

Nacre inspired 3D printing construction for high performance structural member

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Abstract. Inspired by the nacre's hierarchically assembled structure, the authors tried to use ultra-high ductile cementitious composites (UHDCC) and stack approach to fabricate structure possessing high flexural ductility and load bearing capacity. A series of beams with specially design was constructed, i.e., monolithically cast beams, monolithically stacked beams and hierarchically stacked beams. Four-point bending tests were carried out to explore the effect of hierarchical assembly on load bearing capacity, flexural deformation and flexural toughness. The test results have indicated that the monolithically stacked beams outperform the monolithically cast beams in both deformability and loading bearing capacity, indicating the effectiveness of stack-based construction. Moreover, the setup of connect/separation between layers further improves the flexural ductility of the hierarchically stacked beams, as compared with the monolithically stacked beams. Digital Image Correlation (DIC) observations indicate that the nacreous-like structure of the hierarchically stacked beam helps to trigger crack deflecting and branching between layers and inside matrix, lead to limited slide between layers, thus effectively relieving concentrated strain inside matrix, postponing the emergence of the critical crack and consequently improving the flexural ductility of nacreous-like UHDCC beams.

1 Introduction

Engineered cementitious composites (ECC) designed by micromechanics is known for its high tensile strain capacity. ECC performs strain-hardening and multiple cracking characteristics under increasing tension. It has stronger tensile strength and much higher tensile strain capacity over the normal fiber reinforced concrete (FRC). Zhang [1, 2] studied the feasibility of applying ECC on steel bridge deck overlay, the results showed that ECC can overcome the brittleness of normal concrete due to its high deformability capacity. Recently, Ultra-high ductility cementitious composites (UHDCC) emerged as a kind of ECCs with even higher tensile strain capacity. Generally, UHDCC has the tensile strain capacity ranging from 8% to 12% [3, 4], the uniaxial tensile strength ranging from 4 MPa to 20 MPa, and the compressive strength ranging from 20 MPa to 120 MPa [5, 6]. For the first time, a cementitious material has comparable ductility to steel reinforcement. Considering its excellent ductility, this material is named as ultra-high ductility cementitious composites (UHDCC) [7, 8]. Due to its high tensile capacity, UHDCC was expected to be a structural material free from steel reinforcement, which was subsequently verified by the authors [8].

To date, most of the 3D construction printing technologies confront two challenges. First, brittleness of printing materials. Cementitious materials are widely used in 3D construction printing, but due to their

inherent brittleness, they are still highly dependent on steel reinforcement for tensile strength and ductility. The processing and installation of steel reinforcement drastically compromises the efficiency brought by 3D printing. Second, deterioration induced by stack. In most of 3D construction printings, concrete is stacked layer-by-layer into the desired shape, e.g., the contour craft technology [9]. However, the interfaces between adjacent layers become weak links when the stacked concrete structure is subjected to tension and shear. On the other hand, some of bio-materials, which are layered at micro-scale, e.g., nacre of shell, have surprising mechanical property [10]. The secret lies in their hierarchically assembled structures.

In recent years, many researchers tried to reinforce the structural components by different ways. Xia et al. [11, 12] developed a sandwich wall boards with GFRP and web-foam core to upgrade the impact resistance ability of exterior walls of structures. Wang [13, 14] used precambered steel plates to strengthen the preloaded rectangular RC columns. Li et al. [15-19] experimentally and numerically studied the feasibility of using bolted side-plated technique to enhance the shear capacity of RC beams. But the studies on nacre inspired structures at macro-scale have yet to be insufficient.

With all the points above in mind, the authors studied the lessons from nacre, and tried to use stack approach to hierarchically assemble the UHDCC, so as to develop a novel structural form with superior mechanical property.

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The hierarchically stacked structure made of UHDCC is expected to provide a solution for the material and structural issues in 3D construction printing.

2 Experimental programs

The mixture proportion of UHDCC is listed in Table 1. The common raw materials for producing concrete, i.e., cement, fly ash and silica sand, were adopted for mixture. P.II. 525 Portland cement and Class F fly ash were used in the mixture as the binding materials, the maximal size of the silica sand is approximately 0.21mm. To obtain an excellent mechanical property, ultra-high molecular weight polyethylene (UHMWPE) fibers were used as reinforcement material in mixtures. The volume fraction of PE fiber is 2%. The geometric and mechanical properties of PE fiber provided by manufacture are given in Table 2.

