

Strengthening of steel I-section beams by wire arc additive manufacturing — Concept and experiments

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ABSTRACT

An experimental investigation to assess the major-axis flexural behaviour of 10 hot-rolled steel I-section beams, strengthened by the addition of material through wire arc additive manufacturing (WAAM) and tested under either four-point or three-point bending conditions, is presented in this study. The ability of WAAM to pre-camber hot-rolled steel I-section beams, as well as to enhance their bending moment resistance and initial elastic stiffness, has been demonstrated. The geometry of the strengthened beam specimens, including the initial imperfections and pre-camber, were obtained by means of 3D laser scanning. Complementary material testing was conducted to obtain the mechanical properties of both the hot-rolled and WAAM steel under monotonic tensile loading. The experimental results showed that significant pre-cambers of approximately 1/200 of the span of the beam could be achieved with only a 2.6% increase in mass. Moreover, increases of between 11.5% and 33.2% in the ultimate bending moment resistance, and increases of between 8.7% and 35.9% in the initial stiffness, were achieved for increases in mass of between just 2.6% and 12.3%. The presented WAAM-strengthening approach can be employed for the strengthening, repair and retrofitting of steel beams in service, as well as for the fabrication of hybrid steel members with improved flexural behaviour in new structures.

1. Introduction

Metal additive manufacturing, or 3D printing, is a method to produce 3D metal objects in a layer by layer additive fashion [1]. Compared to traditional subtractive and formative manufacturing techniques, metal additive manufacturing provides a series of advantages, including the capability of achieving bespoke complex geometries, reducing material waste and cost, and facilitating the application of structural optimisation [2]. Wire arc additive manufacturing (WAAM) or directed energy deposition-arc (DED-arc) additive manufacturing (AM) is a type of metal 3D printing [3,4] that is capable of achieving high deposition rates compared to other metal 3D printing methods, thus offering significant advantages in producing medium to large-scale objects [5]. Having gained extensive attention in aerospace and mechanical engineering [6–8], metal 3D printing techniques, especially WAAM, is also attracting increasing interest in structural engineering and the construction sector [2,9–13]. A pioneering application of WAAM in construction is the world's first 3D printed stainless steel bridge in Amsterdam [14]. The use of WAAM for producing a variety of steel structural members has been explored in [15–19]. The structural behaviour of steel joints and connections manufactured through WAAM has also been investigated in some early works [20–23]. Research on

computer-aided design and physical testing of optimised WAAM steel structures have been presented in [24–29].

The use of WAAM in the strengthening, rehabilitation and repair of steel structures is an emerging area of research [2]. Traditional methods of strengthening steel structures are usually implemented by welding or bolting steel reinforcing plates [30–33], or by bonding fibre reinforced polymer (FRP) plates (or sheets) [34], to steel members. Carbon FRP is widely employed in strength or stiffness-related strengthening scenarios [35–38], while glass FRP is commonly used in ductility-related strengthening scenarios [39,40]. Recently, shape memory alloys have also been used in the strengthening of steel structures subjected to fatigue loading [41–43]. A pioneering study on WAAM-strengthening has been conducted by Gardner et al. [44], where a number of hot-rolled I-section columns, strengthened by the addition of WAAM stiffeners at flange tips, were tested under axial compression.

The use of WAAM in strengthening traditional hot-rolled I-section steel beams is explored in the present study. Firstly, the concept of utilising WAAM to enhance the flexural response of hot-rolled I-section profiles is introduced, including harnessing the heat input from WAAM for pre-cambering, and increasing material utilisation rates through targeted (optimised) material deposition. Secondly, the design of 10

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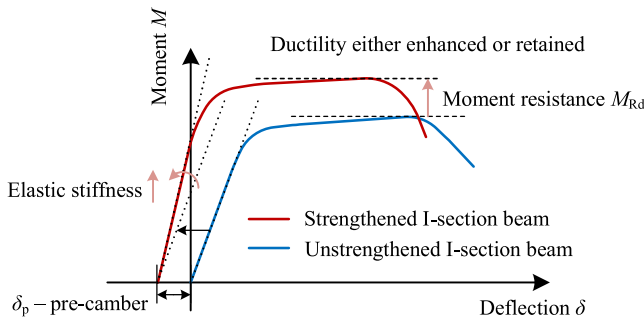


Fig. 1. Illustration of the outlined strengthening objectives for steel beams.

WAAM-strengthened I-section beam specimens with different arrangements of WAAM material on their base I-section profiles is presented. Tensile testing conducted to assess the material properties of both the hot-rolled steel and the WAAM steel is then presented, followed by a description of the pre-camber and cross-sectional dimensions of the strengthened specimens measured using 3D laser scanning. Physical experiments under either four-point or three-point bending conditions to determine the major-axis flexural behaviour of the WAAM-strengthened beam specimens are then presented. The influence of the material arrangement on the pre-camber, strength, stiffness, rotation capacity and failure modes of the strengthened specimens are thoroughly investigated. Lastly, the efficiency of this WAAM-strengthening approach is assessed and then conclusions are drawn.

2. Concept, design and specimen manufacture

The concept of strengthening hot-rolled steel I-section beams through WAAM, to enhance their major-axis flexural behaviour, is introduced in this section, followed by descriptions of the design and manufacture of the strengthened beam specimens.

2.1. Concept

The primary objectives of strengthening steel beams are to enhance their bending moment resistance and elastic stiffness, aiming to increase their load carrying capacity at the ultimate limit state, while reducing deflections at the serviceability limit state, respectively. Additionally, the ductility, or rotation capacity, of the steel beams, which relates to the cross-section classification (as per EN 1993-1-1 [45]) or the full cross-section slenderness (as per the continuous strength method [46,47]), should at least be preserved, if not enhanced, after strengthening. An alternative method to reduce deflection is to pre-camber the beam prior to applying the external loads [48], such that the imposed deflection under service loads can be partially or fully compensated by the pre-camber [49,50]. These outlined strengthening objectives are schematically illustrated in Fig. 1.

Existing studies have investigated the use of heat and thermal stresses in pre-cambering steel members [51–53]. Similarly, the heat input from WAAM can be strategically harnessed to camber steel I-section beams by means of depositing additional material on the outer surface of the tension flange, as illustrated in Fig. 2. The deposited material and the underlying base material, hot as welded, undergoes thermal contraction during cooling; this thermally-induced contraction, primarily on the tension side of the beam, leads to the pre-camber, δ_p (see Fig. 2). By contrast, materials deposited on the compression side of the beam would result in unfavourable adverse cambering (i.e., pre-bending). The physical measurement and simulation of thermally-induced stresses in WAAM-strengthened columns have been presented in [54,55].

The structural response of the strengthened beams is expected to be strongly affected by the arrangement of the additional WAAM material

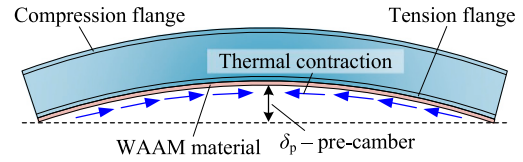


Fig. 2. Pre-cambering induced by thermal contraction of the WAAM material deposited on the tension flange and the underlying base material.

on the base I-section profile. At the cross-sectional level, three types of material arrangements, denoted as ‘T’, ‘TS’ and ‘SS’ respectively, are proposed, as shown in Fig. 3. The ‘T’ type of arrangement implies that all WAAM materials are deposited onto the outer surface of the tension flange, while the ‘TS’ type of cross-section incorporates WAAM materials not only on the tension flange, but also on the tips of the compression flange in the form of stiffeners. The latter WAAM stiffeners are intended to enhance the resistance of the cross-section to local buckling, while limiting the heat input on the compression side (see Fig. 3) to minimise the adverse cambering effect. The ‘SS’ type of cross-section employs a doubly-symmetric material arrangement with WAAM tip stiffeners on both flanges, which is considered suitable for applications in which pre-cambering is unnecessary.

Conventional hot-rolled steel I-section beams are prismatic, and therefore have uniform bending resistance along their length; as a consequence, the cross-sections located outside the critical regions experience a lower level of stress in comparison to those sections within the critical regions, leading to inefficiency in material utilisation — see Fig. 4(a) which shows a typical three-point bending scenario. This shortcoming can be addressed through WAAM-strengthening, whereby additional material is optimally placed predominantly within the critical regions of the member, to enhance the resistance locally and therefore increase the overall utilisation at the member level; essentially, a moment resistance diagram that more closely matches the applied bending moment diagram is sought, as depicted in Fig. 4(b). Thus, at the member level, three types of material arrangements are proposed herein, as illustrated in Fig. 5. The ‘F’ type of arrangement features a ‘T’ type of cross-section, with all weld lines extending to the full length of the beam, aiming to maximise the pre-cambering effect. The ‘O’ and ‘OF’ types of material arrangement are both characterised by an optimised distribution of WAAM material at the member level, with the length of each weld layer optimised based on the applied bending moment diagram (see Fig. 4(b)). However, in the ‘OF’ arrangement, the first layer of weld lines on the outer surface of the tension flange is extended along the full length of the beam to achieve a relatively more pronounced pre-cambering effect. The outlined conceptual principles are applied in the design of the WAAM-strengthened beam specimens, as described in the following section.

2.2. Design and manufacture of the WAAM-strengthened beam specimens

Hot-rolled UB 152 × 89 × 16 profiles in grade S355 steel were employed as the base I-section for the strengthened beam specimens in the present study. The nominal cross-section properties are given in Table 1, where H , B , t_f , t_w , r , A , are the height, width, thickness of flange, thickness of web, root radius and area of the section profile, respectively; I_y , $W_{el,y}$ and $W_{pl,y}$ are the second moment of area and elastic and plastic section moduli about the major axis of the cross-section, respectively. The chemical composition of the hot-rolled steel, as provided by the supplier, is given in Table 2. Unalloyed gas shielded arc welding wire in grade ER 70S-2, as per AWS A5.18 [56] (equivalent to EN ISO 14341-A G2Ti as per EN ISO 14341 [57]), was used as the feedstock for WAAM, while metal inert gas (MIG) welding was the adopted welding process. The typical chemical composition and key as-welded mechanical properties of the welding wire, as provided by

Table 1
Nominal section properties of UB 152 × 89 × 16 section profiles.

Section profile	H (mm)	B (mm)	t_f (mm)	t_w (mm)	r (mm)	A (mm ²)	I_y (mm ⁴)	$W_{el,y}$ (mm ³)	$W_{pl,y}$ (mm ³)
UB 152 × 89 × 16	152.4	88.7	7.7	4.5	7.6	2030	8.34×10^6	1.09×10^5	1.23×10^5

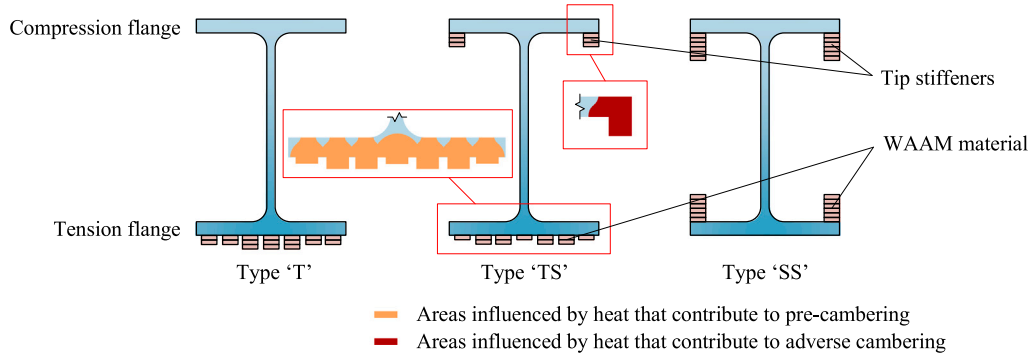


Fig. 3. Cross-sectional material arrangements.

