Australian Earthquake Engineering Society
2022 National Conference, 24-25 November 2022
Mount Macedon, Victoria, Australia

Experimental Study of a New Type of Hybrid Joints with GFRP Bolts and Reinforcements under Cyclic Loading

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Abstract

This study develops a new type of prefabricated hybrid beam-column joint that improves the weaknesses of a previously proposed dry beam-column joint with concrete-end-plate (CEP) and carbon fibre-reinforced polymer (CFRP) bolts to connect prefabricated beam and column. Even though the previously proposed dry joint offers various advantages compared to the conventional monolithic joint in terms of energy dissipation, load-carrying capacity and stiffness, the bulky CEP makes it difficult for slab assembly. To solve this shortcoming, this study proposes a new hybrid joint and investigates its performance under cyclic loading for application in earthquake-resistant designs of frame structures. The failure modes, envelope curves, drift ratio (DR), and energy dissipation (ED) of the new prefabricated beam-column joint were obtained from the laboratory tests. To make the new structural joints more durable and sustainable, new materials such as geopolymer concrete (GPC), glass fibre-reinforced polymer (GFRP) bolts and GFRP reinforcement bars were applied to replace the conventional steel reinforcement bars and steel connecting bolts. The experimental results showed that the energy dissipation and the loading capacity of the proposed hybrid joints were respectively 57% and 17% greater than those of the conventional monolithic joint and the loading capacity was almost the same as the previously proposed dry joint with a large CEP. The DR of the hybrid joint reached 3.5% in the pull direction and 2.5% in the push direction owing to its unsymmetric layout. The test results demonstrated that the new hybrid joint not only resolves the limitations of the previous dry joint with a bulky CEP but also satisfies the performance level for immediate occupancy, i.e. 2% DR, specified in ASCE 41-17.

Keywords: Ductile precast joints, GFRP bolts; GFRP reinforcements, ABAQUS, Cyclic loads.

1. INTRODUCTION

Precast constructions are widely adopted in many countries such as the United States, Japan, China, and New Zealand (Xue and Zhang 2014) because of various advantages including reducing construction costs, high-quality control and mitigating environmental impact. However, the performances of precast concrete structures are mostly governed by seismic responses of the beam-column joints. If the joints are damaged, the building may collapse even though the beams and columns are in good condition. It is, therefore, necessary to evaluate the seismic performances of precast joints used in seismic-prone regions. Up to now, most current studies have experimentally and numerically investigated the performances of monolithic and wet precasted joints subjected to cyclic loading. There has been a limitation of studies on the dry beam-column joints in the literature. It is because the common dry joints show low ductility and strength under seismic loads and are also vulnerable to corrosion damage. The steel connecting elements in conventional dry joints are susceptible to corrosion damage because they are not protected by concrete. Some studies (Clifford 1991; Woodward and Williams 1988; Wouters et al., 1999) indicated that corrosion of the connecting elements can lead to a building collapse. In some cases, the maintenance and repair costs of damaged components could be twice as much as the initial construction cost (Lawler and Polak 2010; Yunovich and Thompson 2003). To foster the use of dry beam-column joints in construction, the authors made attempts to conduct a series of comprehensive investigations on a new proposed dry joint using several methods such as experimental tests, analytical derivations and numerical simulations. The proposed dry joints were connected with FRP bolts to mitigate corrosion damage and demonstrated sufficient strength and ductility as compared to the monolithic joint for application in seismic-resistant designs (Ngo et al., 2019; Ngo et al., 2020a). For instance, the maximum applied load, stiffness, and energy dissipation of the dry joint were higher than those of the reference monolithic joint by approximately 27-61%, 27-55%, and 45-75%, respectively. To help engineers design this new dry joint using steel fibre reinforced concrete and conventional concrete, an analytical model was also proposed Ngo et al., (2020b). In addition, the numerical model using ABAQUS was developed to investigate the structural response of the dry joints. The numerical results proved that shear strength mainly governed the failure of the dry joint which were consistent with observations in the experimental tests. The ratio of CEP/Beam=1.3 was determined as the optimal value of CEP thickness based on parametric studies of the dry joint (Pham et al., 2021). The above series studies demonstrated the superior performance of the proposed dry joint under cyclic loading, and developed design analysis. However, the existence of a large concrete end plate (CEP) at the joint makes the assembly of floor slabs relatively difficult. Therefore a new Hybrid joint is proposed in this study to overcome the shortcoming of the previously developed dry joint.

