Experimental investigation of the buckling interaction between individual components of a built-up steel beam

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ABSTRACT. An experimental program on built-up cold-formed steel beams carried out at The University of Sheffield is presented. The specimens were assembled from plain channel sections with nominal thicknesses of 1.2 mm and 1.5 mm. The specimens were tested in a four-point bending configuration and were designed to fail by local bucking within the constant moment span. Three different connector spacings were used to study their effect on the ultimate capacity of the built-up specimens and on the way the individual sections interact with each other as they buckle. Test coupons, extracted from the corners and the flat portions of the component sections, were tested in order to determine their material properties. The out-of-plane imperfections of each built-up specimen were also recorded using a laser sensor.
The tests revealed that the interaction between the component sections is significantly affected by the connector spacing and that reducing the spacing between connectors results in an increase of the ultimate capacity.

KEYWORDS. Built-up beam; Experiment; Cold-formed steel; Stability; Local Buckling.

INTRODUCTION

The use of cold-formed steel sections as load-bearing members in structures has become increasingly popular during the past decade. It is no longer surprising to see medium-rise multi-storey buildings or cold-formed steel portal frames being constructed entirely out of cold-formed steel [1, 2]. A brief review of the recent advances and the new applications of load-bearing cold-formed steel members, with special focus on North America, has been presented in [3]. Figure 1 shows a 6-storey building constructed using a cold-formed steel framing solution, which, incidentally, is located right next to the venue where this conference is taking place. These new areas of application are putting increased demands on cold-formed structural members in term of the span length and the load-carrying capacity these members need to provide.
Due to the way cold-formed steel members are fabricated, they tend to have a mono-symmetrical or a point-symmetrical cross-section. Also, due to their typically high wall slenderness, their ultimate capacity is normally limited by buckling instabilities. These limitations are at odds with the increasing requirements which cold-formed structural members are experiencing. However, a relatively simple way to meet these new demands consists of joining two or more sections together to form a built-up section. A good example of the benefit a built-up section can provide has been reported in [4],

in which the ultimate capacity of the section constructed by joining two LiteSteel Beam (LSB) sections back-to-back was more than twice the ultimate capacity of the individual LSB sections.

In this paper an experimental program carried out on built-up steel beams, assembled by bolting four plain channels together, is described. The specimens were tested in a four-point bending configuration and were designed to fail by local buckling of their component sections along the constant-moment span. The specimens were tested with three different connector spacings and each test was repeated in order to gain increased confidence in the results.

Figure 1: 6-storey building constructed using a cold-formed steel framing system in Sheffield.

SPECIMEN GEOMETRY AND LABELING

The built-up specimens were constructed by bolting two channels of 1.5 mm thickness back-to-back, and then bolting two channels of 1.2 mm thickness to the flanges of these channels, as illustrated in Figure 2a. M6 bolts, tightened with a torque of 10 Nm, were used to assemble the specimens. All the steel sections were fabricated from pre-galvanized steel plates with a nominal yield stress of 450 MPa and a zinc coating with a nominal thickness of 0.04 mm. The built-up beams had a total length of 3400 mm, with a nominal distance between the end supports of 3000 mm. The specimens were loaded at two discrete locations, a distance of 1600 mm apart. The portion of the beam within these loading points constituted the constant moment span, while the portions of the beam which fell outside this region are referred to as the shear spans. The built-up specimens were designed with zero, two or three equally spaced connectors along the constant moment span. The spacing between the connectors along the shear spans was 100 mm for all the test specimens, as shown in Figure 2b, in order to avoid failure outside the constant moment region. The label used in this paper to refer to each of the test specimens consists of the letter 'B', followed by a hyphen and the number of rows of connectors within the constant moment span. As each test was repeated, the letters 'a' and 'b' were used to differentiate between the first and the second twin specimen tested.