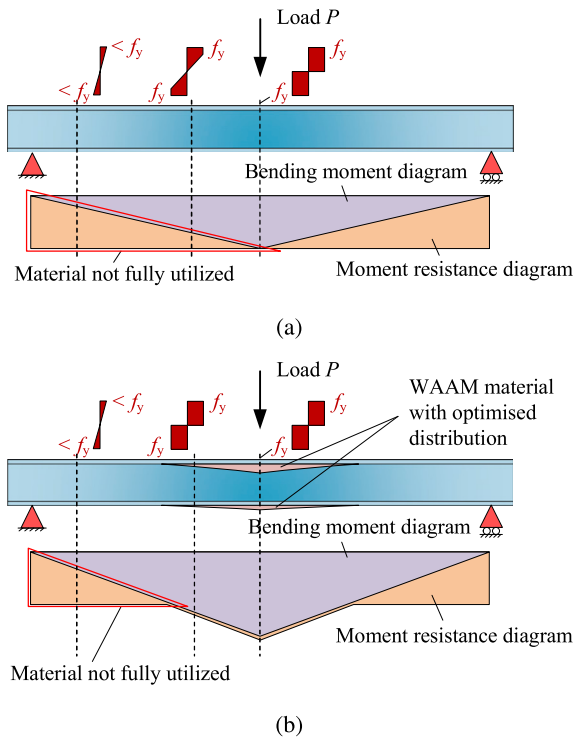


Fig. 4. Schematic illustration of the bending moment diagram, moment resistance diagram and cross-sectional stress distributions of (a) an unstrengthened I-section beam and (b) a WAAM-strengthened I-section beam with an optimised material distribution under three-point bending.

the supplier, are given in Tables 3 and 4 respectively. In Table 4, f_y , f_u and ϵ_f are the yield strength, the ultimate tensile strength and the percentage elongation at fracture respectively. The process parameters adopted for the WAAM process are listed in Table 5, where the deposition rate is calculated excluding the inter-layer dwell time. Note that in the present study, no pre-heating was applied to the base

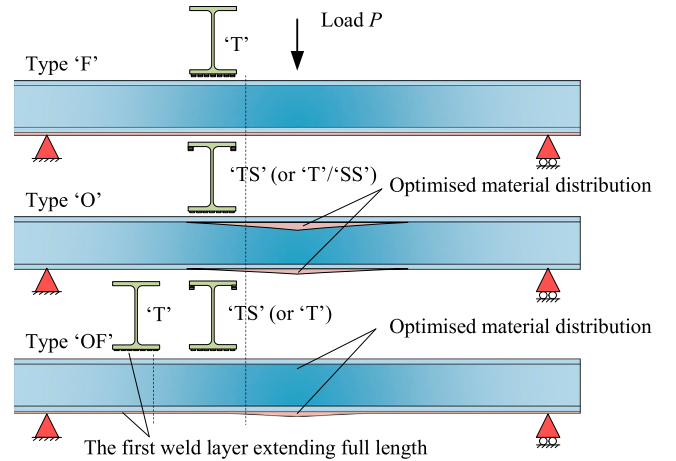


Fig. 5. Member-level material arrangements, using a typical three-point bending scenario for illustration purposes.

beam when depositing the first layer of WAAM material, and the same process parameters were employed for all weld layers.

2.2.1. Specimen design

A total of ten 2 m long (1.8 m span with 0.1 m overhangs at each end) WAAM-strengthened I-section beam specimens were designed for manufacturing and testing, 7 of which were subjected to four-point bending and 3 of which were subjected to three-point bending, as illustrated in Fig. 6. The beam specimens are labelled in sequence with a prefix 'B' and a suffix showing the loading condition (i.e., '4PB' for four-point bending and '3PB' for three-point bending). The design of two typical specimens is detailed in Table 6, while the design information for the remaining eight specimens is given in Appendix A. In Table 6, $M_{c,Rd}$ is the cross-sectional bending moment resistance, which varies along the member length according to the strengthening arrangement, M_{Ed} is the corresponding bending moment diagram under the designated loading condition, while $V_{l,n}$ and $V_{w,n}$ are the nominal volumes of the base I-section beam (excluding the overhangs) and the WAAM portion respectively, calculated from the nominal dimensions as given in Tables 1 and 5. The values of $M_{c,Rd}$ were calculated as the

Table 2
Chemical compositions of the hot-rolled steel (% by weight, balance Fe).

C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	Nb	B	Sn	Ti	N	V
0.15	0.19	1.33	0.009	0.005	0.01	0.003	0.02	0.031	0.008	0.001	0.0002	0.001	0.001	0.01	0.03

Table 3

Typical chemical compositions of the ER70 S-2 welding wire, provided by the supplier (% by weight, balance Fe).

C	Mn	Si	Ti	Al
0.05	1.1	0.55	0.12	0.11

Table 4

Key as-built mechanical properties of the ER70 S-2 welding wire, provided by the supplier.

f_y (MPa)	f_u (MPa)	Impact strength (ISO-V/-30 °C)	ϵ_f ($L_0 = 5L_0$) (%)
min. 400	min. 480	min. 47 J	min. 22

Table 5

Process parameters and nominal weld bead dimensions adopted in WAAM.

Process parameters	Value
Wire diameter (mm)	1.2
Voltage (V)	19
Current (A)	245
Travel speed (mm/s)	8
Wire feed rate (m/min)	7.4
Inter-layer temperature (°C)	<250
Deposition rate (kg/h)	3.95
Nominal weld bead height (mm)	2
Nominal weld bead width (mm)	8

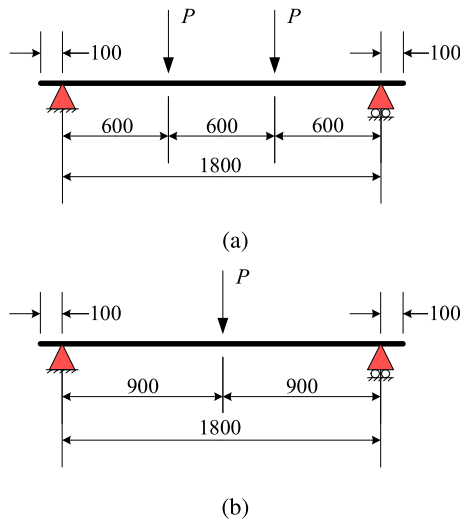


Fig. 6. Schematic illustrations of (a) four-point bending and (b) three-point bending conditions.

plastic bending moment resistances, $M_{pl,y}$, of the cross-sections along the length of the beam specimens, using the nominal dimensions and the nominal yield strengths as per [45] and Table 4 (i.e., 355 MPa for the base I-section and 400 MPa for the WAAM portion). Note that in Table 6, the material arrangement is given in a ‘cross-section type - member type’ fashion (see Figs. 3 and 5), while the loads P (see Fig. 6) were calculated from the maximum values on the bending moment diagrams M_{Ed} .

It should be mentioned that in the specimens designed with ‘F’ or ‘OF’ type material arrangements, the ‘full-length’ layers on the tension

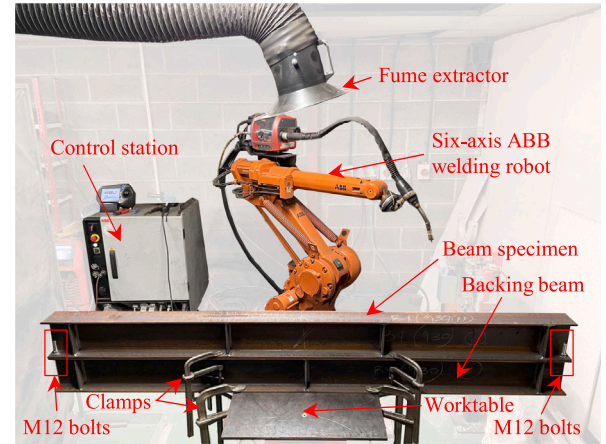


Fig. 7. Set-up for manufacture of WAAM-strengthened beam specimens.

flange extend to 1500 mm, rather than the full span (1800 mm), see Table 6 and Appendix A. This configuration avoids potential clashes between the weld lines and the bearing plates placed between the specimens and the roller supports in the bending tests.

2.2.2. Specimen manufacture

The set-up for the manufacture of the WAAM-strengthened beam specimens is shown in Fig. 7, where a backing beam was attached to the worktable, with the I-section profile placed on top. For the specimens with ‘T’ or ‘TS’ type cross-sections, the weld lines on the tension flange were deposited first, followed, if present, by those on the compression flange tips. The deposition sequence of the weld lines is shown by the indices in Fig. 8(a). For the specimens with the ‘SS’ type cross-section, the deposition sequence of the weld lines is shown in Fig. 8(b). The employed deposition sequences, featuring welding alternately on the two flanges outstands, aimed to reduce the out-of-plane welding deformations of the specimens during manufacturing. The welding direction was the same within a single weld layer, but alternated between layers. The backing beam and the specimen were joined together at each end using a pair of Class 8.8 M12 bolts to increase the in-plane bending rigidity and, therefore, to mitigate the bending deformation arising from the thermal contraction of the tension (top) flange (see Fig. 8(a)) during manufacture, as illustrated in Fig. 9. After manufacturing, the restrained bending deformation was released upon removal of the end bolts, and the anticipated pre-cambering was revealed.

3. Material properties

3.1. Introduction

Dog bone-shaped tensile coupons, designed in compliance with EN ISO 6892-1 [58], were extracted from the parent materials by waterjet cutting. Four coupons were extracted from a bare UB 152 × 89 × 16 I-section profile — two from the flanges and two from the web. Three as-built WAAM-coupons were extracted from a WAAM plate manufactured using the same process parameters as those employed in the manufacture of the beam specimens (see Table 5), as shown in Fig. 10. This approach ensures that the material properties of the extracted WAAM coupons closely reflect the properties of the

Table 6

Details of typical WAAM-strengthened beam specimens B-5-4PB and B-9-3PB (dimensions in mm, not to scale), ENA = elastic neutral axis and PNA = plastic neutral axis.

Beam ID	Profile	Moment diagrams	Material arrangement	Load(s) P (kN)	Nominal $V_{W,n}/V_{I,n}$ (%)
B-5-4PB			'TS-OF'	92.73	11.75
B-9-3PB			'TS-OF'	138.86	10.93

WAAM material deposited on the beam specimens. The dimensions of the hot-rolled coupons and of the WAAM coupons are shown in Fig. 11. Surface cleansing was carried out on all coupons by means of grit-blasting before tensile testing.

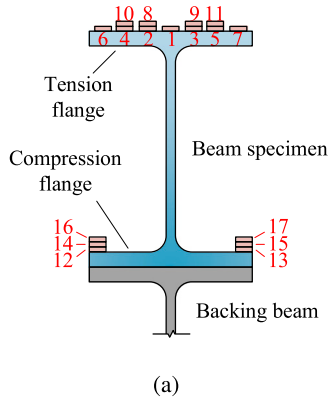
The densities of the hot-rolled coupons and the WAAM coupons were assessed based on Archimedes's principle, using the method specified in [15]. The measured density of the WAAM coupons, ρ_W , and of the hot-rolled coupons, ρ_h , were 7.81 g/cm³ and 7.85 g/cm³ respectively. The density of the WAAM coupons is consistent with the value reported by Huang et al. [9], but lower than that of the hot-rolled coupons, most likely owing to the slight porosity present within the WAAM material.

