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Failure Mechanism of Foam Concrete with C-Channel Embedment

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Abstract

Forty-eight tests have been carried out to find of the failure mode of a new type of the foam concrete using C-Channels as embedment. Four groups of foam concrete specimens with various embedment depths of the steel in the concrete. The modes of failure of this new type of structure are summarized, which include the independent failure of the C-Channels with and without a concrete block inside the channel as well as the combined failure of the two channels, and the failure of the extrusion block. It is concluded that the failure involves independent slippage between two C-Channels, and the steel and the foam concrete blocks inside the C-Channels.

Keywords: *bond-slip; C-Channel; cold formed steel; foam concrete; fly ash*

1. Introduction

The foam concrete is made of cement and fly ash with a compressive strength between 9 and 24 MPa with different densities. With a minimum of 20% (per volume) foam entrained into the plastic mortar. The density of foam concrete usually varies from 400 kg/m³ to 1600 kg/m³. Although foam concrete has been primarily used for non-structural members, there is an increasing trend for its use in structural support (Mohamad et al. [1]). The compression and flexural behaviour of foam concrete have been studied. Due to its inherent low density and low strength, foam concrete is often used with steel reinforcements or composites steel (Flores-Johnson and Li [2], Ikponmwosa et al. [3])

However, when using steel embedment as a means of reinforcement to provide tensile, bending and compression resistance, the mechanical characteristics is found to be greatly improved (Heath [4], Warren G.E. [5]) Therefore, in this paper, the compressive load on an embedded double C-Channel has been experimentally studied and theoretically analysed. The objective of the work is to understand the bond-slip characteristics between steel and foam concrete. The failure mechanism of the steel-foam concrete is also investigated.

In studying the bond-slip characteristics between steel and foam concrete, Ramezani et al. [6] carried out pull-out testing of galvanized steel strips in foam concrete. The bond-stress versus slip displacement showed a typical hardening and softening behaviours. In order to improve the anchorage of the steel strips, holes were punched into the steel. The pull-out resistance was found to be directly proportional to the area of the holes which represents more bonding between the steel and the concrete. However, their analysis showed that the steel strip experiences non-uniform straining which results in a larger displacement at the peak force when the bonding increases (by increasing the diameter and circumference of the holes). Flores-Johnson and Li [2] conducted experiments on plain and fibre reinforced foam concrete with corrugated steel panels. For a foam concrete density of 1200 kg/m^3, the uniaxial compressive strength of the concrete was measured to be about 5 MPa with a uniaxial compression elastic modulus of about 1 GPa. The fibre reinforced foam concrete had almost twice the uniaxial compressive strength, but a slight increase in the elastic modulus by about

20%. A typical stress-strain plot showed a peak compression followed by a rapid decrease in the resistance to a residual value. The residual value refers to the resistance of the material after reaching the peak value. The residual value was zero in some cases.

From above literature review, though some research on the experimental tests of foam concrete have been conducted, little research for foam concrete with steel embedment has been made in the past, therefore the research on the foam concrete using steel embedment's was carried by the authors and the results is shown in this paper. In the research presented in this paper, the density of the foam concrete varies from 800 to 1600 kg/m^3 which provide a good range of compressive and shear strengths. Laboratory tests have been carried out on foam concrete with C-Channel steel to study the bonding and interface characteristics of steel and concrete.

2. Test set up

A series of experiments were carried out in Jilin Jianzhu University, China to determine the failure mechanism of cold formed steel C-Channels embedded foam concrete. As it is shown in Figure 1, vertical compressive forces are applied onto the C-Channels. The foam concrete specimen is supported at its base. The thickness of channels is 3 mm, with a length and width of 120 x 50 mm respectively. The embedment depth of the C-Channel in the foam concrete varied, depending on the size of the foam concrete block. The concrete block has a rectangular cross section of 440 x 360 mm and the embedment depth varies from 100 to 400 mm. In order to study the stress transfer from the channel to the foam concrete, four groups of specimens were tested. Groups A, B, C, and D have a specimen depth of 100, 200, 300 and 400 mm respectively (see Figure 2). Four different densities were studied in each group. The specimens had a density of 800, 1000, 1200 and 1600 kg/m^3 respectively. As it is shown in Table 1, for each density of the foam concrete, three tests were carried out; to ensure the reproducibility of the results. Increases in density result in high compressive and shear strength as well as an increase in the modulus of the material.