Meanwhile, reducing CO_2 and industrial waste are two main tasks for tackling climate change and mitigating the negative effects on human health and planetary ecology. Various studies proved that if no action is taken, CO_2 emitted from the global cement industry can reach up to 2.34 billion tons by 2050 (Ngo et al., 2020c; Tran et al., 2022). GPC is a so-called "green" material because its production process uses industrial waste such as slag, silica fume, calcium fly ash, and rice-husk ash to produce the new binder which can replace conventional cement. It means if the conventional concrete is replaced by GPC, the CO_2 emissions from the cement industry and industrial waste can significantly be reduced.

This study investigates the performances of a new hybrid joint without the bulky CEP existing in the previously developed dry joints (Hao et al., 2019; Ngo et al., 2020a) under cyclic loading. The performances of this new joint constructed with GPC with FRP reinforcements and connected with FRP bolts under cyclic loading were investigated in this study. The feasibility of the application of this new joint in an earthquake-resistant structure is discussed.

2. EXPERIMENTAL PROGRAMME

This study investigates the performances of one reference monolithic joint (namely (1) M1-OPC) and two hybrid joints (namely (2) H2-OPC; (3) H3-GPC) with different concrete types. Letters "M" and "H" denote the monolithic and hybrid joints. The hybrid joints are named based on their characteristics. Although the high-strength concrete needs to be filled into the gap as the wet joints after applying prestress force of GFRP bolts, formwork after filling is not required. It is because the hybrid joints can resist the dead loads even without the filling concrete, as shown in Figure 1. After filling concrete, the top surface of the beam is as flat as the monolithic joint making it convenient to assemble the flat slabs. This characteristic is an advantage of the hybrid joint over the previously proposed dry joint (Ngo et al., 2020a). The beam and column in the hybrid joints were connected by four 25-mm GFRP bolts. Although low torsion and shear resistances of FRP bolts were reported in various studies that make it difficult to apply prestress force (Ngo et al., 2020a; Ngo et al., 2020b; Ngo et al., 2020c), high prestress levels up to 35 kN was still applied to the GFRP bolts by a prestress system (Ngo et al., 2022). The new method to apply high prestress force of FRP bolts by using the prestress system was presented in Ngo et al., (2022). "OPC" indicate ordinary portland concrete whereas "GPC" denotes geopolymer concrete. The concrete-end-plate thickness of the two hybrid joints was 200 mm. The compressive strength and tensile strength of OPC on the testing day were 59.1 MPa and 4.2 MPa while those of GPC were 64.2 MPa and 4.4 MPa, respectively. It is noted that the mechanical properties of GPC were slightly higher than those of OPC owing to different concrete batches and testing days. All the longitudinal and transverse reinforcements were made of GFRP with the tensile strength and elastic modulus of 1,358 MPa and 54 GPa, respectively. Figure 1 shows geometries and detailed reinforcements of the hybrid and monolithic joints. The flat slabs can be placed easily on the beam surface of the hybrid joint as the conventional monolithic joint. All the specimens were tested under cyclic loads. An axial force (65 kN ≈ 0.03 $A_c f_c$) was applied and maintained on the top of the columns during the test. The displacement control was adopted during the test with a loading rate of 6-9 mm/min. The loading history and typical test setup are presented in Figures 2 and 3.