The geometry of the as-built WAAM coupons was obtained by means of 3D laser scanning, using a FARO Design scan arm with the capability of capturing 600,000 points per second with a precision of ± 0.075 mm, as shown in Fig. 12. The 3D point cloud, captured by laser scanning, was then processed into a polygon mesh in the commercial software Geomagic Wrap [59]. The polygon mesh was then exported into the software Rhinoceros [60], where a series of contours with a spacing of 0.05 mm was employed to slice the parallel region of the polygon mesh, as illustrated in Fig. 13. The average cross-sectional area and the average thickness within the parallel region of the WAAM coupons were analysed from the sliced cross-sections. The average thickness of the WAAM coupons, corresponding to the average width of the weld lines, was obtained as 7.97 mm; meanwhile, the average height of the weld lines was 2.02 mm, calculated from the measured height of the WAAM plate (see Fig. 10) and the number of layers printed. The average cross-sectional area of a single weld line is thus calculated as 16.1 mm².

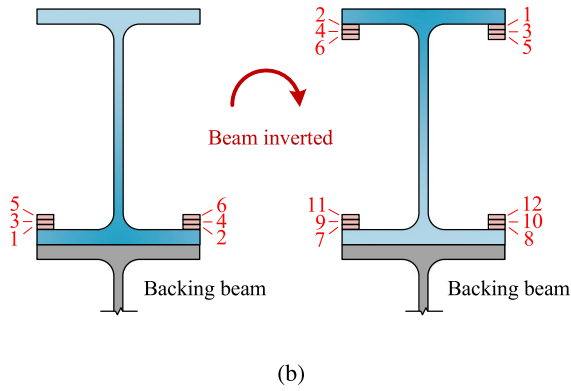
3.2. Tensile coupon testing

The tensile coupon tests were carried out in accordance with EN ISO 6892-1 [58], as shown in Fig. 14. The tensile loading was applied under displacement control using a 250 kN Instron 8802 testing machine. Prior to testing, gauge lengths equal to $5.65\sqrt{A}$ were marked on each side of the coupons for the later calculation of fracture strains, ϵ_f [58], where A is the cross-sectional area of the parallel region. For the WAAM coupons, A was taken as the average cross-sectional area obtained from the scanned geometry. Black and white speckle patterns were sprayed onto both faces of the tensile coupons for the monitoring of displacements/strains using a four-camera LaVision digital image correlation (DIC) system, where two pairs of high resolution cameras were utilised to record the movements of the speckles on each face of the tensile coupons, at a frequency of 1 Hz. During testing, strain rates approximating to 7×10^{-5} /s and 2.5×10^{-4} /s were employed up to and beyond the yield strength respectively.

The strains within the parallel regions of the coupons were processed in the software DaVis [61], based on the recorded images from DIC. The stresses were again determined using the average cross-sectional area of the WAAM coupons. The stress-strain relationships of the tested coupons are presented in Fig. 15. Key mechanical properties, including the Young's modulus E , the yield strength f_y , the ultimate tensile strength f_u , the corresponding strain at f_u , ϵ_u , and the fracture strain ϵ_f calculated as the percentage elongation over the marked gauged length $5.65\sqrt{A}$ at fracture [58], are summarised in Table 7. In Fig. 15 and Table 7, the hot-rolled coupons are labelled with a first letter indicating the location of extraction ('F' for flange and 'W' for web), followed by a number indicating the test number. The WAAM



(a)



(b)

Fig. 8. Sequence of material deposition for (a) 'T', 'TS' and (b) 'SS' type cross-sections.

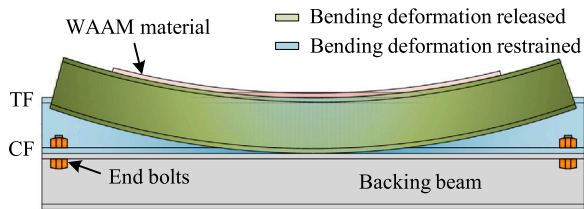


Fig. 9. Method employed for mitigating bending deformations during manufacturing (TF — tension flange, CF — compression flange).

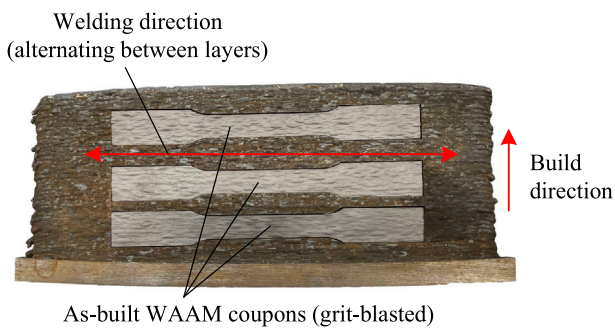


Fig. 10. Coupons extracted from the WAAM plate.

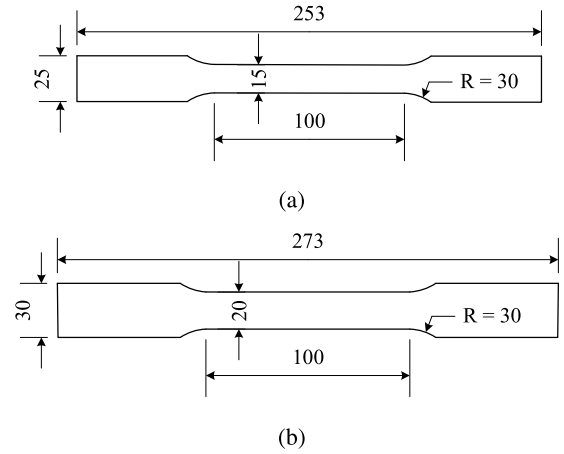


Fig. 11. Dimensions of (a) hot-rolled and (b) WAAM tensile coupons in mm.

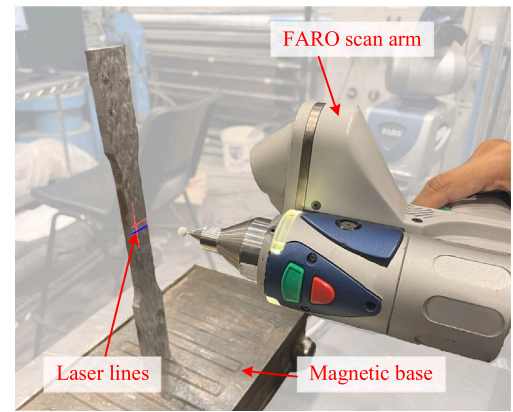


Fig. 12. 3D laser scanning of as-built WAAM coupons.

Table 7

Key material properties obtained from tensile coupon tests.

Coupon ID	E (MPa)	f_y (MPa)	f_u (MPa)	ϵ_u (%)	ϵ_f (%)	f_u/f_y (—)
WAAM-1	206 000	380	496	15.8	32.3	1.30
WAAM-2	208 000	373	492	17.0	29.2	1.32
WAAM-3	210 000	374	493	17.6	30.8	1.32
Average	208 000	376	494	16.8	30.8	1.31
F-1	208 000	400	553	15.9	31.32	1.38
F-2	215 000	405	553	15.3	33.63	1.36
Average	211 000	403	553	15.6	32.48	1.37
W-1	205 000	432	567	15.9	28.47	1.31
W-2	209 000	435	568	15.6	28.36	1.31
Average	207 000	433	567	15.8	28.42	1.31

coupons are labelled with a similar convention. The colour maps of the longitudinal surface strains of a typical WAAM coupon – WAAM-1, at some key stress levels on the stress–strain curve, are shown in Fig. 16. Both the hot-rolled and WAAM steel coupons exhibit a similar form of stress–strain response, featuring a sharply defined yield point, a yield plateau and strain hardening, with good ductility. Comparing Table 7 with Table 4, it can be observed that the yield stress f_y of the WAAM material is lower than its nominal as-built value (i.e., ≥ 400 MPa). This is attributed to the slower cooling rates associated with WAAM in comparison with conventional welding [9]. Nevertheless, both the yield stress f_y and the ultimate tensile strength f_u of the WAAM material are greater than the nominal values given in EN 1993-1-1 [45] for grade S355 steel (355 MPa and 490 MPa respectively).

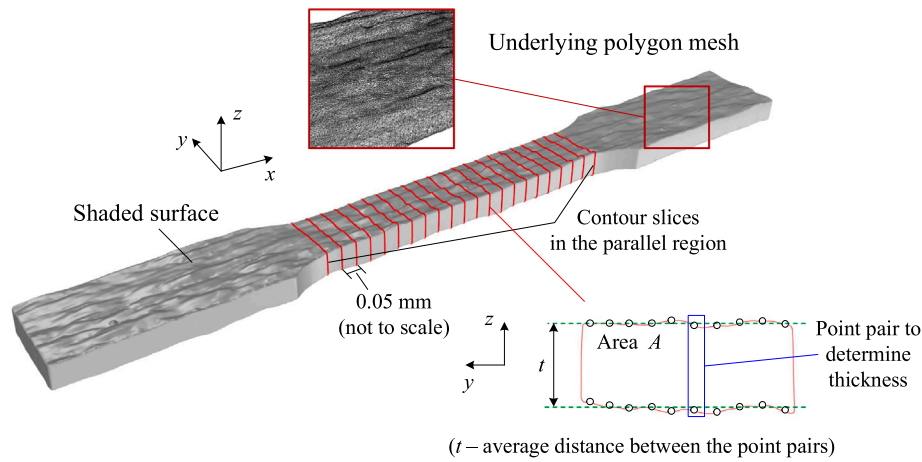


Fig. 13. Contour slicing and processing of the polygon mesh constructed from the scanned 3D point cloud.

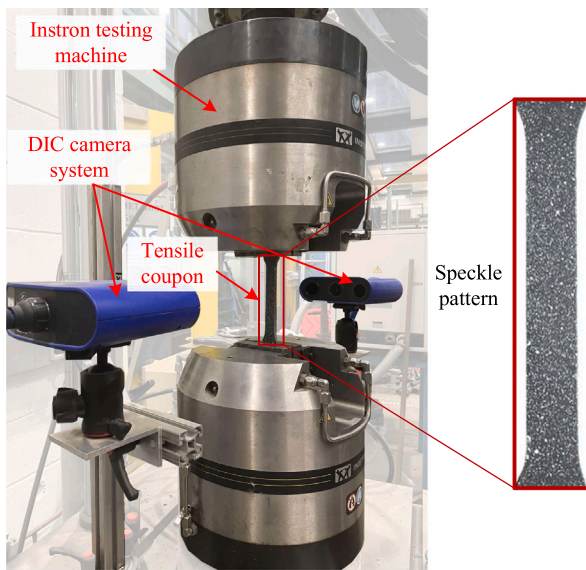


Fig. 14. Experimental set-up for tensile coupon tests.

4. Geometric analysis of beam specimens

The geometry of the strengthened beam specimens was determined by means of 3D laser scanning. The 3D point clouds scanned from the specimens (see Fig. 17(a)) were converted into polygon meshes in the software Geomagic Wrap [59] (see Fig. 17(b)). Investigations into the pre-cambering and the cross-sectional geometric properties of the specimens are conducted based on the scanned geometry and presented in this section. The mass/volume of the deposited WAAM material was also analysed.

4.1. Cross-sectional properties and mass analysis

The cross-sectional geometric properties of the beam specimens were analysed based on the constructed polygon meshes (see Fig. 17). The cross-sections of the polygon meshes were cut through a series of contour slices at a spacing of 2 mm in the software Rhinoceros [60], as shown in Fig. 18. The area, A , of each cross-section was obtained using the built-in functionalities of Rhinoceros.

In Fig. 19, the variation in cross-sectional area A along the length of some typical strengthened beam specimens are plotted, excluding the regions corresponding to the web stiffeners. Overall, the distributions

of A along the length were relatively uniform within the strengthened regions. Based on the mean areas of the unstrengthened bare I-section regions, A_I , and of the strengthened region, A_s , the average cross-sectional area of a single weld line, A_{wl} , was determined to be 16.18 mm^2 , which is consistent with the value employed in the design stage and the value measured from the WAAM plates (16.10 mm^2 , see Section 3), with a small discrepancy of only 0.5%.