Table 1. Mixture proportions for UHDCC (kg/m³).

| Silica Sand | Cement | Fly ash | Water | Fiber | HRWR |
|-------------|--------|---------|-------|-------|------|
| 569.3 | 711.6 | 853.9 | 394.5 | 22.8 | 2.5 |

Table 2. Properties of PE fiber.

| Fiber | Diameter (μm) | Tensile Strength (GPa) | Elastic Modulus (GPa) | Rupture Elongation (%) | Density (g/cm ³) |
|-------|---------------|------------------------|-----------------------|------------------------|------------------------------|
| PE | 24 | 2.9 | 116 | 2.6 | 0.97 |

Totally 4 dogbone-shaped specimens were prepared for the standardized tension test recommended by the Japan Society of Civil Engineers. All the dogbone-shaped specimens were tested on an MTS CMT4204 electro-servo machine (±1N resolution) after 28d curing. As shown in Figure 1, the tensile strain capacity of UHDCC dogbone reached 7.7%, which exceeded the lower requirement for steel reinforcement, i.e., 7%.

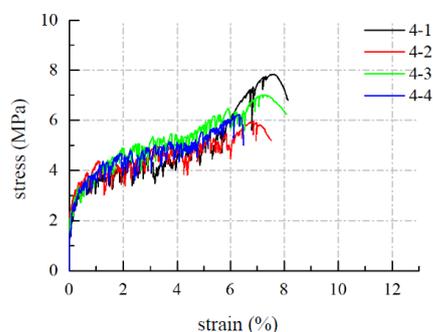


Fig. 1. Stress- strain curves of UHDCC.

Totally 20 beams were prepared for four-point bending test, including 2 monolithically cast beams, 2 monolithically stacked beams and 14 hierarchically stacked beams made of UHDCC, as well as 2 plain concrete beams, as listed in Table 3. The geometric size of all the beams was uniformly 100×100×550mm. The hierarchically stacked beams were cast using specially designed moulds, as shown in Fig 3. To mimic the brick-and-mortar structure of nacre, UHDCC was stacked

layer-by-layer. And to further mimic the mineral bridges and slip-interlock effect, PVC membranes with pre-cut holes were installed into UHDCC when cast layer-by-layer, thus alternating connect/separation zones between UHDCC layers were realized. Table 3 presents the differences in fabrication among specimens. For the hierarchically stacked beams, there were 8 categories of connect/separation cases. The numbers in the column of “fabrication case” in Table 3 refer to specific connect/separation length. For example, 5:5 stands for a connect zone of 5 mm in length followed with a separation zone of 5 mm in length. Figure 2 illustrates the planar layout of a 5:5 PVC membrane.

Table 3. Test scheme for four-point bending beams.

| Specimen | Fabrication case |
|----------|---------------------------|
| L-1 | plain concrete |
| L-2 | plain concrete |
| L-3 | monolithically cast |
| L-4 | monolithically cast |
| L-5 | stack without separation |
| L-6 | stack without separation |
| L-7 | 5:5 |
| L-8 | 5:5 |
| L-9 | 5:10 |
| L-10 | 5:10 |
| L-11 | 10:5 |
| L-12 | 10:5 |
| L-13 | 10:10 |
| L-14 | 10:10 |
| L-15 | 10:20 |
| L-16 | 10:20 |
| L-17 | 10:10 |
| L-18 | 20:20 |
| L-19 | 20:10 (10:10 in mid span) |
| L-20 | 20:10 (10:10 in mid span) |

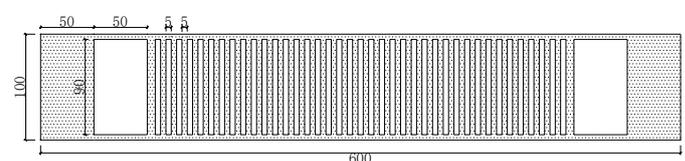


Fig. 2. Planar layout of the 5:5 PVC membranes (Unit: mm).