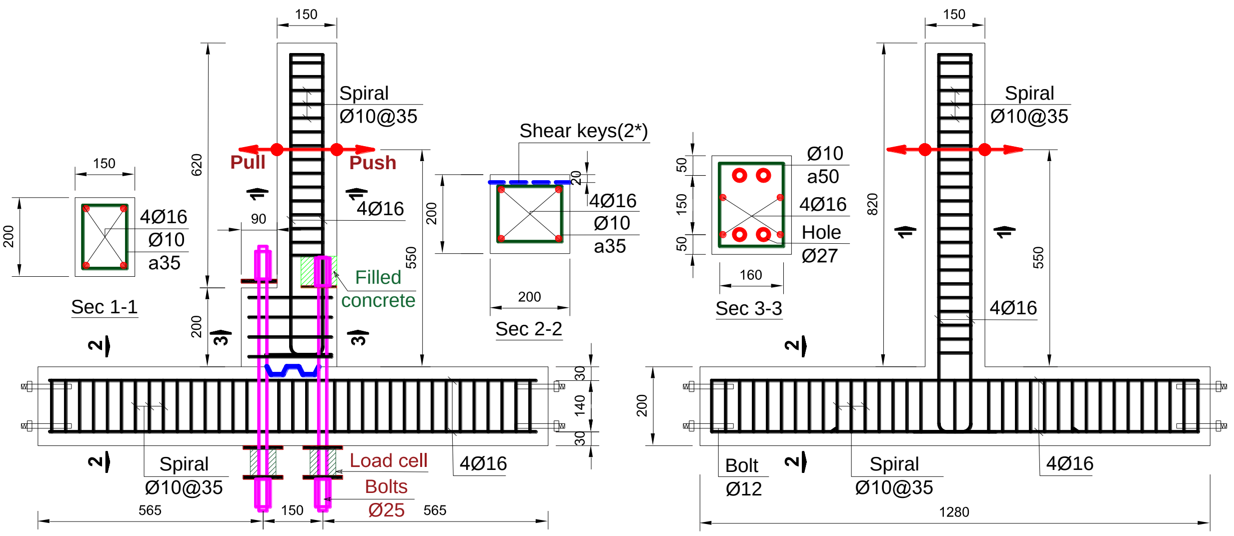


Figure 1. Designs of the hybrid joint (Left) and monolithic joint (Right) (unit: mm).

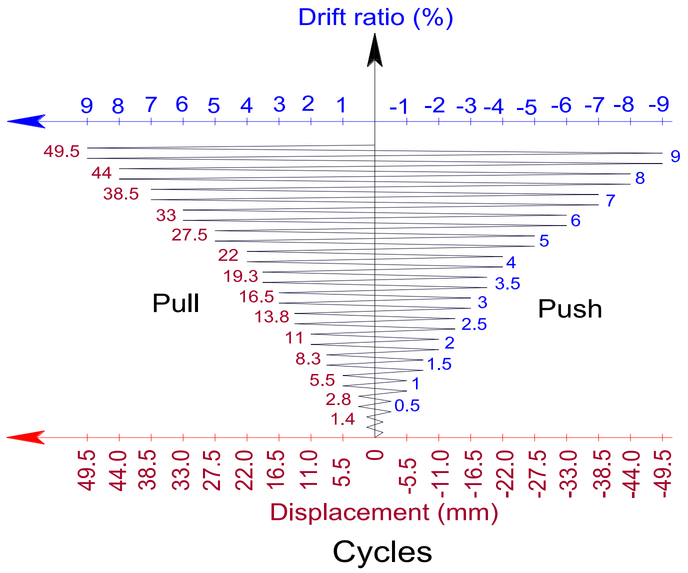


Figure 2. Cyclic loading history.