The mass of the bare I-section, m_I , and the mass of the WAAM material, m_W , can be subsequently determined from A_I and A_{wl} and the corresponding measured densities (see Section 3). In Table 8, the cross-sectional dimensions, together with the percentage increase in mass, m_W/m_I , are listed for all specimens, including two unstrengthened bare-I-section specimens used later as benchmarks and both labelled with an index '0'. The second moment of area I_y , the elastic bending moment resistance M_{el} and the plastic bending moment resistance M_{pl} of the mid-span cross-section about its major axis, calculated from the measured cross-sectional dimensions and material yield stresses (see Table 7), are also presented in Table 8 for all specimens.

4.2. Pre-cambering of the strengthened beam specimens

The pre-cambered profiles of the strengthened beam specimens were obtained from the polygon meshes in the software Rhinoceros [60], by extracting the z -coordinate of the midpoint on the outer surface of the compression flange at each sliced cross-section (see Fig. 18). In Fig. 20(a), the cambered profiles of the strengthening beam specimens, excluding Specimens B-7-4PB and B-10-3PB, which had an 'SS' type cross-section, within the 1800 mm span, are plotted. The magnitudes of pre-camber, δ_p , the percentage increases in mass, m_W/m_I , as well as the corresponding material arrangements of the examined specimens, are shown in Fig. 20(b), where L is the span of the beam specimens. As expected, Specimens B-3-4PB and B-8-3PB, with around 11% increases in mass and a 'T-F' material arrangement, displayed the largest δ_p values of approximately 1/140 of the span. Specimen B-4-4PB exhibited a similar pre-camber to Specimens B-3-4PB and B-8-3PB, albeit with a 'T-OF' material arrangement. Moreover, by comparing the results of Specimens B-5-4PB and B-6-4PB to the results of Specimens B-3-4PB and B-8-3PB, it can be observed that approximately 66% of the pre-camber is counteracted by the pre-bending effect caused by the WAAM stiffeners on the compression side of the specimens. This reduction in δ_p is also observed in Specimen B-9-3PB, but is less severe, since the distribution of the WAAM stiffeners on Specimen B-9-3PB is more concentrated around the mid-span in comparison with Specimens B-5-4PB and B-6-4PB (see Tables 6 and A.1).

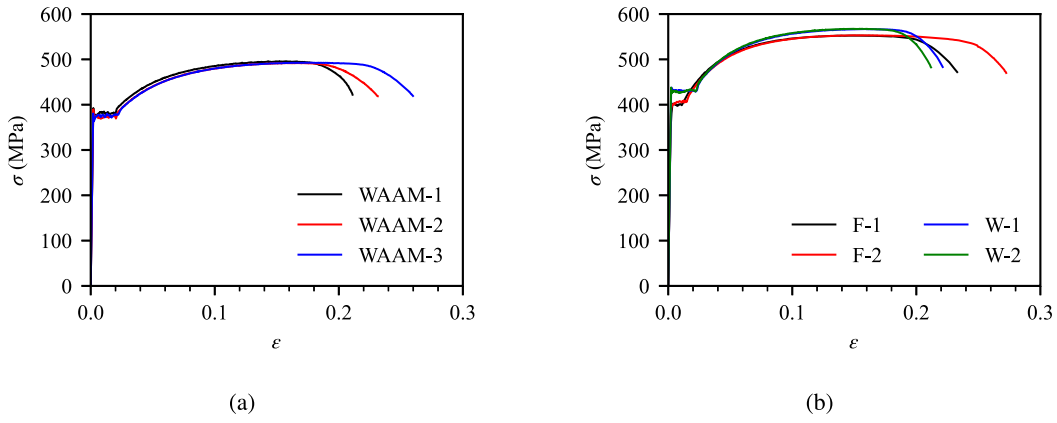


Fig. 15. Stress-strain curves obtained from (a) WAAM and (b) hot-rolled steel tensile coupons.

Table 8

Cross-sectional dimensions and masses of the beam specimens.

Beam ID	H (mm)	B (mm)	t_f (mm)	t_w (mm)	r (mm)	A_I (mm ²)	m_w/m_l (%)	I_y (mm ⁴)	M_{el} (kN m)	M_{pl} (kN m)
B-0-4PB	152.28	90.49	7.40	4.66	7.75	2031	–	8 274 000	43.80	50.02
B-0-3PB	152.25	90.34	7.29	4.64	7.86	2009	–	8 173 000	43.26	49.43
B-1-4PB	152.77	90.23	7.42	4.67	7.88	2037	2.61	8 712 000	43.08	52.07
B-2-4PB	152.61	90.41	7.36	4.68	7.76	2028	4.63	8 930 000	44.74	53.09
B-3-4PB	152.99	90.63	7.40	4.65	7.67	2034	11.34	9 930 000	46.42	57.38
B-4-4PB	153.14	89.91	7.44	4.56	7.65	2019	11.56	10 610 000	47.22	59.70
B-5-4PB	152.87	90.60	7.45	4.67	7.76	2045	11.68	10 630 000	51.83	61.99
B-6-4PB	152.43	90.05	7.36	4.66	7.67	2026	11.88	10 300 000	48.75	60.77
B-7-4PB	152.26	90.93	7.36	4.66	7.67	2030	12.27	9 239 000	48.91	61.93
B-8-3PB	152.86	90.65	7.44	4.71	7.69	2049	11.10	9 919 000	46.58	57.50
B-9-3PB	153.24	90.23	7.41	4.71	7.80	2041	11.05	11 820 000	54.74	68.96
B-10-3PB	152.26	89.94	7.33	4.58	7.61	1999	11.64	9 597 000	50.80	69.03

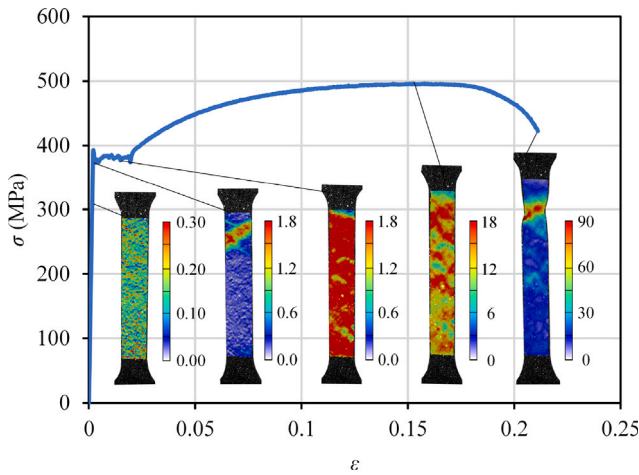


Fig. 16. Longitudinal surface strain fields of the coupon WAAM-1 at different stress levels. (unit of the colour maps: %). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5. Experiments on WAAM-strengthened beams

An experimental study was performed to investigate the major-axis flexural behaviour of the beam specimens subjected to four-point bending or three-point bending scenarios. In this section, the configurations of the test rig, the data acquisition processes and the experimental results are reported in detail.

5.1. General

In the four-point bending tests, a pair of even concentrated loads was applied vertically at third points along the span of the beam specimens, producing a central region under pure flexure between the loading points. In the three-point bending tests, a single concentrated load was applied at the mid-span of the beam specimens, resulting in two equal regions with either side of the loading point with a moment gradient and uniform shear force. Schematic views of the configurations of the test rigs and the arrangements of the instrumentation for the four-point bending tests and the three-point bending tests are depicted in Fig. 21(a) and (b) respectively. A 500 kN Instron hydraulic jack was used for the application of the vertical loads, under displacement control. Roller supports were placed at the ends of the span, enabling in-plane rotation and longitudinal translation of the specimens at these locations. Load cells were placed under the roller supports to record the vertical reaction forces. Additionally, bearing plates were positioned between the roller supports and the specimens to reduce the local stress concentration at the contact points.

In the four-point bending tests, a spreader beam with an HEB 180 cross-section profile was employed to distribute the load from the loading jack into a pair of concentrated loads, which acted onto the beam specimens through a pair of rollers placed between the specimens and the spacer blocks. The roller at the left loading point was welded onto the underlying bearing block to prevent displacements in the longitudinal direction at that location. A knife edge was placed between the spreader beam and the loading jack to ensure two equal vertical loads and to allow free in-plane rotation. Inclinoimeters were affixed to the web stiffeners under the loading points to measure the in-plane rotations. Three string potentiometers were installed under the tension flange at the mid-span and at the loading points respectively to measure the vertical displacements at these locations. Additionally, two pairs of strain gauges were mounted onto the middle of the outer surfaces

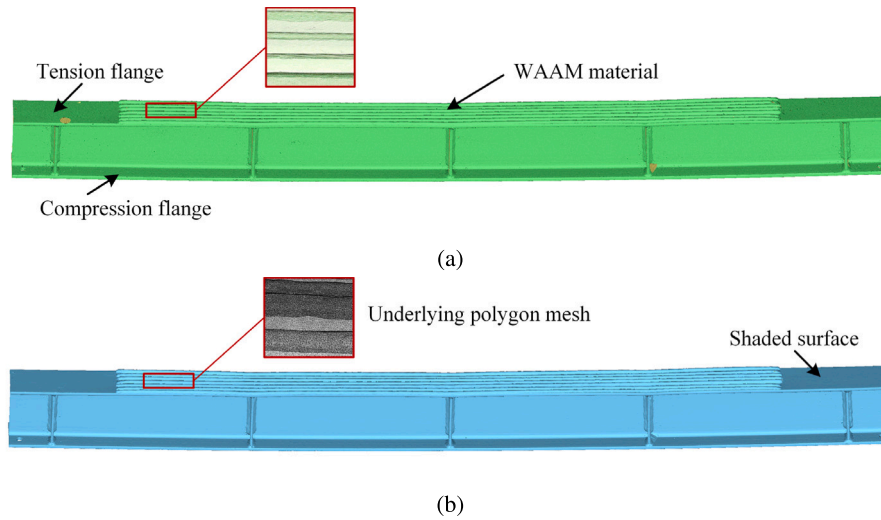


Fig. 17. (a) The 3D point cloud and (b) the polygon mesh of Specimen B-8-3PB.

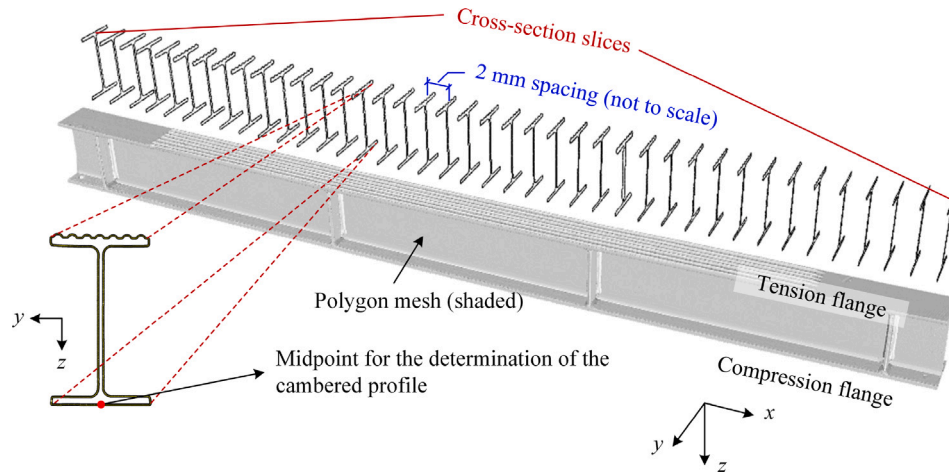


Fig. 18. Cross-sections of the polygon mesh of a typical strengthened beam specimen – B-2-4PB sliced in Rhinoceros [60].