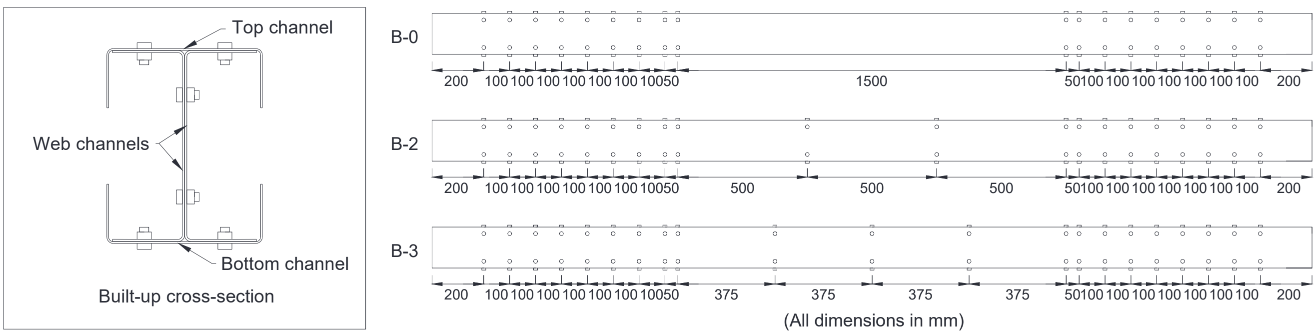

Figure 2: a) Built-up cross-sectional geometry and b) connector distribution along the constant moment and shear spans.

The cross-sectional dimensions of all the individual sections were measured prior to assembling them, and the relative positions of the components within the built-up section were recorded. Table 1 lists the measured dimensions and the relative position of the components, with reference to Figure 2a. All reported measurements correspond to outside dimensions.

Beam	Web channel				Flange channel				Connector spacing (mm)
	location	Web (mm)	Flange (mm)	Thickness (mm)	location	Web (mm)	Flange (mm)	Thickness (mm)	
B-0a	Left	129.36	43.38	1.493	Top	104.35	39.82	1.141	1500
	Right	129.15	43.49	1.487	Bottom	104.10	39.92	1.139	
B-0b	Left	129.31	43.48	1.495	Top	104.24	39.95	1.136	1500
	Right	129.20	43.45	1.493	Bottom	104.05	39.72	1.137	
B-2a	Left	129.26	43.45	1.489	Top	103.95	39.94	1.137	500
	Right	129.13	43.53	1.496	Bottom	104.06	40.04	1.139	
B-2b	Left	128.95	43.78	1.501	Top	104.04	39.99	1.139	500
	Right	129.02	43.66	1.496	Bottom	104.01	39.97	1.144	
B-3a	Left	128.93	43.74	1.498	Top	103.95	39.98	1.141	375
	Right	128.90	43.69	1.501	Bottom	104.18	39.97	1.140	
B-3b	Left	128.83	43.70	1.506	Top	104.22	39.86	1.147	375
	Right	128.87	43.69	1.497	Bottom	103.96	39.93	1.146	
Average		129.08	43.59	1.496		104.09	39.92	1.141	-
St. Dev.		0.183	0.136	0.005		0.129	0.087	0.004	-

Table 1: Measured dimensions of the component sections.

MATERIAL PROPERTIES

The material properties of the component sections were determined by means of tensile coupons tests. As the forming process alters the mechanical properties of the virgin material (and more so with increasing cold-working), separate coupons were extracted from the flat portions and the corner regions of the individual cross-sections. More specifically, for each type of channel section used to construct the built-up geometry, two coupons were taken along the center line of the web and two more from the web-flange junction. Therefore, a total of 8 coupons were tested. The coupons were extracted from the end portions of the beams after they were tested. In this region, the level of strain the specimen experienced during the test was expected to be low enough not to affect the mechanical properties of the steel.

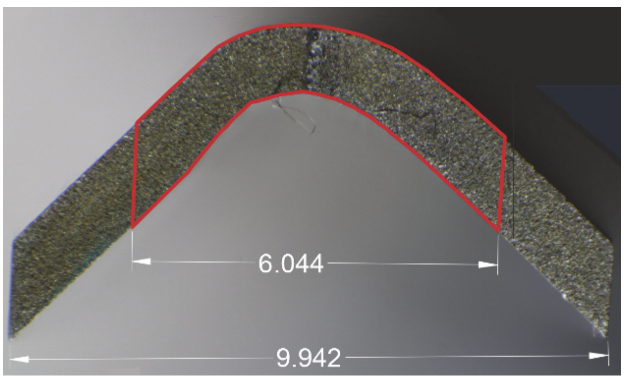

Figure 3: Photograph of the cross-section of one of the corner coupons.