Table 1. Configurations of Test Specimens

Group	Specimen Number	Depth (mm)	Foam Density (kg/m^3)	Stirrup Configuration	Stirrup Percentage
A	A1-A3	100	800	ϕ6@60[a]	0.55%
	A4-A6	100	1000	ϕ6@60	0.55%
	A7-A9	100	1200	ϕ6@60	0.55%
	A10-A12	100	1600	ϕ6@60	0.55%
B	B1-B3	200	800	ϕ6@80[b]	0.41%
	B4-B6	200	1000	ϕ6@80	0.41%
	B7-B9	200	1200	ϕ6@80	0.41%
	B10-B12	200	1600	ϕ6@80	0.41%
C	C1-C3	300	800	ϕ6@85[c]	0.39%
	C4-C6	300	1000	ϕ6@85	0.39%
	C7-C9	300	1200	ϕ6@85	0.39%
	C10-C12	300	1600	ϕ6@85	0.39%
D	D1-D3	400	800	ϕ6@90[d]	0.36%
	D4-D6	400	1000	ϕ6@90	0.36%
	D7-D9	400	1200	ϕ6@90	0.36%
	D10-D12	400	1600	ϕ6@90	0.36%

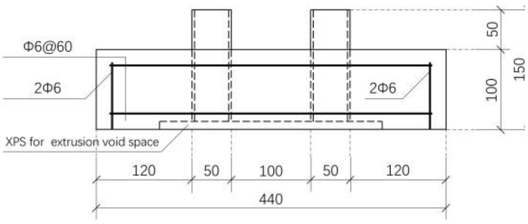
Note: Stirrup has 20 mm concrete cover.
[a] Denotes grade II bar, with diameter of 6 mm, and spacing of 60 mm.
[b] Denotes grade II bar, with diameter of 6 mm, and spacing of 80 mm.
[c] Denotes grade II bar, with diameter of 6 mm, and spacing of 85 mm.
[d] Denotes grade II bar, with diameter of 6 mm, and spacing of 90 mm.

2.1. Test arrangement

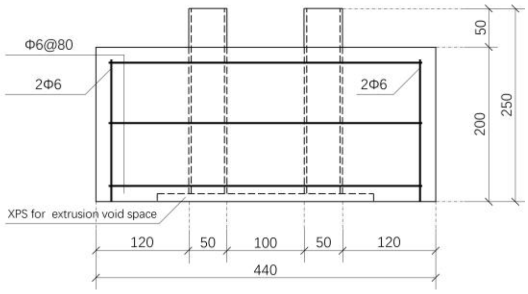
The reinforcement used in the foam concrete blocks are 6 mm diameter rebars with two to five stirrups, see Figure 2. The stirrups have a 20-mm concrete cover. The stirrups provide lateral support and confinement of the foam concrete blocks when they are subjected to vertical shear through the steel channels, thus minimizing the splitting failure of the concrete blocks.