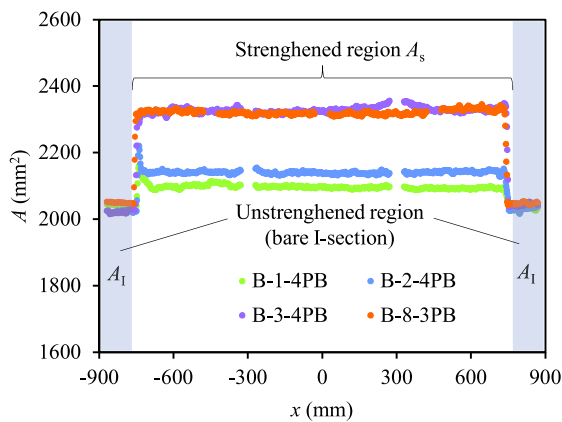


Fig. 19. Variation of cross-sectional area along the longitudinal direction of some typical strengthened beam specimens.

of both the compression flange and the tension flange, positioned at a 20 mm offset to the mid-span.

In the three-point bending tests, a spacer strut with an SHS 100/10 profile was used to transfer the load between the loading jack and

the beam specimens. A pair of inclinometers were affixed to the web stiffeners above the roller supports for the rotation measurements. At the mid-span, a single string potentiometer was installed to measure the deflection, while a pair of strain gauges were placed at a 50 mm offset to the mid-span.

In addition to the strain gauges, an LaVision two-camera digital image correlation (DIC) system was deployed to monitor the displacement/strain developments in the specimens. Speckle patterns were sprayed onto the specimens before testing to facilitate the strain monitoring. Note that the images of the speckle patterns were recorded at a frequency of 2 Hz by the camera system during the bending tests.

To evaluate the in-plane major-axis flexural behaviour of the beam specimens, lateral restraints were applied at several locations (five for the four-point bending tests and four for the three-point bending tests, see Fig. 21(a) and (b) along the span to prevent premature lateral torsional buckling. A novel lateral restraint system, aiming to provide effective lateral restraint, but with minimal influence on the local buckling behaviour of the specimens, was designed and used herein. A schematic illustration of the lateral restraint system is depicted in Fig. 22. On each side of the beam specimens, a triangular frame was anchored to the ground, providing resistance to lateral movements. Horizontal rails were affixed to these triangular frames, to which vertical rails were connected via horizontal linear guides. Load cells were mounted to the vertical linear guides on the vertical rails to measure

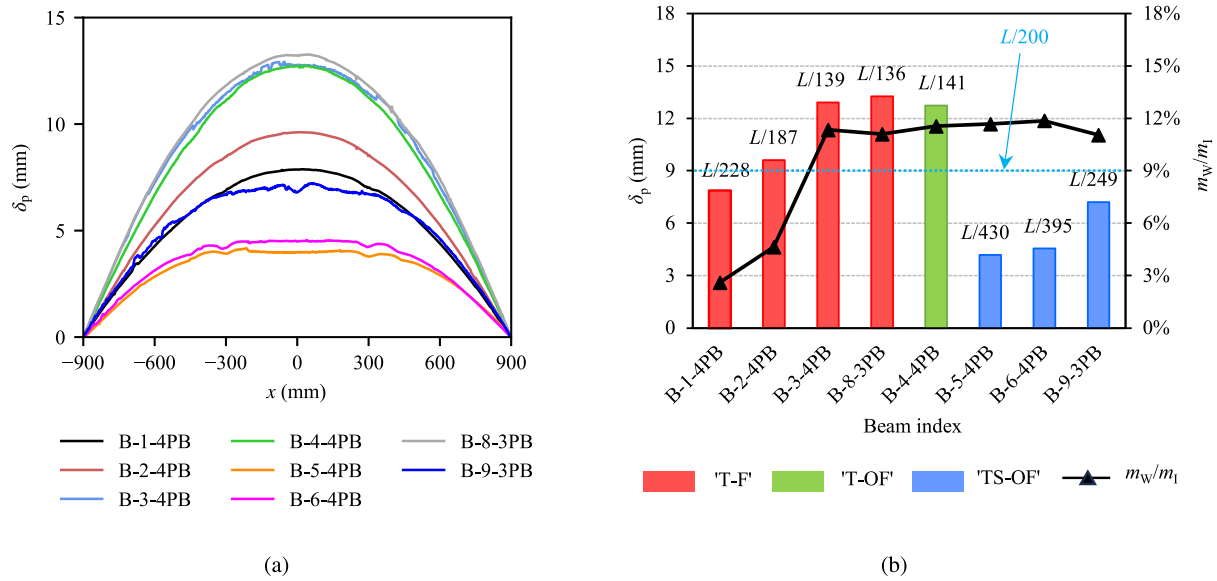


Fig. 20. (a) Cambered profiles and (b) magnitudes of pre-cambers of the examined specimens.

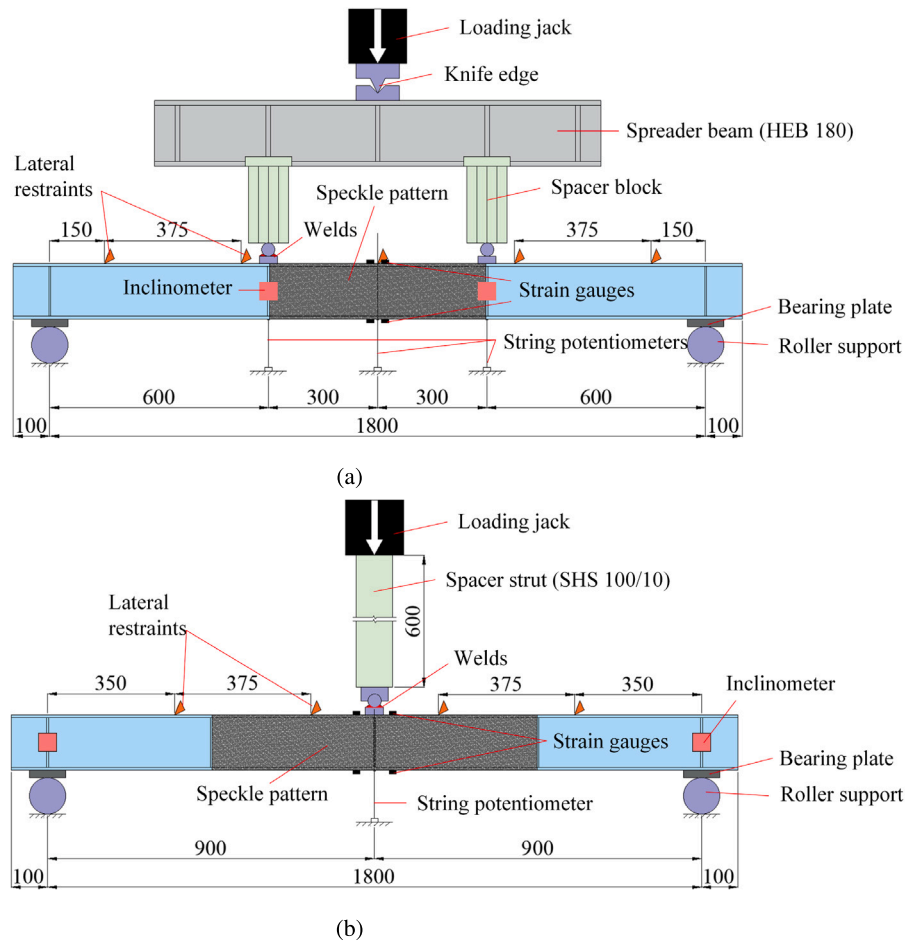


Fig. 21. Schematic views of the configuration of the test rig and the arrangement of instrumentation for (a) four-point bending tests and (b) three-point bending tests.

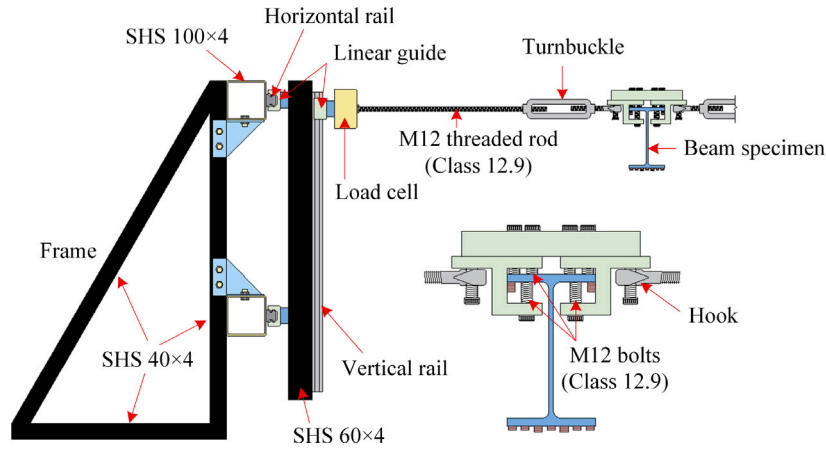


Fig. 22. Schematic view of the lateral restraint system.

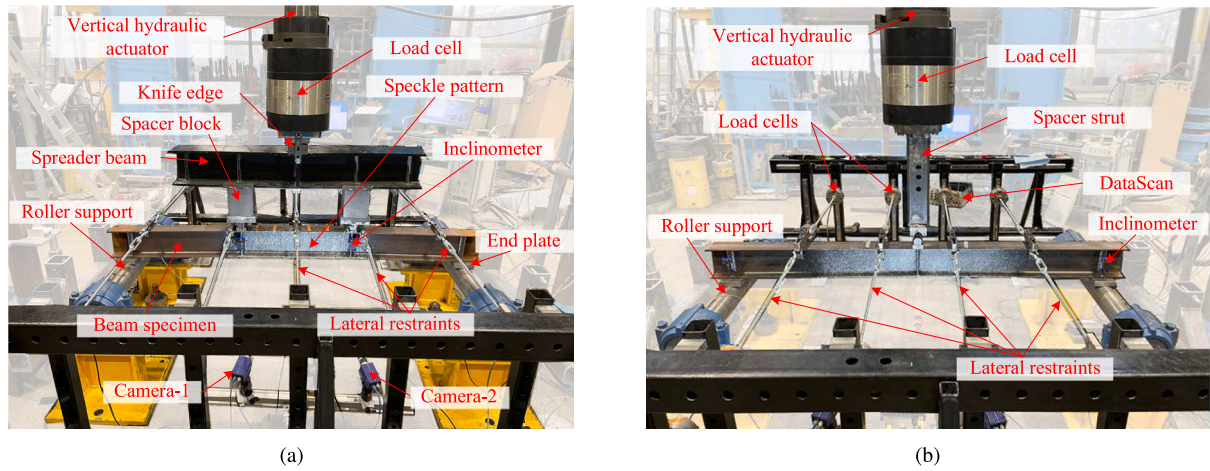


Fig. 23. Experimental set-up of the test rig for (a) four-point bending tests and (b) three-point bending tests.

the lateral forces resisted. A ‘channel’-shaped clamping system was employed to clamp the compression flange of the beam specimens at the designated lateral restraint locations. These clamps were linked to the load cells on the vertical rails via Class 12.9 M12 threaded rods with a hook connected to the clamping system on one end, and a turnbuckle in the middle. The turnbuckle allows the threaded rods to be lightly pre-tensioned prior to testing, thereby stabilising the lateral restraint system. The installed rails and linear guides enable the horizontal and vertical movements of the lateral restraints, which allows the lateral restraining forces to remain perpendicular to the plane of deformation as the specimens deform during testing. This proposed lateral restraint system was very effective in preventing lateral torsional buckling without affecting the in-plane response of the tested beams, and is therefore recommended to other researches.

