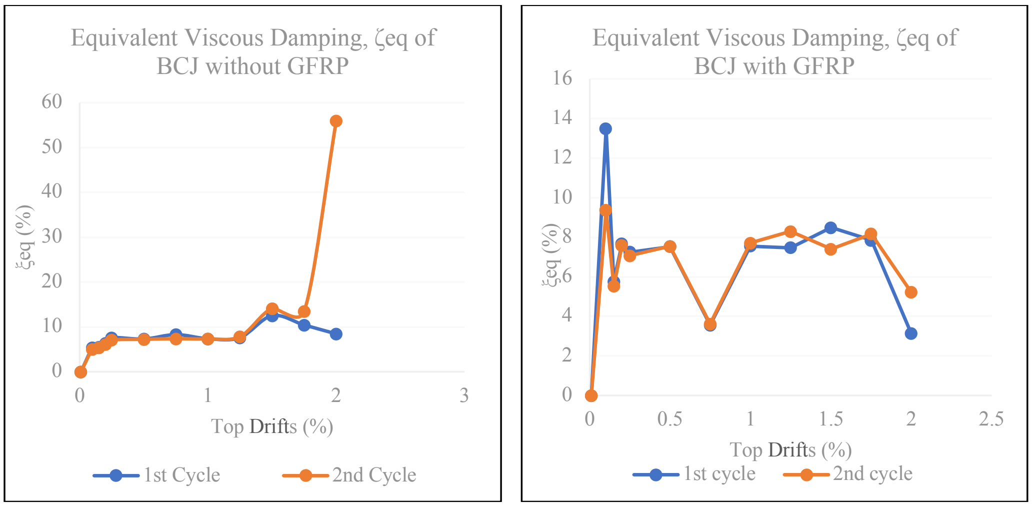

FIGURE 11. The graphs of Equivalent viscous damping, ζeq versus the drifts of the beam-column joints with and without GFRP

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations can be derived based on the visual observation, experimental data, and discussion presented in this paper:

1. In this experiment, two specimens of beam-column joints are tested to failure. The first specimen is a typical RC exterior beam-column joint without GFRP while the second specimen is RC exterior beam-column joint that is pre-installed with Glass Fibre Reinforced Polymer (GFRP) using Near-Surface Mounted (NSM) technique. However, during the experimental work on BCJ with GFRP specimen, there is an error occurred due to a malfunction on the machine (the machine keeps on running and fail to stop during the process to adjust the set-up of actuator at the very beginning of the experiment) which causes cracks on the specimen. Therefore, there might be errors in the results of the beam-column joint with GFRP.
2. Visual observation during the experiment shows that severe cracking is evident on the inner part of the beam-column joint in both specimens. Therefore, a new location of GFRP-NSM would be suggested for a future experiment. On the other hand, at BCJ with GFRP specimen, there are no major cracks or spalling of the concrete that lead to reinforcing bar exposure, whereas this is the case at BCJ without GFRP specimen. This indicates that GFRP can effectively displace the plastic hinge away from the face of the column. However, the problem of de-bonding the GFRP sheet to the face of the beam-column joint needs further investigation.
3. The load value for the beam-column joint without GFRP for the first cycle in the positive (compressive) direction is the highest with a drift of 0.75% with a value of 6.4kN, while the lowest value for negative (tensile) direction is -5.34kN. For the load value of beam-column joint with GFRP, the first cycle in positive (compressive) direction is the highest at ±2.00% drift with a value of 3.12kN, while the lowest value for negative (tensile) direction is -5.16kN. From the amplitudes of both specimens, it can be seen that the amplitude of BCJ with GFRP is lower than BCJ without GFRP. This shows that the presence of GFRP lowers the loading's intensity.
4. Because the first cycle requires more energy to withstand the strength of the beam-column joint than the second cycle, the equivalent viscous damping, ζeq of both specimens is higher for the first cycle than for the second cycle. However, with a drift of ±1.25%, the second cycle of the beam-column joint without GFRP has a higher value of equivalent viscous damping than the first cycle. This means that at ±1.25% drift, during the second cycle, the specimen will absorb more energy and be more damaged than during the first cycle. The first cycle usually refers to the earthquake's first shock, whereas the second cycle refers to the earthquake's aftershocks. The same applies to the beam-column joint with GFRP, which experienced the same condition with a drift of ±0.50%.

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DECLARATION OF COMPETING INTEREST

None

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