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Flexural Response of Bolt-Connected UHPFRC-AAC-Steel Composite Panel

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Abstract. This study investigates and advances the existing research on the performance of concrete-steel composite panels connected by bolts. A Ultra-High Performance Fibre Reinforced Concrete (UHPFRC)-AAC-Steel Composite Panel is proposed aiming to provide prefabricated exterior wall solutions for buildings. The concrete-steel composite panel system consists of a UHPFRC layer, an autoclaved aerated concrete (AAC) middle layer, and one steel beam, for which all three components can be bolt-connected.

Keywords: UHPC; positive moment; critical condition.

1. Introduction

The development of composite concrete and steel panels began in the 1920s. Bolt-connected composite structures can be regarded as one of the fundamental types. The concrete layer helps protect the steel beam from fire and high temperature, while the composite action has been extensively researched and later considered in the structural design. The application of composite beams has gradually extended to industrial and residential buildings, especially in high-rise buildings, in the 1960s and then become popular and widely applied even nowadays. The lightweight concrete with a density of around 1800 kg/m3 has been used in the composite structures[1].

UHPC material is a better option when combined with steel beams to form composite beams or panels. However, most studies focus on permanent composition [2, 3], relying on headed stud connectors. He et al. investigated the anti-sliding mechanism of high-strength steel-Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) composite beams. A Dowel bar insert through the openings in the welded steel plate was embedded in UHPFRC material to provide sliding resistance and thus ensure a strong interfacial bond [4]. While performing under the positive bending moment is critical for a composite beam, the responses under the negative bending moment are also of interest for the application that requires a continuous composite beam[2, 5]. Liu investigated the shear performance of partially filled narrow-width steel box-UHPFRC-combined girders under negative moment action and found that the box girder with partially filled concrete greatly enhances the shear resistance and is compatible with the top UHPFRC flange[5]. Wan investigated the response of composite beams strengthened with UHPFRC overlays under a negative bending moment. The additional UHPFRC layer provides additional restraint for early shrinkage and helps reduce the cracking. However, their contribution to ultimate resistance is minimal.

Sustainable development has become a global target, and thus, the design for disassembly (DfD) has become essential, even for structure components such as composite panels. Katarzyna reviewed the literature on DfD after 1990 and found that the concrete-steel composite system is the most applied technique to achieve easy deconstruction [6].

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Autoclaved Aerated Concrete (AAC) is a lightweight, porous building material with excellent insulation properties. AAC concrete is widely used in many applications, including building walls, partition walls, and floors. Compared to regular concrete, AAC is a precast concrete material with low density and outstanding thermal insulating qualities. This study explores the potential of a UHPFRC-AAC-Steel composite system comprising a top thin UHPFRC layer, AAC middle layer and steel beams. The three components can be joined together using bolts with heads embedded in the UHPFRC layer. The composite panel aims to satisfy the strength and thermal performance requirements while supporting DfD design principles. Sectional analyses were conducted, followed by experiment investigations.

2. Materials

2.1 UHPFRC

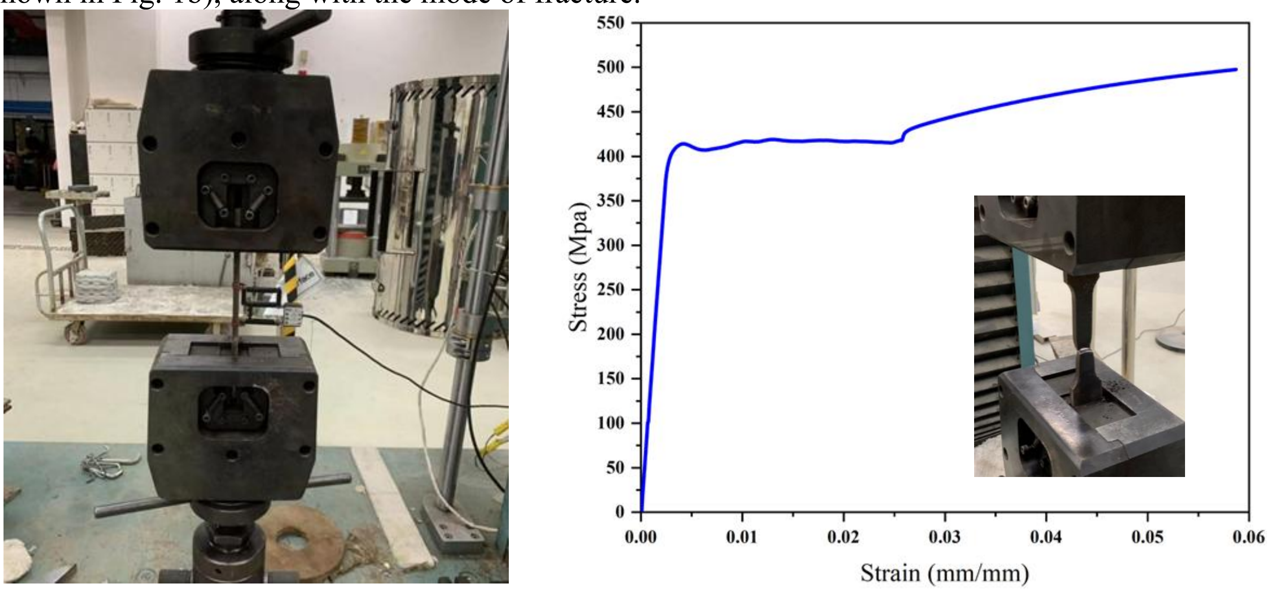
The UHPFRC material used in the study is a home-made material with mix design, as shown in Table 1. The average compressive strength based on three 100 mm cube specimens is 118 MPa at 28 days under normal curing at around 20 degrees Celsius room temperature.