After 28d curing, all the hierarchically stacked beams were tested on an MTS CMT4204 electro-servo machine (±1N resolution). 5 Linear variable differential transformers (LVDTs) were installed to obtain the deflection of beams, as shown in Fig 4. Meanwhile, digital image correlation (DIC) technique, a non-contact measurement method, was unitized to record the full field displacement and strain distribution. The results of DIC were used to observe the initiation and propagation of cracks, and monitor the slips between layers.



Figure 3. Hierarchical casting mould.

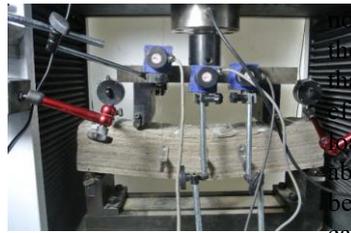


Figure 4. Schematic diagram of four-point bending test.

not only can enhance the flexural deformability but also the peak bearing capacity. However, it should be noted that inappropriate assembly may also lead to negative effect on the mechanical property. As mentioned, the load bearing capacities of the 10:20 and 20:20 beams are about 75.38% and 56.16% of the monolithically stacked beams and 89.57% and 66.73% of the monolithically cast beams. The degradation is due to the premature and excessive slips between layers since comparative small connect/separation ratios were used in fabrication.

3 Result and discussion

The crack patterns obtained by DIC method were plotted in Fig 5. Obviously, much more cracks were triggered in the monolithically stacked beams than the monolithically cast beams. And for most of hierarchically stacked beams, cracks occurred both in the pure bending region and the shear -bending region, which are beneficial to the ductility and energy dissipation. In some cases, e.g., the 5:10, 10:10, 10:20 and 20:10 beams, cracks were clearly seen deflecting and branching between layers. The similar phenomena were widely observed in the fracture process of natural nacre, which was commonly attributed as the formation of the super mechanical property of nacre.

Table 4. Peak load and corresponding deflections of beams.

| Specimen | Peak load (kN) | Deflection at peak load (mm) |
|----------|----------------|------------------------------|
| L-1 | 15.34 | 0.07 |
| L-2 | 15.04 | 0.89 |
| L-3 | 28.40 | 8.67 |
| L-4 | 27.07 | 9.94 |
| L-5 | 38.94 | 23.22 |
| L-6 | 35.51 | 19.14 |
| L-7 | 35.74 | 26.40 |
| L-8 | 36.27 | 23.34 |
| L-9 | 32.23 | 23.84 |
| L-10 | 31.91 | 25.40 |
| L-11 | 32.88 | 19.47 |
| L-12 | 38.15 | 24.12 |
| L-13 | 31.60 | 30.16 |
| L-14 | 31.44 | 28.01 |
| L-15 | 20.97 | 17.95 |
| L-16 | 20.85 | 24.48 |
| L-17 | 31.17 | 20.97 |
| L-18 | 24.84 | 34.64 |
| L-19 | 35.68 | 28.60 |
| L-20 | 33.03 | 27.77 |