The experimental set-ups for the four-point bending and three-point bending tests, as well as the lateral restraint system, are shown in Fig. 23(a) and (b) and Fig. 24 respectively. The readings from the load cells, string potentiometers, inclinometers and strain gauges were recorded using the data acquisition equipment DATASCAN and logged using the DSLOG software. All the specimens were tested under displacement control at a vertical displacement rate of 3.0 mm/min at the loading points.

5.2. Experimental results

5.2.1. Four-point bending tests

All the specimens tested under four-point bending failed by either inelastic local buckling or distortional buckling or a combination of

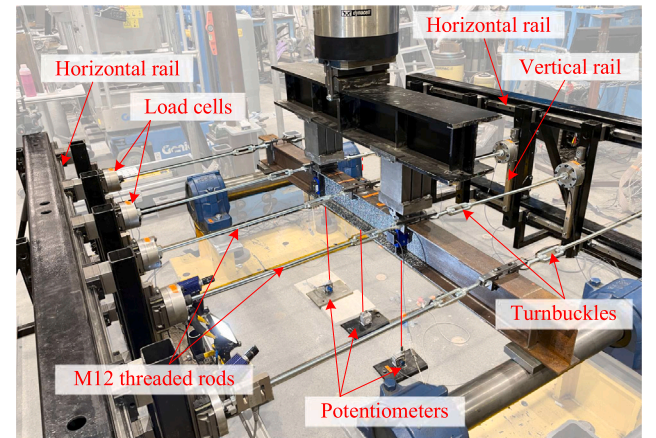


Fig. 24. Experimental set-up of the lateral restraint system (in four-point bending tests).

these two buckling modes at the critical regions with some lateral displacements between the point of lateral restraints at and beyond the peak load. An exception was Specimen B-2-4PB, which experienced premature failure caused by excessive local deformation of the connection to the lateral restraint at the mid-span of the beam. The deformed shapes of all the four-point bending specimens after testing are

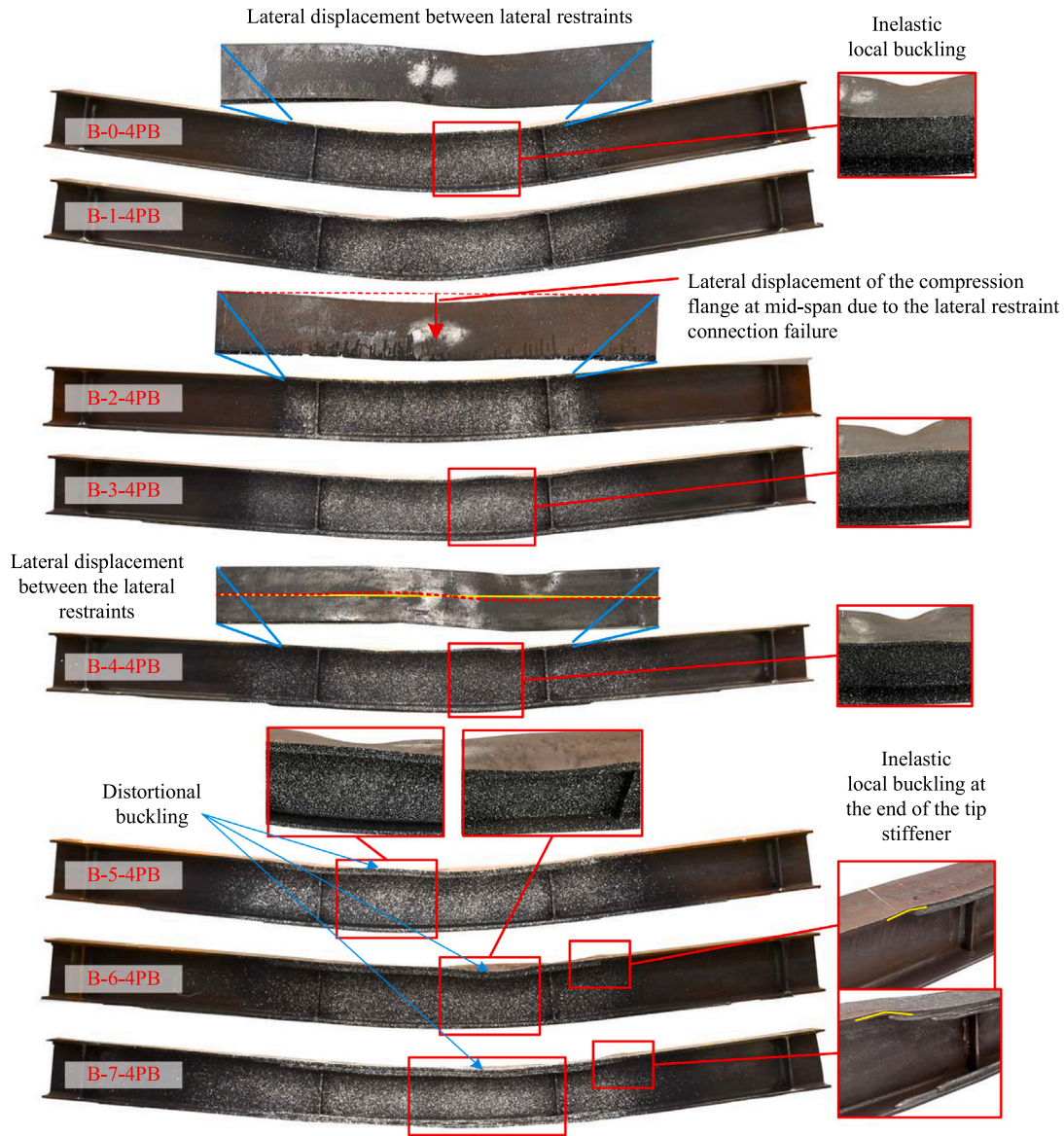


Fig. 25. Deformed shapes of the four-point bending specimens and typical buckling profiles.

presented in Fig. 25. Significant lateral displacement can be observed at the mid-span of Specimen B-2-4PB, owing to the lateral restraint connection failure.

In Fig. 26, the applied bending moment in the central uniform moment region of the beam (referred to as the flexural span), M , calculated from the reaction forces measured by the load cells under the roller supports, are plotted against the mid-span vertical displacement δ , measured by the string potentiometer, for all four-point bending specimens, with the pre-camber δ_p taken into account.

To assess the flexural behaviour of the examined specimens further, the normalised bending moment M/M_{pl} versus the normalised curvature κ/κ_{pl} within the flexural span is presented in Fig. 27, where κ denotes the curvature and $\kappa_{pl} = M_{pl}/EI_y$ is the elastic component of the curvature at M_{pl} . The curvature, $\kappa = (\varphi_1 + \varphi_2)/L_f$, was determined from the readings of the two inclinometers, where L_f is the length of the flexural span and φ_1 and φ_2 are the rotations measured by the two inclinometers in rads. This calculation assumes uniform curvature within the uniform moment region such that the flexural span forms a circular arc. Note that in Fig. 27, the initial curvatures resulting from the pre-camber are not included, to facilitate comparisons across the specimens. The longitudinal strain fields in the beam specimens were

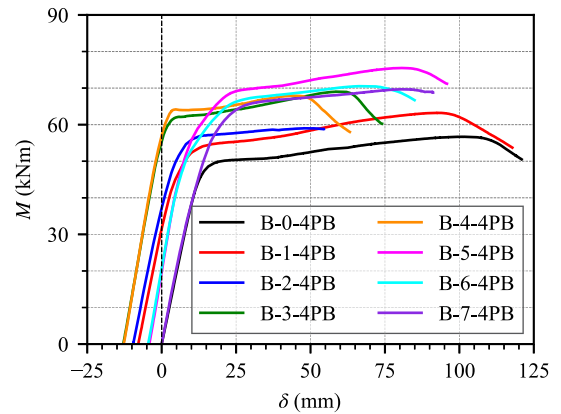


Fig. 26. Bending moment versus vertical displacement at the mid-span of the four-point bending specimens.

Table 9
Summary of key experiment results for the four-point bending specimens.

Beam ID	M_u (kN m)	M_{pc} (kN m)	M_u/M_{pl} (–)	M_{pc}/M_{pl} (–)	M_{pc}/M_u (–)	κ_{pl} (m^{-1})	κ_u (m^{-1})	R (–)	K (kN m ²)	K/K_{ana} (–)
B-0-4PB	56.70	0.00	1.13	0.00	0.00	0.0291	0.382	12.15	1696	0.99
B-1-4PB	63.25	31.47	1.21	0.60	0.50	0.0287	0.368	11.80	1843	1.02
B-2-4PB	59.04	37.17	1.11	0.70	0.63	0.0286	0.193	5.77	1863	1.06
B-3-4PB	69.08	55.57	1.20	0.97	0.80	0.0278	0.254	8.14	2125	1.03
B-4-4PB	67.93	56.97	1.14	0.95	0.84	0.0271	0.198	6.33	2305	1.04
B-5-4PB	75.53	19.69	1.22	0.32	0.26	0.0280	0.278	8.92	2219	1.00
B-6-4PB	70.57	20.66	1.16	0.34	0.29	0.0284	0.235	7.29	2178	1.02
B-7-4PB	69.70	0.00	1.13	0.00	0.00	0.0322	0.264	7.20	1858	0.97

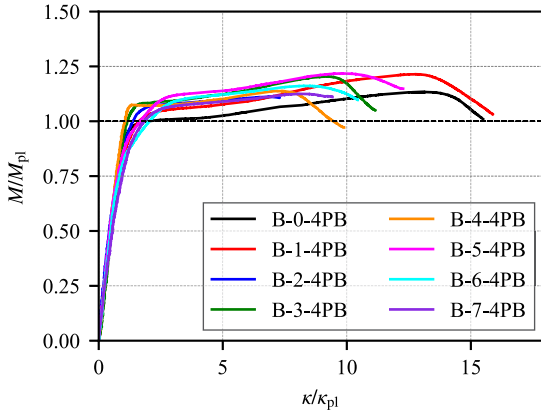


Fig. 27. Graphs of normalised bending moment versus curvature within the flexural span for four-point bending specimens.

processed from the images of the speckle patterns recorded by the DIC camera system, using the software Davis [61]. The colour maps of the longitudinal strains in some typical four-point bending specimens, at some key bending moment levels, are shown in Fig. B.1 in Appendix B, alongside the normalised moment–curvature curves.

The rotation capacity R of flexural members is commonly evaluated as $R = \kappa_{rot}/\kappa_{pl} - 1$ [16,62,63], where κ_{rot} is defined as the curvature corresponding to the point where the applied bending moment descends to M_{pl} after its peak. However, in the current tests, the specimens were loaded past their ultimate bending moment capacities M_u but unloaded prior to reaching M_{pl} on the descending branch of the moment–curvature curves, in order to avoid excessive forces in the lateral restraints. Thus, to facilitate comparisons across the specimens, κ_{rot} is replaced by κ_u (i.e. the curvature at M_u) in the calculation of R .

A summary of the key experimental results for the four-point bending specimens is given in Table 9, where M_{pc} is defined as the required bending moment to counter the pre-camber (i.e., the bending moment corresponding to zero δ in Fig. 26); meanwhile K denotes the initial elastic stiffness of the specimens, obtained as the slope of a linear fit to the initial linear portion of the M – κ curves (without normalisation), using ordinary least-squares regression. The ratio between K and its corresponding analytical value, denoted as K_{ana} and calculated as EI_y , is also provided in Table 9 for comparison purposes, where good agreement can be observed.

5.2.2. Three-point bending tests

The specimens tested under three-point bending failed by either inelastic local buckling or a combination of local buckling and distortional buckling. The deformed shapes of all the three-point bending specimens after testing are presented in Fig. 28. In Fig. 29, the applied bending moments M at the mid-span cross-section, are plotted against the vertical displacement at the mid-span δ , with the inclusion of the pre-camber.