In order to accurately determine the mechanical properties of the component sections (i.e. yield stress, ultimate strength and elastic modulus), special care was taken in measuring the cross-sectional area of the tensile coupons. It is stipulated in [5] that the error in determining the original cross-sectional area of a tensile coupon should not exceed ±2 %. For flat coupons, this can easily be achieved using a micrometer or caliper to measure the thickness and the width of the coupon. However, this technique is not suitable for measuring the cross-sectional area of a curved corner coupon, which was instead determined by taking a macro photograph of the cross-section with a digital camera using the reversing lens technique. The images were then imported into AutoCAD® software and scaled based on the measurement of the width of the end section of the coupon, as illustrated in Figure 3. The width of the coupon along the gauge length was also measured and drawn on the photograph, allowing the area to be calculated.

The process was repeated with pictures taken from the other end of the coupon and the average value of the areas was used. Differences in the calculated areas of less than 1.60 % and 1.94 % were obtained when using the photographs taken from each end of the corner coupons for the 1.2 mm and 1.5 mm thick channels, respectively.

All coupons were tested following the specifications given in the relevant European standard [5]. According to standard practice in the Cold-formed Steel Research Group at The University of Sheffield, the corner coupons were tested in pairs, in order to avoid the introduction of unwanted bending moments during testing [6]. Table 2 lists the average values of the Young's modulus (E), the 0.2% proof stress ($\sigma_{0.2\%}$) and the tensile strength (σ_u) obtained from each pair of twin coupons.

Type	Section	E (GPa)	$\sigma_{0.2\%}$ (MPa)	σ_u (MPa)
Flat	Flange	206	434	465
Flat	Web	206	534	622
Corner	Flange	210	459	472
Corner	Web	213	590	648

Table 2: Coupon test results.

Imperfection measurements

The initial imperfections of the built-up specimens were recorded using the same measuring system described in [6, 7]. As the built-up specimens were designed to fail by local buckling, only the out-of-plane imperfections of those components expected to participate in local buckling were of interest. These imperfections were recorded by moving a laser sensor along several longitudinal lines, as illustrated in Figure 4. The imperfections of the web of the channels were recorded along three lines, while the imperfections of the flanges were measured along two lines. Also, as the test specimens were designed to fail within the constant moment span, only the imperfections within this region were recorded. The measured imperfections in the webs of the top channels and channels comprising the web of the built-up cross-section were smaller than 0.75 mm and 0.83 mm, respectively, while the imperfections in the flanges of the top channels were smaller than 0.66 mm.

Figure 4: Set-up used to measure the out-of-plane imperfections of the built-up specimens.

TEST SET-UP

All the built-up specimens were bent about their major axis using a four-point bending configuration, as illustrated in Figure 5. The built-up specimens were supported at the ends on rollers located 3000 mm apart. A lateral support system was used to restrain the spreader beam against any out-of-plane movement. Friction between the spreader beam and the uprights was reduced by using nylon blocks, which worked as linear bearing pads. The load, applied by a 160 kN actuator, was transmitted from the spreader beam to the test specimen through simple supports (one roller and one pin) located 1600 mm apart. These supports were also designed to restrain any out-of-plane displacement of the test specimen. Distortion of the end sections of the specimens was prevented by packing the cross-section tightly with wooden blocks.

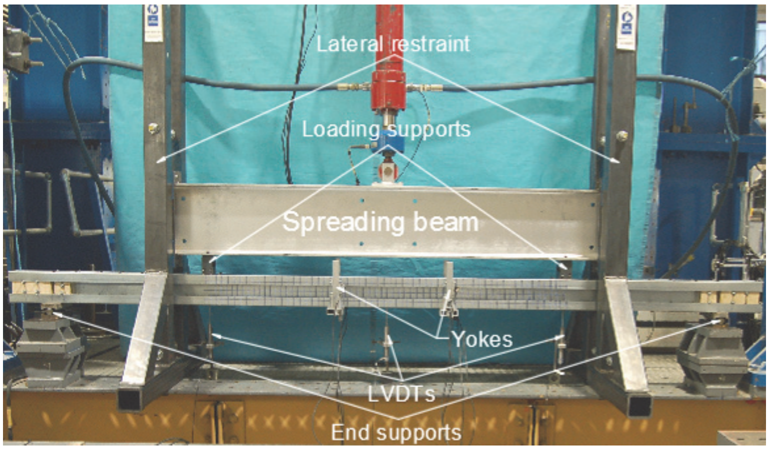

Figure 5: Four-point bending test set-up.