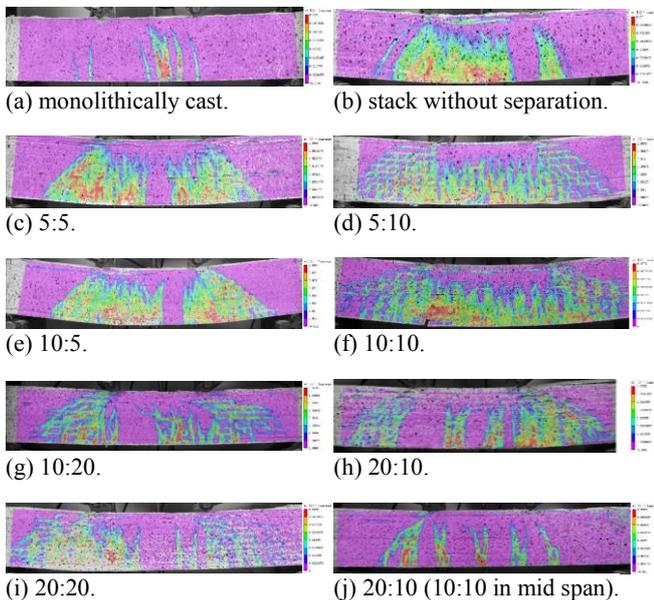
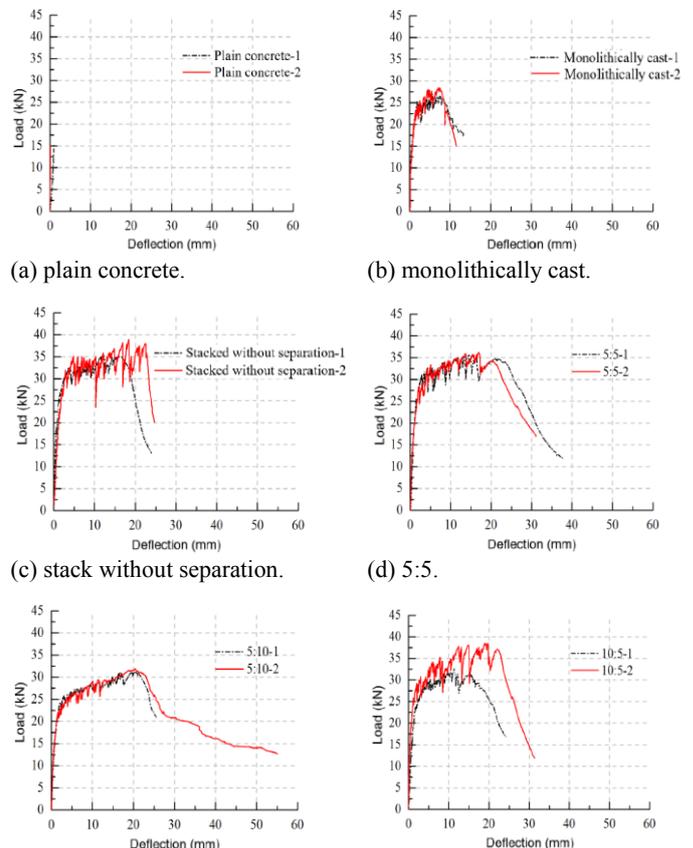


Figure 5. Crack pattern of beams under bending.

The load-deflection curves of beams are plotted in Fig 6. It is clear that all 8 categories of hierarchically stacked beams exhibited multiple cracking and flexure-hardening characteristics. The values of the peak bearing capacities and the corresponding deflections are summarized in Table 4. The test results have indicated that hierarchically stacked beam performs much better in deflection when subjected to bending and shear. And apparently, the flexural load bearing capacities of the hierarchically stacked beams are generally higher than that of monolithically cast beams except the 10:20 and 20:20 beams. It is demonstrated that hierarchical stack



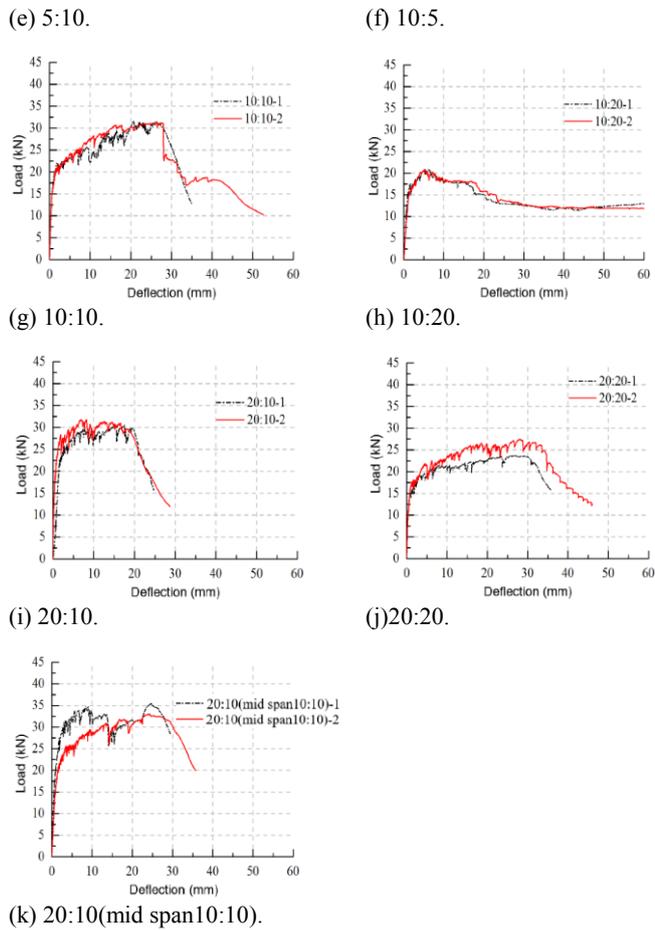


Figure 6. Load-deflection curves of beams.