Graphs of the normalised bending moment M/M_{pl} versus the normalised mid-span rotation, φ/φ_{pl} , are plotted in Fig. 30 for all three-point bending specimens, where $\varphi = \varphi_1 + \varphi_2$ is the mid-span rotation of the specimen calculated from the readings of the two end inclinometers (φ_1 and φ_2), and φ_{pl} is the elastic component of the mid-span rotation at M_{pl} . For the benchmark specimen B-0-3PB with a uniform I-section along its length, $\varphi_{pl} = M_{pl}L/2EI_y$. For the strengthened specimens with non-uniform cross-sections along their length, φ_{pl} can be determined through the integration of curvature from the end of the span to the mid-span, as specified in Eq. (1).

$$\varphi_{pl} = 2 \int_0^{L/2} \frac{1}{EI_y(x)} \frac{2M_{pl}x}{L} dx. \quad (1)$$

Here, $I_y(x)$ represents the distribution of the major-axis second moment of area of the cross-section along the half span. The rotation capacity of the three-point bending specimens can be calculated as $\varphi_{pl} = \varphi_{rot}/\varphi_{pl} - 1$, where φ_{rot} is defined as the mid-span rotation when the applied bending moment decreases to M_{pl} on the descending branch of the moment–mid-span rotation curve. Again, φ_{rot} is replaced by φ_u in the calculations of R , since φ_{rot} was not achieved in the tests. The colour maps of the longitudinal strains in the three-point bending specimens, at some key bending moment levels, are shown in Fig. B.2 in Appendix B, alongside the normalised moment–mid-span rotation curves.

A summary of the key experimental results for the three-point bending specimens is given in Table 10. The initial elastic stiffness K was obtained as the slope of a linear fit to the initial linear portion of the moment–mid-span rotation curves (without normalisation), using ordinary least-squares regression. The ratio between K and its corresponding analytical value K_{ana} , calculated using:

$$K_{ana} = 2 \int_0^{L/2} EI_y(x) \frac{L}{2x} dx, \quad (2)$$

was also provided in Table 10 for comparison purposes.

6. Analysis of experimental results

6.1. Rotation capacity and failure modes

From the test results presented in Tables 9 and 10, an overall decreasing trend can be observed in the rotation capacity of the beam specimens relative to an increasing amount of deposited WAAM material. More specifically, for Specimens B-(0–4)-4PB (excluding B-2-4PB owing to its premature failure) with a ‘T’ type cross-section, increases in the cross-sectional area within the flexural span between 3.1% (B-1-4PB) and 20.6% (B-4-4PB) resulted in reductions in R between 2.9% and 47.9%. A more severe reduction was observed by comparing Specimen B-8-3PB to Specimen B-0-3PB, where a 16.3% increase in the mid-span cross-sectional area resulted in a 64.3% decrease in R . The strengthened specimens B-(1–4)-4PB failed by inelastic local buckling within the flexural span under four-point bending (see Fig. 25), while Specimen B-8-3PB failed by inelastic local buckling adjacent to the mid-span under three-point bending (see Fig. 28). The failure mode of these

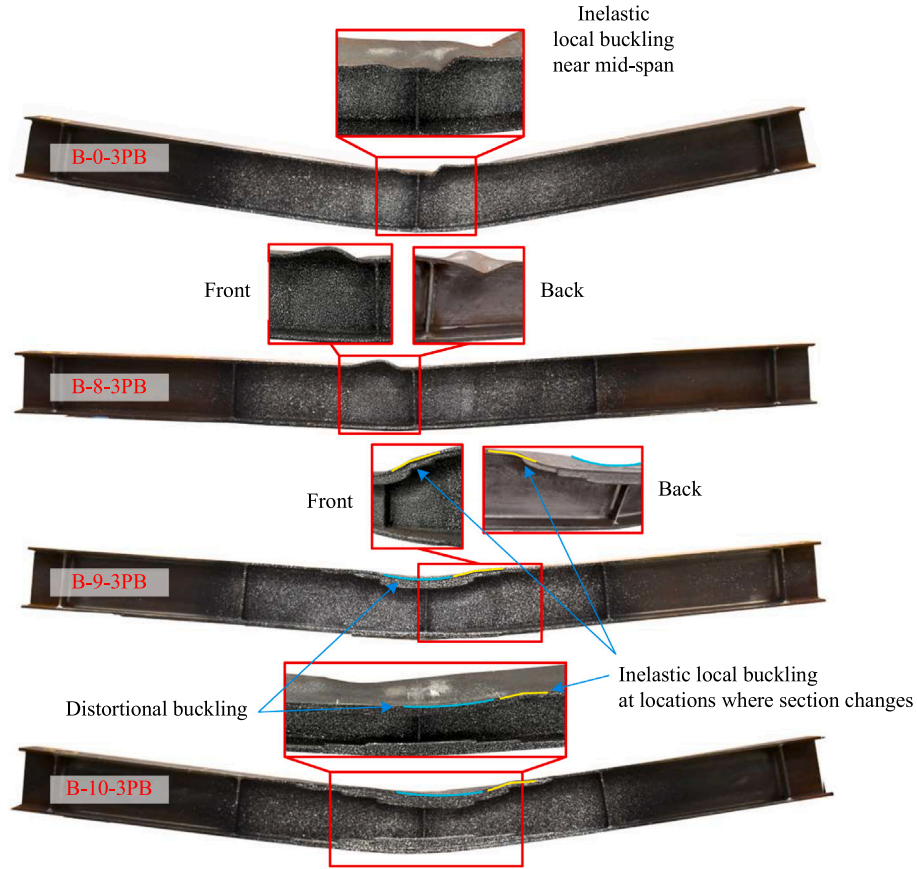


Fig. 28. Deformed shapes of the three-point bending specimens.

Table 10
Summary of key experiment results for the three-point bending specimens.

Beam ID	M_u (kN m)	M_{pc} (kN m)	M_u/M_{pl} (–)	M_{pc}/M_{pl} (–)	M_{pc}/M_u (–)	ϕ_{pl} (rad)	ϕ_u (rad)	R (–)	K (kN m/rad)	K/K_{ana} (–)
B-0-3PB	67.36	0.00	1.36	0.00	0.00	0.0262	0.2630	9.05	1866	0.99
B-8-3PB	73.69	64.13	1.28	1.12	0.87	0.0255	0.1077	3.23	2304	1.02
B-9-3PB	84.75	42.51	1.23	0.62	0.50	0.0300	0.1504	4.01	2283	0.99
B-10-3PB	81.54	0.00	1.18	0.00	0.00	0.0344	0.2294	5.68	1982	0.99

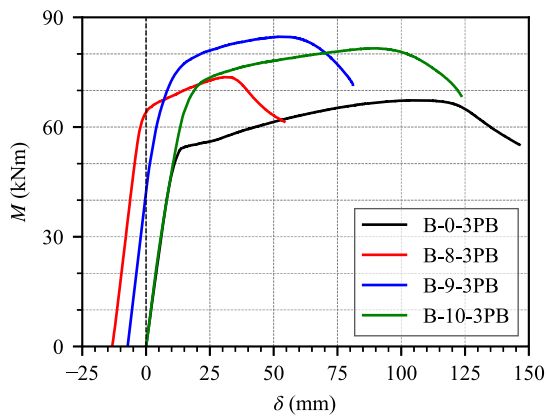


Fig. 29. Bending moment versus vertical displacement at the mid-span of the three-point bending specimens.

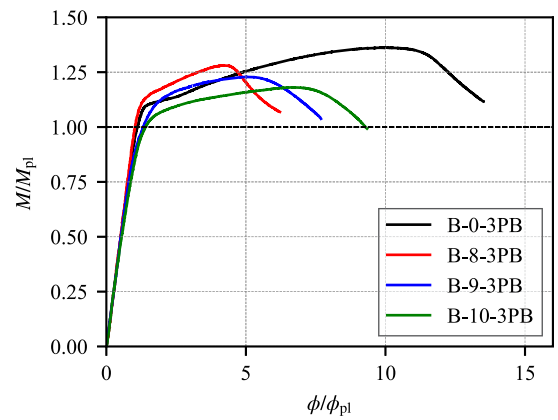


Fig. 30. Bending moment versus vertical displacement at the mid-span of the three-point bending specimens.

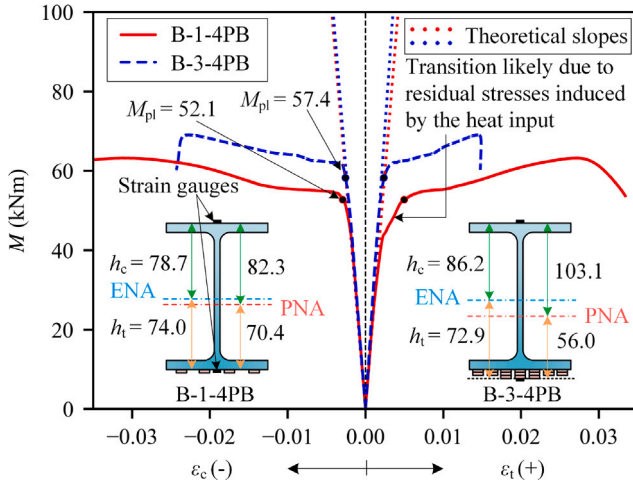


Fig. 31. Development of axial strains at the top and bottom extreme fibres of Specimens B-1-4PB and B-3-4PB against the applied bending moment (unit of cross-section dimensions: mm, unit of bending moment: kN m).

strengthened specimens was consistent with that of their corresponding benchmark specimens. Note that in Specimens B-0-3PB and B-8-3PB, inelastic local buckling occurred adjacent to the mid-span rather than at the mid-span, which was the most critically loaded region, since the mid-span was stiffened by the web stiffener and the loading plate.

To further investigate the reduction in R , the compressive surface strain ϵ_c and the tensile surface strain ϵ_t measured by the strain gauges attached adjacent to the mid-span (see Fig. 21(a)), are plotted for Specimens B-1-4PB and B-3-4PB in Fig. 31, relative to the applied bending moment M . The theoretical initial slopes of the presented curves, determined from the elastic M - ϵ relationship thus:

$$\epsilon = \frac{Mh}{EI}, \quad (3)$$

are also plotted and show good agreement with the experimental measurements. In Eq. (3), h is the distance from the strain gauge to the elastic neutral axis (ENA). In Specimen B-1-4PB, ϵ_c and ϵ_t developed at similar rates against the applied bending moment, continuing until failure. By contrast, in Specimen B-3-4PB, ϵ_c developed approximately 1.17 times faster than ϵ_t within the elastic range, in consistency with the h_c/h_t ratio; a more rapid development of ϵ_c was observed after M_{pl} was reached, as the cross-sectional centre of rotation shifted downwards to the plastic neutral axis, which likely precipitated the onset of the local buckling at the compression flange, thus resulting in a lower rotation capacity.

For the strengthened specimens with a 'TS' or 'SS' type cross-section (i.e., B-(5-7)-4PB and B-(9-10)-3PB), distortional buckling was observed within the WAAM tip stiffener regions (see Figs. 25 and 28), most likely attributed to the tip stiffeners enhancing the cross-sectional resistance to local buckling and, thus, altering the buckling mode. It can be observed that the change of buckling mode effectively improved the rotation capacities of these specimens compared to their corresponding counterparts with a 'T' type cross-section (i.e., B-(3-4)-4PB and B-8-3PB). These specimens failed by a combination of distortional buckling and local buckling, with local buckling observed where the tip stiffener ends or where the height of the tip stiffeners changes, since these locations were also particularly heavily loaded as a result of the optimised distributions of $M_{c,Rd}$ (see Table 6 and Appendix A).