Table 1. Mix Design of UHPFRC

Component	Quantity (kg/m³)
Cement	712
Silicon fume	231
Quartz sand	1020
Quartz powder	211
Water	143
Plasticizer	50
steel fibres	156
Total	2380

2.2 Steel

The steel used in the composite panel is Q345. The material's average yield strength and modulus of elasticity are approximately 400MPa and 185GPa, respectively, based on three tensile specimens, as shown in Fig. 1a). Typical stress and strain curve obtained from the experiment is shown in Fig. 1b), along with the mode of fracture.



a. Tensile testing setup b. Stress-strain curve

Fig. 1 Design of composite panel

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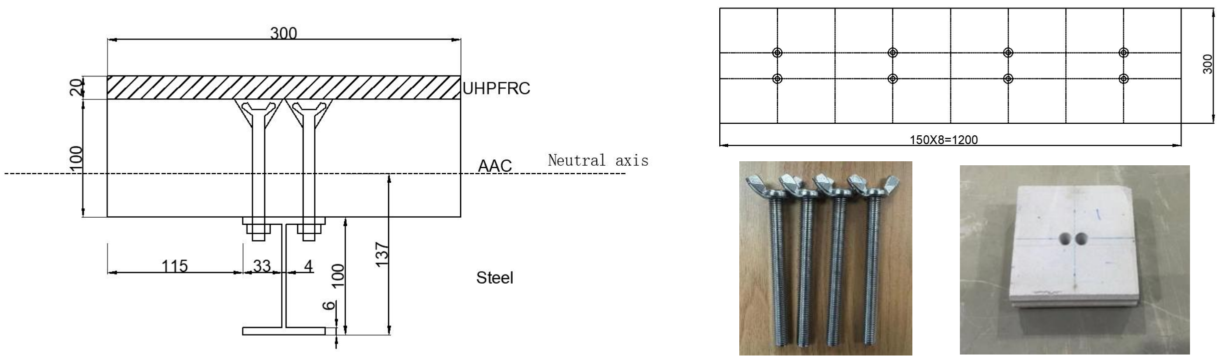
2.3 AAC

The AAC blocks were cut from a full-size AAC panel, and the dry density, compressive strength, and flexural strength were 527kg/m3, 3.95 MPa, and 1.02 MPa, respectively.