Fig. 1. Test Rigs for Foam concrete specimens test

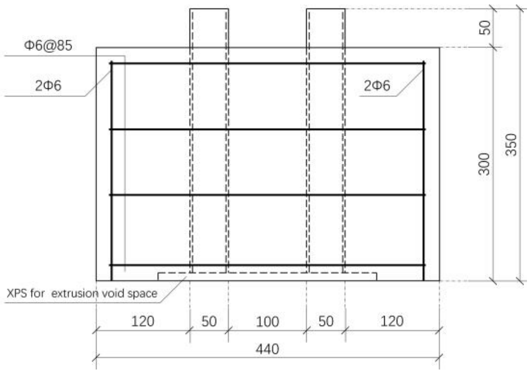
As it is shown in Figure 1, the vertical compressive forces were loaded directly on the steel channels. In order to investigate longitudinal shear stress and slips between the steel channels and foam concrete, an extrusion void space was created at the bottom of the specimen by using polystyrene when the concrete was poured, see Figure 2. The extrusion space at the bottom of the specimen is 280 x 180 x 10 mm in size, thus allowing a maximum of 10 mm for the vertical displacement of the steel channel. A panel saw was used to cut the wood for the template which formed the mold for the foam concrete assembly, and double sided adhesive tape was used to hold tailored extrusion plates onto the bottom of the mold. Since the foam concrete has a low density, there is a good possibility that the foam bubbles could easily burst and evaporation would take place, thus resulting in higher volume shrinkage during curing. Therefore, the depth of the mold was slightly greater than the height specified in the design of the concrete specimen used for testing. The coupon test for the C channels and foam concrete cubes were also conducted in the same time to monitoring the strength of the C channels and foam concretes.



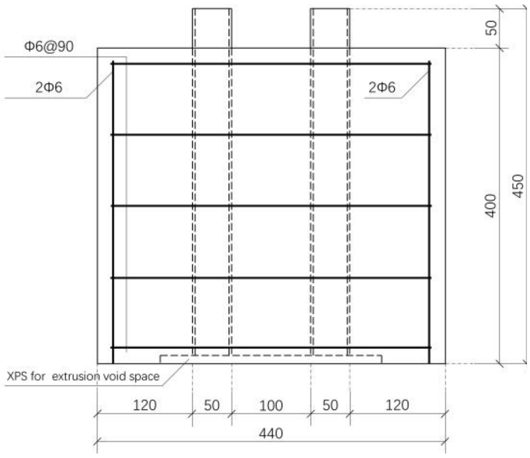
(a) Group A



(b) Group B



(c) Group C



(d) Group D

Fig. 2. Sections of Foam Concrete Specimens and C-Channels (XPS – extruded polystyrene to provide extrusion cavity, all dimensions in mm)

2.2. Test arrangement

2.2.1 Foam concrete

The foam concrete was casted with cement, sand, fly ash and foam. Cement and fly ash were mixed by using a high-speed electric mixer. Foam was added to the cement, and fly ash was added into the cement during the casting procedure. The slurry was poured into a steel mold with the reinforcing bars, stirrups, and C-

Channels in place. All the samples have a fly ash/cement ratio of 25% and a water/cement ratio of 0.5. The water cement ratio was kept constant during the testing to provide a consistent strength of the foam concrete. However, the strength will change because of the density which is controlled by changing the volume of the foam. The composition of the materials in the foam concrete specimens is shown in Table 2.

Table 2. Composition of Foam Concrete

Density (kg/m^3)	Weight of Cement (kg/m^3)	Weight of Fly Ash (kg/m^3)	Weight of Water (kg/m^3)	Weight of Blowing Agent (kg/m^3)	Water/ Cement	Fly Ash/ Cement
800	456.36	114.09	228.18	1.37	0.50	0.25
1000	570.77	142.69	285.38	1.15	0.50	0.25
1200	685.18	171.29	342.59	0.94	0.50	0.25
1600	914.00	228.50	457.00	0.51	0.50	0.25

The foam concrete was initially cured in water for 24 hours and subsequently air cured in the mold for 7 days. After 7 days, the specimens were removed from the mold and cured for 28 days before testing. A plastic enclosure was used to surround the groups of concrete specimens to keep the foam concrete from drying, thus reducing the possibility of shrinkage cracks.

2.2.2 C-Channels

The C-Channels are thin-walled C type cold formed steel with grade Q235. The C120 has a cross-sectional size of 120x 50x20 with a thickness of 3 mm. Vertical round bars with a diameter of 6 mm and made of Q235 grade steel were used for the transverse reinforcement. The C-Channels were prefabricated in factory and cold formed, and then manually cut and polished. The test specimens were made of steel with double sections; therefore, in the final stages of preparing the specimens, grinding was carried out to align the two channels to ensure that there was even loading on the flat and smooth contact surfaces on both channels. The round bars were modified, and cut, bent, bound and spot welded for the horizontal and vertical reinforcements.