The vertical deflections of the built-up specimens were recorded using three LVDTs. One of them was located at mid-span, while the other two were located below the spreader beam supports. The onset of local bucking was captured by eight potentiometers mounted on two yokes supported by the bottom flange of the specimen (Figure 5).
The load was applied using displacement control at a rate of 1 mm/min. The test was continued until well into the post-buckling range.

TEST RESULTS

All specimens failed due to local buckling in the constant moment region (see Figure 6), with significant interaction taking place between the top channel and the channels comprising the web of the built-up cross-section during the test. The top channel was observed to buckle before the web channels in all test specimens. The potentiometers mounted on the yokes thereby recorded a buckled shape of the top channel which was symmetrical about the plane of bending. The web channels also buckled in a symmetrical shape with respect to the plane of bending only in those specimens without any connectors in the constant moment span. In the remaining specimens, the connectors forced the webs channels to buckle simultaneously in the same direction.
In built-up specimens B-0b, B-3a and B-3b, the buckling pattern of the top channel was seen to be significantly affected by buckling of the web channels. This interaction was most pronounced in the test specimens with three connectors, in which the flanges of the top channel were seen to invert the direction of their buckles when subsequent buckling of the web channels occurred.
Table 3 lists the ultimate capacities obtained for all test specimens, as well as the average value for each pair of twin specimens. The result of test B-0a should thereby be disregarded since the test was carried out without packing the cross-section with wooden blocks and significant lateral distortion of the end sections accompanied by in-plane bending of the top flange was observed, resulting in a slightly lower ultimate capacity. The results show that the specimens with two

connectors experienced an average increase in ultimate capacity of 2.8 % relative to the specimens without connectors, while the specimens with three connectors experienced an average increase in their ultimate capacity of 11.0 %.

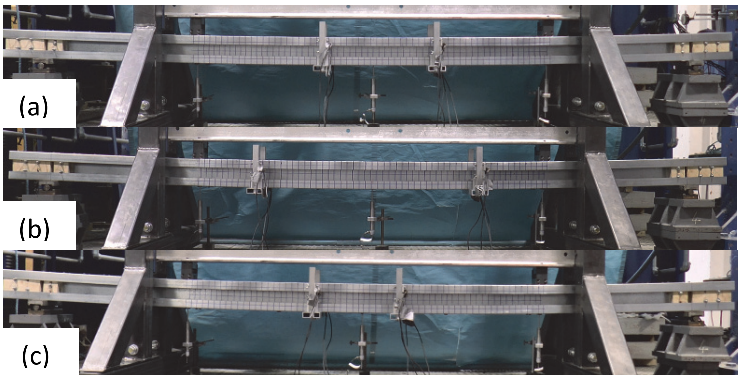

Figure 6: Buckled shape of built-up specimens a) B-0b b) B-2b c) B-3b.

Beam	Ultimate capacity (kNm)	Avg. Ultimate capacity (kNm)
B-0a	(10.56)	11.84
B-0b	11.84	
B-2a	12.51	12.17
B-2b	11.83	
B-3a	13.28	13.14
B-3b	13.01	

Table 3: Ultimate capacities of test specimens.

CONCLUSIONS

The results of an experimental program on six built-up cold-formed steel beams, tested in a four-point bending configuration, have been presented. The paper also details the procedures followed to determine the material properties and the initial out-of-plane imperfections of the specimens.
The test program revealed significant interaction between the components of the built-up specimens while buckling. This interaction was more pronounced in the specimens with shorter connector spacings. The tests also showed a relatively modest increase in the ultimate capacity of the built-up specimens when reducing the spacing between the connectors.

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