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Experimental study on ultra-lightweight-concrete encased cold-formed steel structures Part I: Stability behaviour of elements subjected to bending

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ABSTRACT

In the field of structural engineering the design of cost efficient structures is highly important. This led to the development of cold-formed steel structures (CFS). An advanced CFS structure is introduced in this paper, which uses a special type of polystyrene aggregate concrete (PAC) as bracing material. This material has beneficial insulating and fire protection properties, which makes it a reasonable choice for residential buildings. An experimental program was performed, to gain information on the flexural and axial behaviour of PAC-braced CFS elements and panels. Both unbraced and braced members were tested to gain information on increment of load-bearing capacity. Several different element sizes were used to be able to investigate the different stability failure modes (i.e. local, distortional and global). Results showed that PAC was able to restrain the global and distortional buckling modes of steel elements, thus providing "full bracing" in most practical cases. These results are introduced in two papers (Part I and II), detailing the failure modes, load increments and the effect of composite action. In this paper – Part I – the background and the results of bending tests are presented, and the experiments on the compression elements are detailed in Part II [1].

1. Introduction

In the field of structural engineering the design of cost efficient structures is highly important. The intention of designing efficient structures led the way to develop steel structures made of cold-formed steel (CFS) elements. The research of the theoretical background began in the middle of the 20th century, and even nowadays many papers are written about this topic. The long research process resulted in advanced design codes (AISI S100-07 in the USA, AS/NZS 4600 in Australia and New Zeeland, EC-1-3 in Europe), which allowed the spread of CFS elements. In recent years CFS elements are used more and more as primary load bearing structures in pallet racks, industrial buildings and residential houses. CFS structures are found to be efficient for moderate load levels and provide fast and effective construction method, which reduces the cost of erection.

During the construction of CFS residential buildings, however, one of the disadvantageous features is that the several requirements arising during design can only be satisfied by several different materials (heat insulation, insulation against moist, finishing of surface). This drawback can be avoided if a single material with optimised material properties is used. Such building material may be the polystyrene aggregate concrete (PAC), which contains polystyrene granules and admixtures to improve material properties [2]. Since the mixture used for this research does not include gravel, the mechanical behaviour of the PAC is quite similar to those produced by foams, and is governed by the amount of cement paste [3]. For practical application the material properties can be characterised through the bulk density of the mixture, which is also the function of the amount of cement paste. Nowadays PAC is mostly used for non-structural elements such as insulation, filling material and fire protection [4].

To illuminate the mechanical behaviour of PAC, compression and three-point-bending material tests were carried out on $250 \times 70 \times 70\ mm^3$ prisms. During the compression tests the end-to-end deformations and the deformations of the middle 10 cm zone were measured separately, thus allowing to investigate the behaviour of the load introduction zone and the pure compression zone separately. In the case of the flexural tests the deflection was recorded at mid-span where the load was applied. The results are shown in Fig. 1. Under compression the middle zone of the specimen remained fully in the elastic range, no damage occurred here. Regarding the overall deformations a plateau is present, which implies that the failure of the specimen was localised at the

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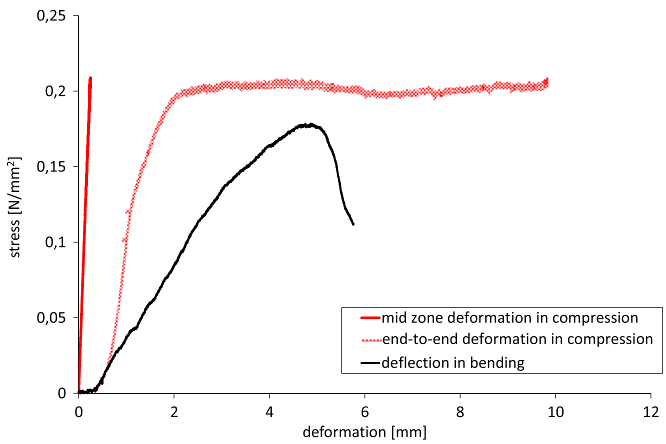

Fig. 1. Stress-deformation behaviour of PAC material subjected to compression and bending.

load introduction zone. Based on the flexural tests, in the tensile regime the material behaviour is elastic until the fracture. As it is shown in Fig. 1, the tensile and compressive strength of the material are quite close to one another. Altogether the stress-deformation curves are similar to those produced by elastic-brittle foams [5].