3. Testing procedures

Prior to the testing, the C-Channels and foam concrete were visually examined for any obvious defects. To determine the mechanical characteristics of the C-Channel steel, specimens of the C-Channel steel and round re-bars were tested by following the current Chinese national standards found in GB6397-86, 'Metal Tensile Test Specimens' (National Standard of the People's Republic of China, 1986). The yield stress, ultimate tensile strength, elastic modulus, and Poisson's ratio are shown in Table 3. The yield stress of the cold formed steel is about 330 MPa with an ultimate tensile strength of 488 MPa. The elastic modulus is around 208 GPa with a Poisson's ratio of 0.26. The round re-bars have slightly lower mechanical parameters.

Table 3. Properties of Cold Formed Steel C-Channel and Re-bars

Specimen Type	Specimen No.	Yield Strength (MPa)	Ultimate Strength (MPa)	Elastic Modulus (GPa)	Poisson's Ratio	Elongation
Cold Formed Steel	1	330	488	208	0.26	0.27
	2	330	489	209	0.26	0.27
	3	329	487	209	0.26	0.27
	Average	330	488	208	0.26	0.27
	Std Dev	0.87	0.92	0.58		
Round bar	1	319	455	205	0.25	0.27
	2	317	452	205	0.25	0.27
	3	314	448	205	0.25	0.27
	Average	317	452	205	0.25	0.27
	Std Dev	2.49	3.91			

Testing was carried out at the Jilin Jianzhu University in Changchun, China, by using a YAW-2000kN hydraulic compression testing machine (as it is shown in Figure 1). This hydraulic compression testing machine can be programmed by using a micro-control system which controls the load increment and records load-displacement measurements at the required intervals. The system can also detect the peak load and switch to a displacement control state to measure the post peak softening response. Since the strength of the foam concrete varied, depending on its density, load increments of 5, 10, 15 and 20kN were used on the specimens in Groups A, B, C, and D respectively. The rate of the application of the load was 0.2 kN/s until it reached the peak force. When the sample was loaded under displacement control, the loading rate was 0.01mm/s. The properties of the foam concrete of different densities are shown in Table 4.

Foam concrete blocks with a C-Channel were tested under compression. Each test was repeated three times to account for small variations in the test results. The average value of each test is reported as follows.

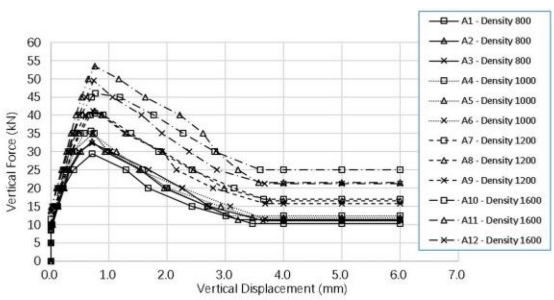
Table 4 Properties of Foam Concrete

Test Block No.	Density (kg/m^3)	Failure Loading (kN)	Compressive Strength (MPa)	Average Compressive Strength (MPa) (Std Dev)	Average Failure Loading (kN)
800-1	813	224	10		
800-2	807	210	9.3	9.62	1.18
800-3	808	216	9.6	(0.32)	
1000-1	1003	297	13.2		
1000-2	1006	304	13.5	13.57	1.48
1000-3	1007	316	14	(0.42)	
1200-1	1211	463	18.3		
1200-2	1209	448	17.9	18.08	1.79
1200-3	1206	481	18.1	(0.18)	
1600-1	1604	552	24.5		
1600-2	1598	518	23	23.68	2.14
1600-3	1596	528	23.5	(0.78)	