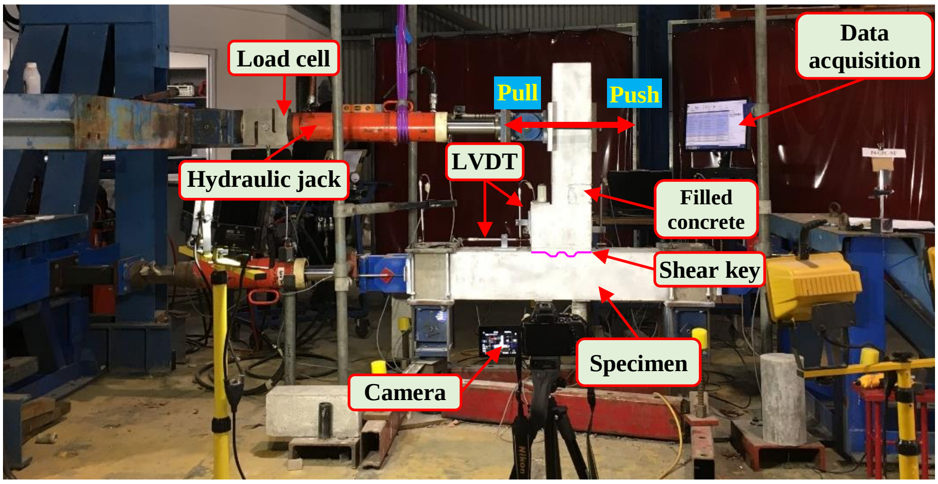


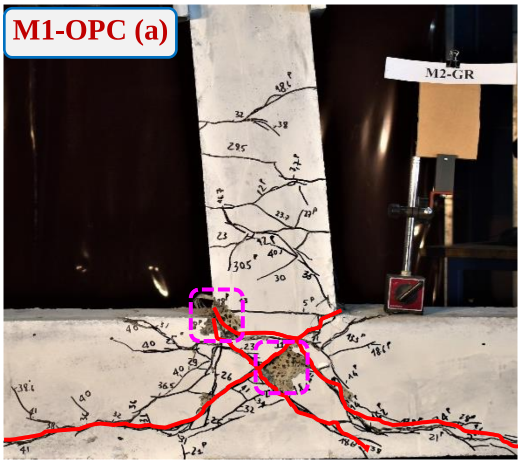
Figure 3. Details of the test setup.

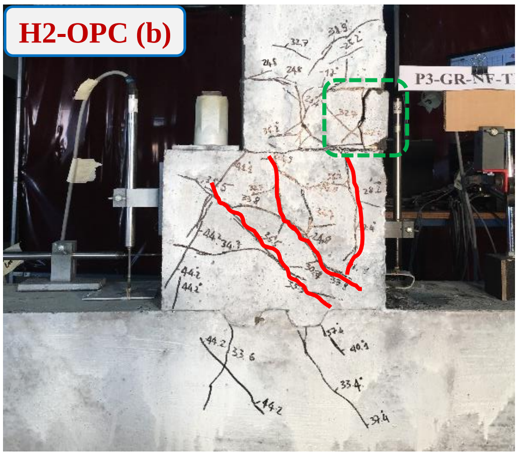
3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Failure modes

Figure 4(a) depicts the main failure patterns of the monolithic joints. The flexural crack at the fixed-end of the beam formed early at 0.3-0.5% DR. Afterwards, these flexural cracks propagated to the loading point when the beam soffit was in high tension. The inclined cracks developed in the joint area of the column after 1% DR. Severe damage in the middle joint and concrete spalling at the fixed-end governed the main failure of Specimen M1-OPC due to very large displacement up to 10.5% DR at the end of the test. In addition, the shear keys were created at the interface between the beam and column to resist the shear force (see Figure 3). Hence, there was no slip between the column and CEP surfaces. The foam moulds were attached to the formwork before concrete was poured into it to create the shear keys on the column and CEP. More details about this method were presented in the previous study (Ngo et al., 2022). After the test, the GFRP thread bars and nuts were removed and checked. No failure was observed on GFRP threaded rods and nuts during the test. The GFRP bolts showed excellent performances under cyclic loading. In addition, the data of strain gauges proved that the strain of GFRP reinforcements did not reach the nominal strain. For example, the strain of GFRP reinforcements in Specimen M1-OPC was 9666 με which was lower than the nominal rupture strain of 25,238 με. It means the concrete governed the main failure modes of all the specimens and the application of FRP material satisfied the design requirements for structures without brittle failures. The columns of the two hybrid joints depicted very good performances without severe damage which satisfies the philosophy of strong columns-weak beams in designing concrete structures under earthquake loads. It is noted that only minor inclined cracks occurred on the columns of the hybrid joints because the shear force from the beam was transferred to the column due to the effect of the shear keys.

To evaluate the failure modes between specimens using OPC and GPC, a comparison was made between Specimens H2-OPC and H3-GPC, as shown in Figure 4. In general, the two hybrid joints exhibited similar failure modes and crack development. Both joint and beam failures were observed on the hybrid joints. It is because low bonding between new and old concrete led to initial cracks around the filled concrete block at a very low DR of 0.5% in the pull direction and caused a failure of the filled concrete block in the push direction. As a result, more severe damage occurred at the fixed-end owing to reducing the cross-section of the beam. From 1% DR, an inclined crack was observed in the middle zone of the CEP due to shear and tensile stress. Hence, the strain of the middle stirrup in this zone reached a high value of 3,866 με on Specimen H2-OPC. However, these two hybrid joints also had some differences related to the stage of crack development. Although the cracks on Specimen H2-OPC developed earlier than those on Specimen H3-GPC, more inclined cracks at the CEP and concrete crushing at the fixed-end were observed on Specimen H3-GPC (see Figures 4(b) and 4(c)). These different performances were attributed to different concrete properties. The tensile strength (4.4 MPa) and compressive strength (64.2 MPa) of GPC were higher than those of OPC (4.2 MPa and 59.1 MPa), respectively. Therefore, GPC Specimen (H3-GPC) more effectively resisted tensile/shear stress and compressive stress, compared to OPC Specimen (H2-OPC) in the initial stage. However, when the GPC specimen reached the maximum load-carrying capacity, more severe damage was observed in the GPC hybrid joint due to the brittleness of GPC at the peak load. This finding was also consistent with the previous study (Ngo et al., 2020c).