3. Specimen Design

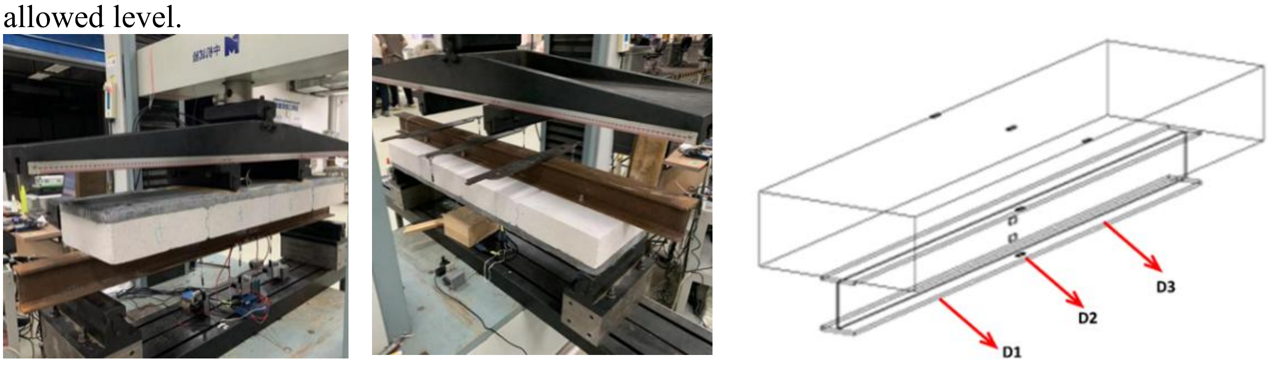
The specimen design and geometries can be found in Fig. 2. The steel beams with dimensions of 100mm x 68mm x 5mm x 8mm are used with 12mm holes pre-drilled, as shown in Fig. 2 b). Precast AAC slabs with dimensions of 300mm x 300mm x 100mm with 10mm pre-drilled holes were placed side by side on the top flange along the steel beam. Butterfly studs made of 304 stainless steel, as shown in Fig.2 b) were inserted into the AAC panel (300mm x 300mm x 100mm), and 20mm of UHPC concrete was cast on top of the AAC slabs. The size of the butterfly studs is M10x120mm. The total length of the specimen is 1200 mm, and four rows of bolt connectors were installed. The 18.57 N·m pre-tension force was applied to all bolts to ensure uniform fastening. Two specimens with the same configuration were prepared for positive and negative bending scenarios.



a. Cross section b. Top View

Fig. 2 Design of composite panel

The composite panel was subjected to positive and negative bending, as shown in Fig. 3 a) and b). The four-point loading method was used with a clear span of 1800 mm and a space between the loading points of 600 mm. Three displacement string pots were set at the midpoint and quarter points of the panel. Seven strain gauges were applied at the midspan, with three on top of the UHPFRC layer (s5,s6,s7) and four on the steel beam at different heights (s1-s4), as shown in Fig. 3 c). Displacement control at 1 mm/minute was used to control the loading process. The test stopped when the load dropped below 50% of the peak loading or if the displacement reached the maximum allowed level.



a. Positive moment b. Negative moment c. Instrumentation plan

Fig. 3 Test setup and instrumentation

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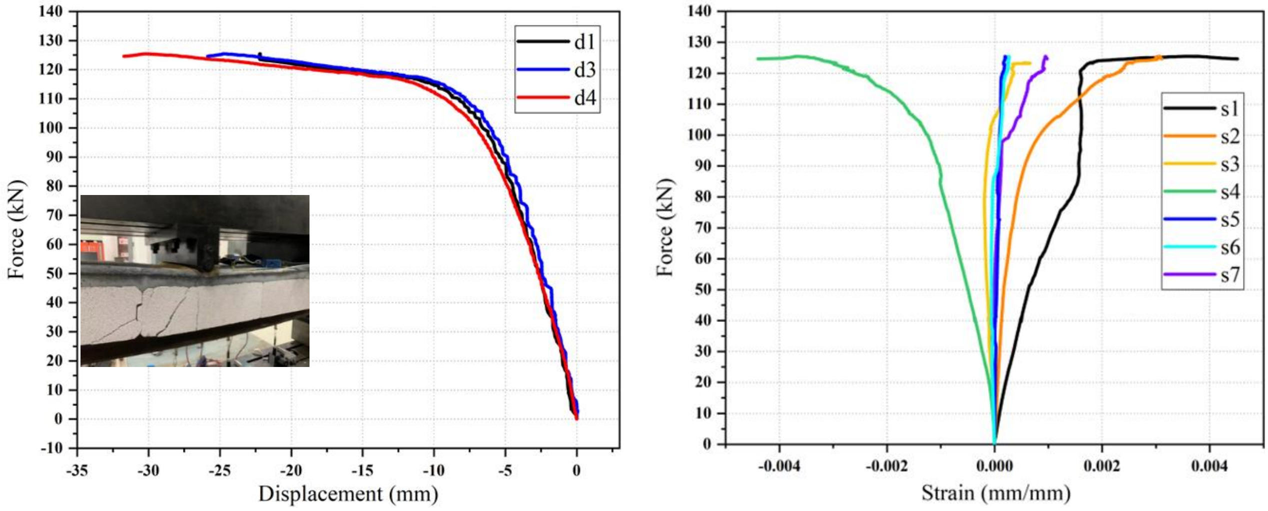
4. Experimental Results

4.1 Positive Bending Moment

The displacement versus force and strain versus force diagrams are shown in Fig. 4a) and b), respectively. The trends and values of the displacements are very close to each other. Two stages of responses were identified. In the first stage, the relative slip between the steel plate and concrete slab is very small, and the load-displacement curve is essentially linear. Diagonal cracks in the AAC layer near the loading point appeared toward the end of the first stage. The significant slip occurred when the load increased, and the specimen entered the second stage.