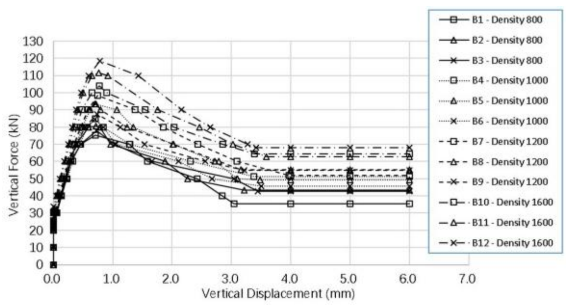
4. Tests Results

Group A specimens have the smallest depth of 100 mm and therefore the least amount of surface area in the concrete bonding with the steel. The vertical force versus vertical displacement plots are shown in Figure 3A. With different densities, the maximum measured vertical forces are 31, 35, 41, and 53 KN for foam concrete densities of 800, 1000, 1200 and 1600 kg/m3 respectively. All the specimens show a peak force followed by a steady decline of the vertical force to a residual value that varies from 12 to 23 kN. The residual values are reached at a vertical displacement between 3 to 4 mm. The tests were terminated at 6 mm. It was observed that all the specimens reach the peak stress at a vertical displacement of about 0.7 mm, regardless of the density of the foam concrete.

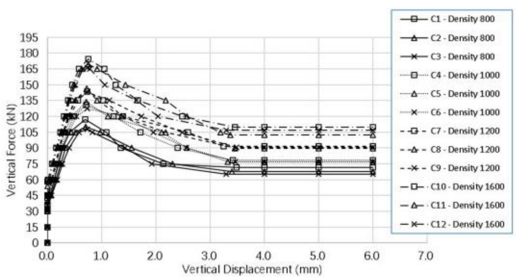
Similar test results were obtained for the specimens in Groups B, C, and D as shown in Figures 3B, 3C, and 3D respectively. It is noted that the specimens in Groups B, C, and D have concrete embedment depths of 200, 300 and 400 mm respectively. The results show remarkable similarity with the peak force measured at a vertical displacement of approximately 0.7 mm. In all cases, there is a steady decline from the peak to residual force and the residual force is reached at a displacement between 3 and 4 mm. Of course, the peak and residual forces increase with higher density and increased specimen thickness.



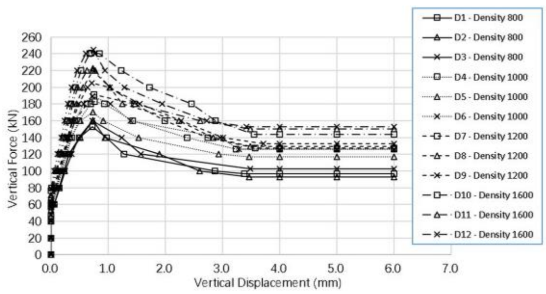
(a) Force Displacement Plot of Group A Specimens



(b) Force Displacement Plot of Group B Specimens



(c) Force Displacement Plot of Group C Specimens



(d) Force Displacement Plot of Group D Specimens

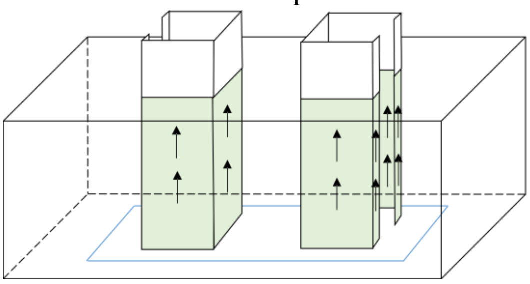
Figs.3 Force Displacement Plot of All Specimens

4.4 Modes of Failure

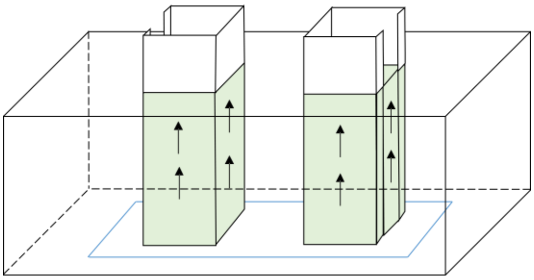
Based on the experiment results and research from other researchers. Figure 4 summarized the modes of failure. Four modes of failure can be identified.