Using PAC as infill of walls in light-gauge residential buildings the beneficial properties of the material may be utilised. Good heat and moisture insulation capacity could be achieved, while the fire protection could also be satisfied by new developments of admixtures. Moreover, since the PAC would fully surround the CFS elements, bracing of CFS elements can also be counted on, which results in even more cost efficient structures.

The aim of a current research and development project at the Department of Structural Engineering, Budapest University of Technology and Economics, is to develop a design method for residential buildings made of PAC encased CFS elements. The complexity of stability phenomena, which govern the failure modes of elements and connections require experimental tests to understand and evaluate the behaviour. Thus as the first step of research work, several tests on beams and columns were performed to gain information on the load-bearing behaviour of the structural system under investigation. Both member tests (with single beam or column) and large scale panel tests (made up of several members) were studied. The results referring beam tests are presented in the current paper, while the results on axial compression tests can be found in the related paper [1].

Since the governing failure mode of CFS thin-walled elements is buckling (either local, distortional or global), intensive experimental research were carried out on the effect of secondary structures, which can significantly increase the standardised ultimate strength of steel elements. The first tests were reported in the 1940-ies by Winter and others in [6], where the required stiffness of the sheathing fastened to the steel element was investigated to achieve full bracing. Based on these results the American Iron and Steel Institute released a standard in which the effect of discrete bracing, i.e. where the bracing system develops its beneficial effect through discrete connection points, was handled. Other authors treated the sheathing as a shear diaphragm [7], which was also included in standards temporarily.

The field of cold-formed thin-walled braced steel elements remains an active research topic, although no such results can be found in the literature for elements subjected to bending. Peterman investigated beam-columns made up of lipped channel sections with various sheathing plates [8]. OSB and gypsum boards were used in the experiments, where symmetrical and asymmetrical build-ups were investigated to derive design formulae. Results showed that for the case of interacting bending moment and axial compression the effect of sheathing is significant, the failure was governed by local mechanisms instead of global which was observed in the unbraced experiments. For continuously braced members subjected to bending a quite innovative example can be found in [9], where sandwich plates are introduced made up of foamed concrete and corrugated CFS sheathing. Since the foamed concrete shows rigid material behaviour it cannot be used as a primary load-bearing structure, but it can serve as a secondary, bracing material. Utilising the bracing capacity of concrete a very ductile structure can be produced. The dominant parameters influencing the load-bearing capacity were identified by detailed experimental and numerical investigation.

Although several researchers work on the field of braced CFS elements, yet few paper deals with braced flexural elements, and no similar structural system was investigated as continuously braced PAC encased steel structures. The aim of the flexural member tests was to study the behaviour, the failure mode and the increment of load-bearing capacity for single C-channel (asymmetric) and double C-channel (symmetric) cross-sections. Panel tests were performed to investigate arrangements similar to real structures in arrangement and loading conditions and also to confirm the advantageous behaviour of PAC encased CFS beam elements in full scale.

2. Member tests

2.1. Test program

In the member tests the behaviour of single beam elements were investigated through four-point bending tests. A loading frame was designed as shown in Fig. 2, where the position of supports and load introduction (both made of hinges) could be varied. Lateral displacements were restricted only at the end supports of the beam. The weight of the loading beam was measured and added to the total load at post-processing of experimental results. Lifting and loading was done with two hydraulic jacks.

Two different cross-sections were tested, both types made up of the same lipped C-channel sections with 200 mm of total height, 41 mm total width and 13 mm of lips. Nominal plate thickness of 1.5 mm was used and the actual thicknesses were measured. The first type of cross-section was a built-up I-section (Fig.3(a)) where the C-sections were fixed together with self-drilling screws. The second type was also made up by two lipped channels (battened type arrangement), but with 120 mm distance between them (Fig. 3(b)). The connection was provided by channel sections between the support and load transmitting point, thus symmetrical and also asymmetrical sections could be investigated. The second type of cross-section is referred to as 2C-section. The applied PAC-block dimensions were the same for each specimen, 200 mm × 400 mm.

To gain information on different failure modes (local, distortional, global) three element lengths were used, namely 1000 mm, 2300 mm and 4000 mm. Two 1000 mm long specimen types were investigated, one with simple web, and one with stiffened web by means of an overlaid plate with same thickness as the base section. The distance of supports and load transferring points was 300 mm for the 1000 mm long specimens, while 600 mm in all other cases. The total span of a member was 100 mm less than the length of the element. To prevent crippling of the web wood-filling was applied at the supports. Material tests were performed prior to the structural tests, to determine the material properties of steel and PAC. Five coupon tests were carried out for steel (for results, along with those obtained from the panel tests, see Table 1), and