To further investigate the flexural property of the hierarchically stacked beams, ductility index was obtained based on the JSCE-SF4 codes [20], which uses the area underneath the load-deflection curves to define the flexural toughness and uses the average strength at a specific deflection to define the toughness factor, where the recommended ratio of deflection to span is 1/150. To evaluate the energy dissipation capacity of beams in wider range of deformation, Li and Xu [21] improved this method by extending the ratio of deflection to span to 1/3000~1/100. The ratio of bending strength to initial cracking strength at different deflections was defined as deformation hardening coefficient (Deformation Hardening Indices-DHI). The values of DHI are calculated by the following Equation (1) and (2).

$$\sigma_n = \frac{T_{bn} l}{bh^2 \delta_n} \quad (1)$$

$$DHI_n = \frac{\sigma_n}{\sigma} \quad (2)$$

where T_{bn} is the toughness index under the load-deflection curves when the deflection is δ_m , b , h and l are the width, depth and span of the specimen, respectively

In comparison, DHI at different deflections was plotted by histogram was plotted in Fig 7. DHI is increased with the increase in deflection. Most of the hierarchically stacked beams outperformed the monolithically cast beams in DHI. The DHI at ultimate

deflection is plotted in Fig 8. It is clear that the DHI of the hierarchically stacked beams is commonly higher than that of the monolithically stacked beams. At the ultimate deflection, DHI of the hierarchically stacked beams are 2~3.7 times larger than that of monolithically cast beams. It is indicated that hierarchical stack can effectively enhance the energy dissipation capacity without sacrificing strength.

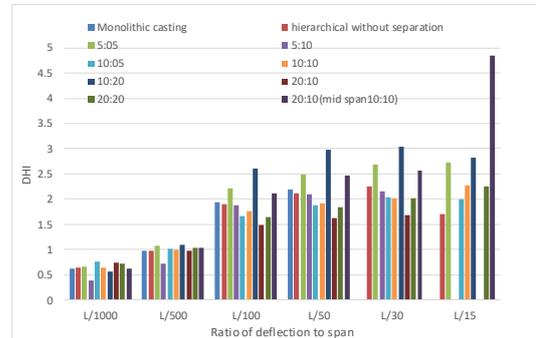


Figure 7. DHI at different deflections.

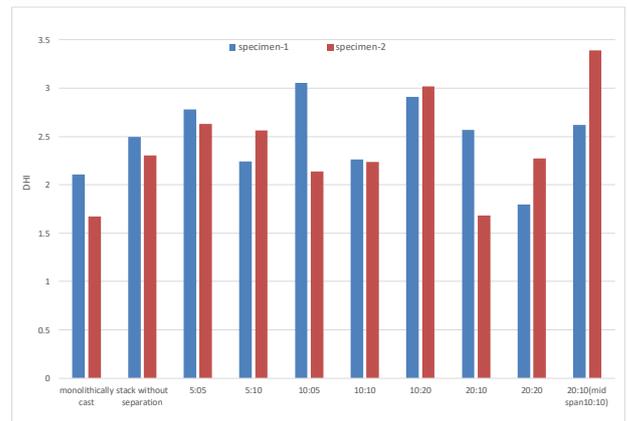


Figure 8. DHI at ultimate deflection.

4 Conclusions

The bending performance of nacre-inspired cementitious beams constructed by stack was experimentally studied. Based on the mechanical performance obtained from four-point bending test, the following conclusions can be drawn.

1) The bending performances of the hierarchically stacked beams and the monolithically stacked beams are obviously superior to those of the monolithically cast beams. The deformability and ductility were significantly enhanced without reducing in strength or toughness.

2) Some special damage modes of nacre-like structure, i.e., slipping in layers, crack deflecting and branching between layers and inside matrix were realized in the hierarchically stacked beams subjected to bending and shear. These special damage modes are closely related to the improved bearing capacity, flexural ductility and energy dissipation capacity.

3) The proposed hierarchically assembly method provides a new option for 3D printing construction. But the studies on the relative design theory and construction

method are very limited. A more systematic study is urgently needed before applying this technology into engineering practice.

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