1. Mode of failure 1 and 1A

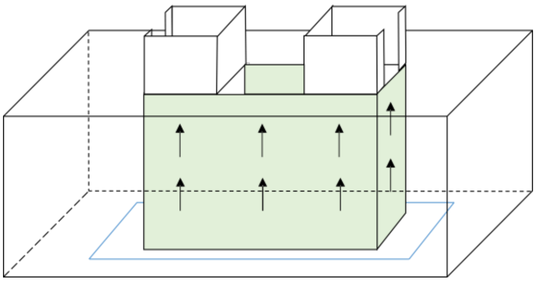
Bond failure at the interface between the steel and foam concrete around the perimeter of the C-Channel, that is, both the inside and outside perimeters. The failure involves the core material inside the C-Channel. Mode 1A involves failure at the interface between the steel and foam concrete on the outside perimeter, but not on the inside perimeter of the C-Channel. In developing a mechanism of failure in Mode 1A, failure occurs in the foam concrete between the steel flanges.



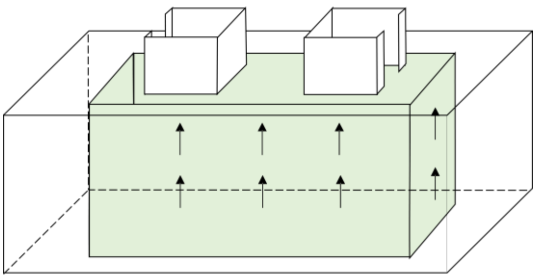
(a) Mode 1 – Shearing at steel concrete contact including inside C channel



(b) Mode 1A – Shearing at steel concrete contact and concrete inside C channel fails as a block



(c) Mode 2 – Shearing of two channels together



(d) Mode 3 – Shearing of extrusion block

Figs. 4 Modes of Failure

2. Mode 2 failure of the two C-Channels together
3. Mode 3 concrete block extrusion

Based on the experimental observations, Modes 2 and 3 have not been observed for the range of densities and strengths of the foam concrete that were tested. Both Modes 2 and 3 provide much higher resistances compared to Modes 1 and 1A since they involve much larger surface areas of concrete failure.

Previous studies have found that the failure of brittle concrete is mainly attributed to the splitting of the whole concrete (Min et al. [7], Bažant and Cedolin [8], Stratford and Burgoyne [9]), but rarely in cases where the core area is split as found from the failure modes of the specimens in this study. The reasons could be as follows: The C section steel has greater lateral restraint, which influences the stress state of the concrete in the core areas, due to the characteristics of the cross section and lack of thickness of the cold formed thin walled C section steel samples. On the other hand, foam concrete has lower strength because it does not contain coarse aggregates, and therefore it has lower shear strength than ordinary concrete. Consequently, when there is sufficient lateral restraint, the foam concrete that is outside the core area will not incur severe damage.

The embedment length of the specimens in Group A was shorter in comparison to those in Groups B, C, and D. Therefore, the inferred embedment length is too short, thus leading to failure due to splitting in the core areas of the foam concrete. In comparing against the density of the specimens in Group A, it was found that splitting occurs in the core areas of the samples with a density of 800 and 1000 kg/m^3. However, it was also found that splitting occurs in the core areas of the specimens with a density of 1200 and 1600 kg/m^3 in both Groups A and B. Therefore, it can be inferred that as the strength of the foam concrete increases, the brittleness also increases, in that the cracking damage on the bottom surface is more pronounced.

5. Conclusions

Based on the study represented in this paper, following conclusions can be made:

- Three major failure modes of this type of structure are discovered
- The failure mechanism of the double C-Channels involves shear failure at the interface between the steel and concrete and shearing portion of the concrete inside the channels.
- Depends on the strength of the foam concrete, the failure mode that mostly matches the peak forces is Mode1A on the failure at the steel-concrete interface and through the concrete. This also agrees with the experimental findings based on observations of the bottom of the specimens.

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