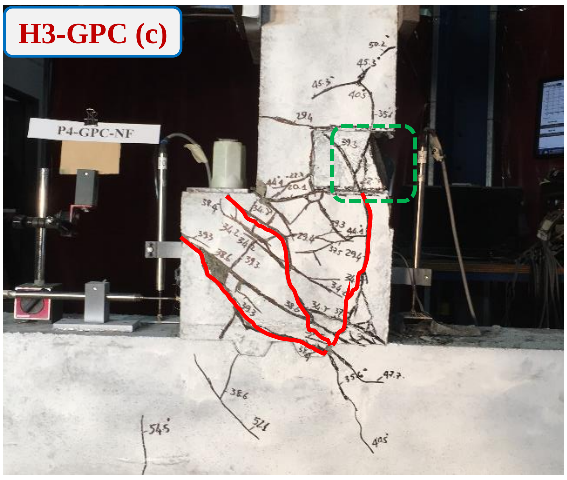


Figure 4. Failure patterns.

3.2. Drift ratio and Load-carrying capacities

The drift ratio is a necessary parameter to evaluate the ductility of the beam-column joint under cyclic loading. The drift ratio is determined as the ratio of the transverse displacement of the beam to the distance from the column surface to the loading point (see Figure 3). In general, the maximum DR in all the specimens satisfied the requirement of the immediate occupancy structural performance level (2% DR) and the life safety structural performance level (3% DR) specified in ASCE 41-17. It means the application of GPC and FRP materials in the hybrid joints satisfies the design requirements for structures under cyclic loading without brittle failure.

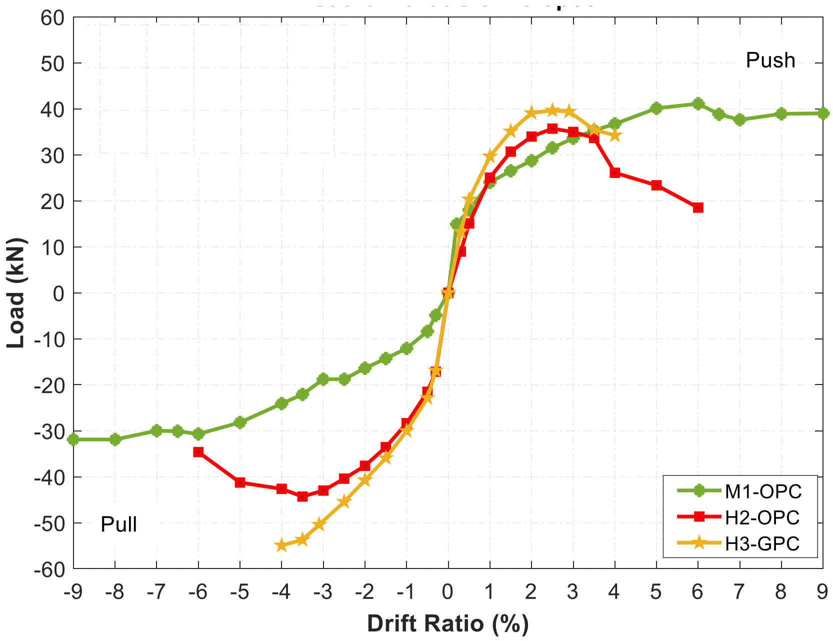


Figure 5. Load-drift ratio envelopes of all the specimens.