Along with the yielding of the steel beam, the curve became flat, and the diagonal crack widened significantly. The test stopped due to excessive deformation, and the peak loading capacity is around 125 kN, which is 31.5% higher than the pure steel beam at 95 kN. The responses of strain gauges installed on the steel beam worked properly, which indicates a neutral axis slightly above the middle height of the section due to the existence of the top concrete layer. The responses of strain gauges on top of concrete are much smaller. The pattern changed suddenly after reaching 80 kN, which corresponds to the onset yielding of the steel beam.



a. Displacement versus force b. Strain versus force

Fig. 4 Test setup and instrumentation

4.2 Negative Bending Moment

The displacement versus force and strain versus force diagrams are shown in Fig. 5a) and b) for the specimen tested under negative bending moment, respectively. The specimen behaves linearly until reaching a load level of 80 kN. Then, there is a sudden load drop along with the cracking of the UHPFRC layer towards one side of the support. Horizontal cracks in the AAC layer can also be observed and widened quickly. The UHPFRC layer is fully mobilized based on the strain versus force curves. However, due to the low tensile strength of the UHPFRC material, the contribution to the resistance of the negative bending moment is not significant. It seems the bolted connector may not be sufficient to resist the shear force required in the negative bending scenario since the load shall be transferred through connectors to the steel girder, and the local failure may happen at the UHPFRC layer. The weak tensile strength of AAC may also contribute to the sudden failure and drop of the load. Based on the strain profile of the steel beam, it can be concluded that the neutral axis at the midspan was located slightly below the middle height of the beam.

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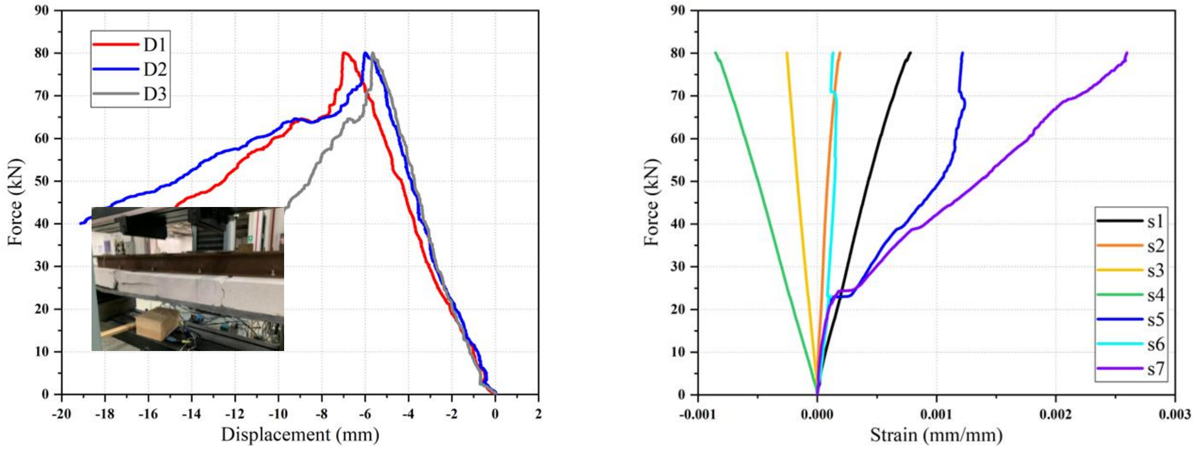

a. Displacement versus force b. strain versus force

Fig. 5 Test setup and instrumentation

5. Conclusion and Discussions

Flexural tests have been conducted on two UHPFRC-AAC-Steel composite panels under the positive and negative bending moment, respectively. The following preliminary conclusion can be drawn.

(1) Certain composite actions can be achieved through the bolted connections. The peak load reached 125 kN, which is 31.5% higher than that of the pure steel beam.

The composite action under the negative bending moment is negligible, which is mainly due to the local failure of the UHPFRC layer. The low tensile strength of AAC also triggered the premature failure.

(2) Further Investigation will adopt more bolt connections, and the impact of the thickness of the UHPFRC layer on the strength of the steel beam will be investigated.

Acknowledgements

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