Figure 5 shows the envelope curves of all the tested specimens. The cyclic loading was applied to test specimens until the push or pull direction reached 85% of the post-peak load. However, the test was stopped prior to the failure of Specimen M1-OPC as LVDT reached its ultimate capacity. In general, the maximum load-carrying capacity of the two hybrid joints was greater than that of the reference monolithic joint. Although all the specimens had the same beam and column, the maximum applied load of Specimens H2-OPC and H3-GPC was 44.3 kN and 54.9

kN, respectively whereas that of the monolithic specimen was 41.1 kN. It is attributed to the effects of CEP. The cross-section of CEP on the hybrid joint was 200 × 250 mm^2 while that of the beam of the monolithic joint was 200 × 150 mm^2. A larger cross-section of CEP on the hybrid joints results in higher maximum load-carrying capacity. In addition, the maximum applied load of Specimen H3-GPC was higher than that of Specimen H2-OPC by approximately 24% due to higher material compressive and tensile strengths as mentioned above.

3.3. Energy dissipation

Energy dissipation (ED) is a crucial parameter to evaluate the joint performances under cyclic loading. This parameter is determined by the area enclosed (A_h) inside the hysteretic loop of the first cycle of each loading level (see the small figure in Figure 6). Figure 6 shows the comparison of the energy dissipation of all the specimens. Due to elastic behaviour in the initial stage, the ED of two joint types was similar up to 0.5% DR. Afterward, the ED of the monolithic joint was lower than the hybrid joints because of two possible reasons. (1) at the same DR, the load-carrying capacity of the hybrid joints was greater than that of the monolithic joint, as shown in Figure 5. (2) the hybrid joints opened under high loading levels and closed after unloading owing to the effects of the prestressing forces. These performances led to the greater ED of the hybrid joints because of the damping of material and friction between interfaces. In addition, the ED of Specimen H3-GPC was slightly higher than that of H2-OPC with the maximum variation of 21% at 3% DR. This difference was attributed to higher load-carrying capacity and wider flexural crack at the fixed-end/inclined crack at the joint area. The above results indicate that the proposed hybrid joint meets the seismic-resistant design requirement for application in the seismic-prone area.

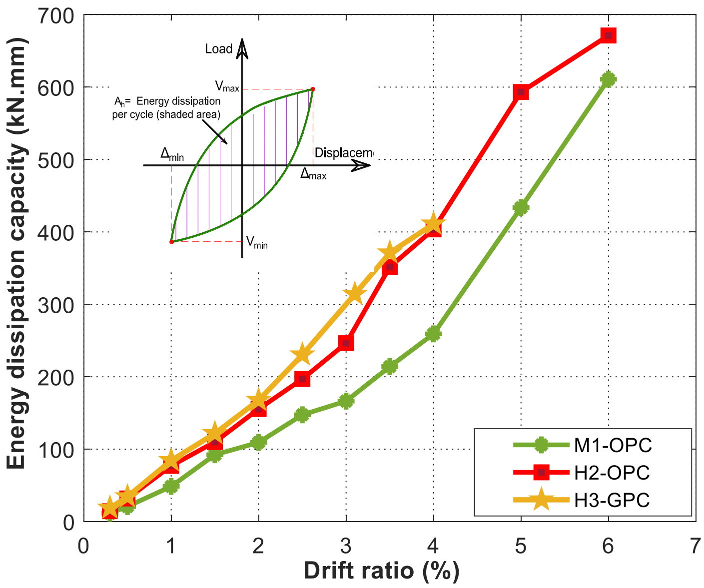


Figure 6. Comparison of energy dissipation capacity.

4. CONCLUSIONS

The performances of the hybrid joints using GPC and FRP materials were investigated in this study. Based on the above discussions, a few conclusions are summarised as follows:

- The GFRP bolts and reinforcements showed promising performances without brittle failure during the test.

- The general crack patterns of GPC and OPC hybrid joints were almost the same but severe damage was observed on the GPC hybrid joint after reaching the peak loads because of the brittle characteristics of GPC.

- GPC hybrid joint showed good performances in terms of load-carrying capacity, DR, and ED, satisfying the requirements for designing the precast structure to resist seismic loads.

5. ACKNOWLEDGEMENT

The authors want to thank the financial support from the Australian Research Council Laureate Fellowships FL180100196, and staff at the Civil Engineering Laboratory, Curtin University, for their technical help during the experimental tests.

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