6.2. Pre-cambering

It can be observed from Fig. 20(b) that a pre-camber of approximately $L/200$, which is a typical serviceability deflection limit [45],

can be achieved with the addition of as little as 3% of WAAM material, relative to the mass of the bare steel beam. This indicates the high effectiveness of using WAAM to pre-camber steel I-section profiles. Additionally, from Tables 9 and 10, it can be observed that the moment required to counter the pre-cambering, M_{pc} , accounts for up to 87% of the ultimate bending moment resistance M_u . The results suggest that it may be feasible to downsize beams by optimising the balance between pre-cambering and strengthening to satisfy both serviceability and ultimate limit state requirements through WAAM, enabling reduced material use and improved material utilisation.

6.3. Resistance and stiffness

The enhancements in the resistance and the initial elastic stiffness of the WAAM-strengthened beam specimens are assessed using multiple metrics as proposed herein. To facilitate this evaluation, two key resistance levels, $M_{1\%}$ and $M_{5\%}$, are defined in addition to M_u for the four-point bending and the three-point bending specimens respectively, as depicted in Fig. 32(a) and (b) respectively. For the four-point bending specimens, $M_{1\%}$ is defined as the bending moment at which the tangent slope of the M - κ curve decreases to 1% of the initial elastic stiffness [64]. Similarly, for the three-point bending specimens, $M_{5\%}$ is defined as the bending moment where the tangent slope of the M - ϕ curve decreases to 5% of its initial value. These defined resistance levels offer stable measures of resistance that can be achieved without very excessive deformations.

The overall strengthening effect of the beam specimens in terms of resistance and stiffness, in comparison with the benchmark specimens, denoted as ϕ_X , is evaluated herein thus:

$$\phi_X = \frac{X_s - X_b}{X_b}, \quad (4)$$

where X represents the attribute to be examined (e.g., M_u , $M_{1\%}$, $M_{5\%}$ or K), the subscript 's' denotes the strengthened specimens, while the subscript 'b' refers to the bare benchmark specimens.

The calculated ϕ_X values, together with the percentage increases in mass, m_w/m_i , as reported in Table 8 (Section 4.1), are shown in Fig. 33(a) and (b) for the four-point bending and the three-point bending specimens respectively. Note that ϕ_{M_u} of the Specimen B-2-4PB is considered unrepresentative owing to the premature failure of the specimen, and is therefore excluded from the following discussion.

In general, the increases in the resistance and initial stiffness of the specimens are observed to be disproportionately high relative to the increases in mass. From Fig. 33(a), it is evident that the resistance and the initial stiffness of the four-point bending specimens grow with an increasing amount of additional WAAM material. By comparing Specimen B-4-4PB ('T-OF') with Specimen B-3-4PB ('T-F'), it is found that higher $\phi_{M_{1\%}}$ and ϕ_K values are achieved for B-4-4PB by the employment of an optimised material arrangement at the member level; however, ϕ_{M_u} of Specimen B-4-4PB is lower than that of Specimen B-3-4PB, which is likely to be attributed to its lower rotation capacity that limited further gains in the bending moment resistance from material strain-hardening before the failure of the specimen. Moreover, a comparison across Specimens B-(4-7)-4PB reveals that with similar increases in mass, M_u and $M_{1\%}$ can be further enhanced through adopting a 'TS' or 'SS' type cross-section, as expected from the conceptual design. However, these further enhancements are achieved at the expense of the pre-camber (see Fig. 20). Among all four-point bending specimens, Specimen B-4-4PB exhibits the highest initial stiffness, K , owing to its highest second moment of area within the flexural span (see Table 8). Overall, Specimens B-5-4PB and B-6-4PB are observed to demonstrate a good balance between resistance, stiffness and pre-camber. Similar trends can be found in the three-point bending specimens, with Specimen B-9-3PB demonstrating the best strengthening outcome.

Overall, for the four-point bending specimens, increases in mass from 2.63% to 12.26% resulted in increases in M_u between 11.5% and 33.2%, increases in $M_{1\%}$ between 9.4% and 38.5%, and increases in K

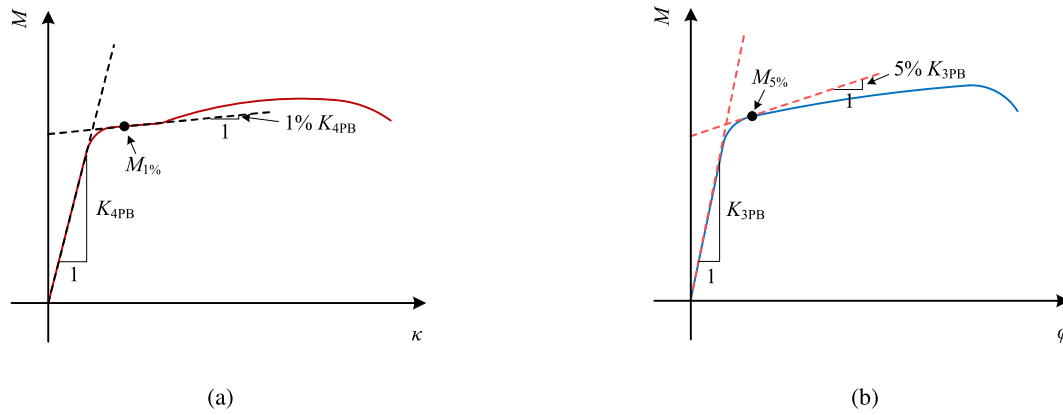


Fig. 32. Illustration of (a) $M_{1\%}$ for four-point bending specimens and (b) $M_{5\%}$ for three-point bending specimens.

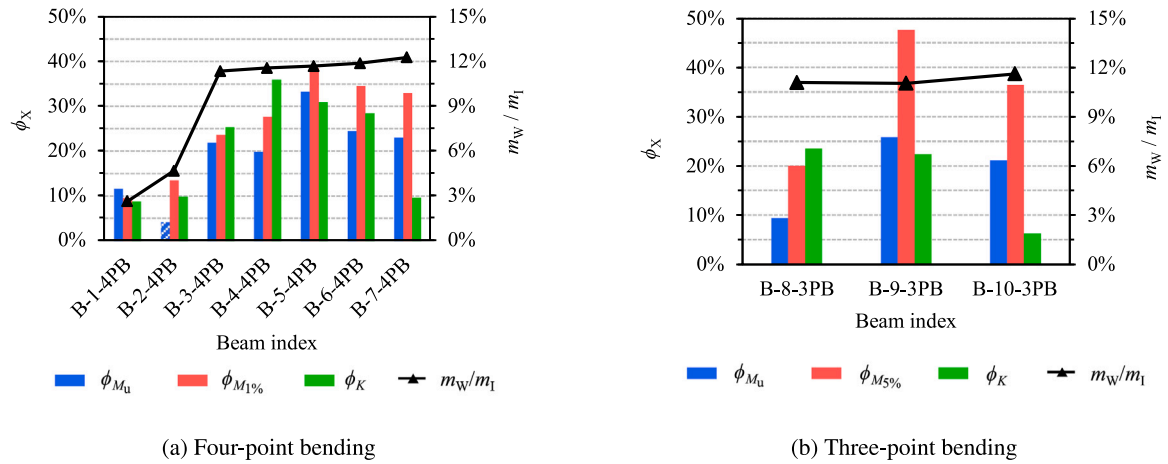


Fig. 33. Overall strengthening effect ϕ_X for (a) the four-point bending specimens in terms of M_u , $M_{1\%}$ and K , and of (b) the three-point bending specimens in terms of M_u , $M_{5\%}$ and K .

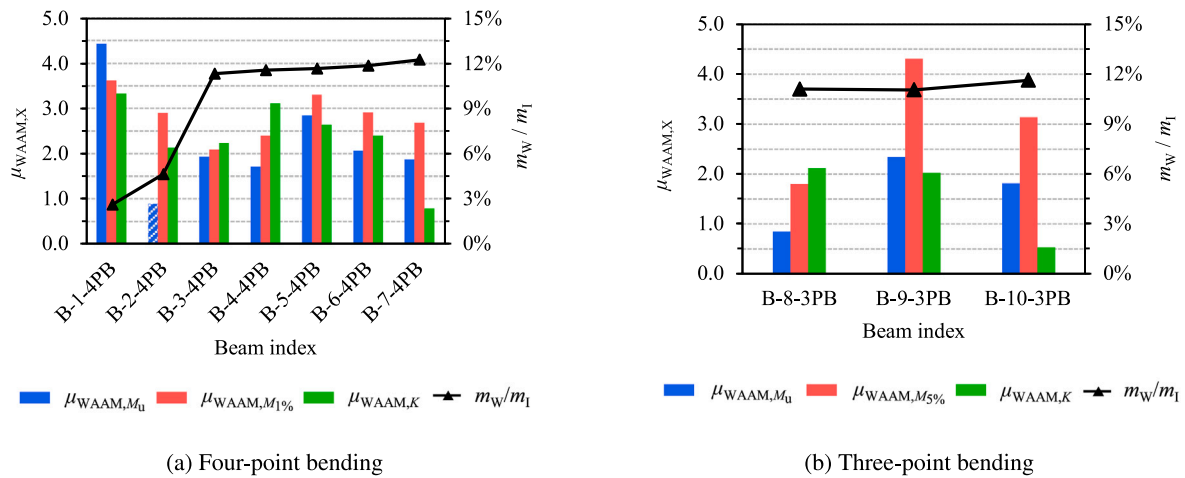


Fig. 34. Normalised efficiency of the additional WAAM material, $\mu_{WAAM,X}$, of (a) the four-point bending specimens in terms of M_u , $M_{1\%}$ and K , and of (b) the three-point bending specimens in terms of M_u , $M_{5\%}$ and K .

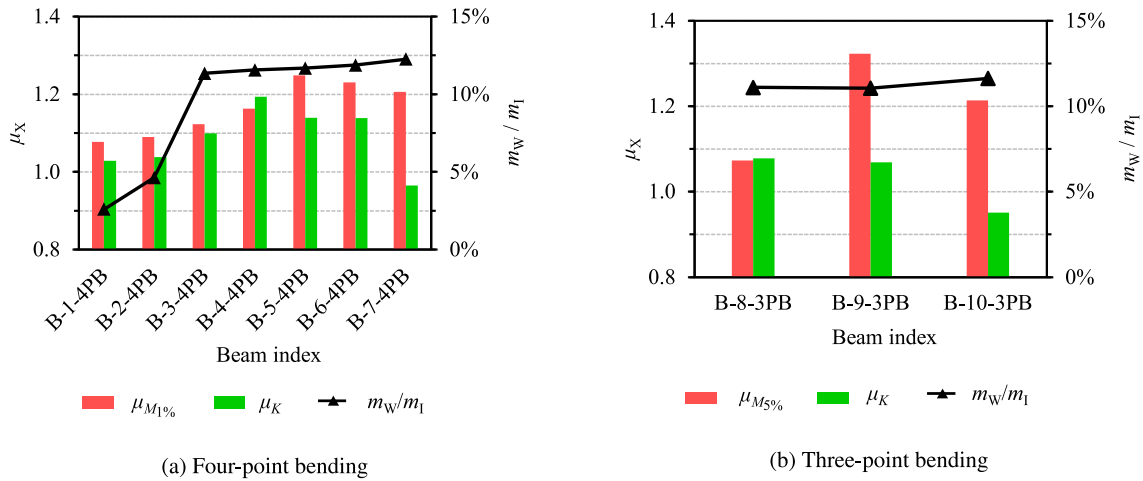


Fig. 35. Normalised strengthening performance, μ_X , of (a) the four-point bending specimens in terms of M_u , $M_{1\%}$ and K , and of (b) the three-point bending specimens in terms of M_u , $M_{5\%}$ and K .

between 8.7% and 35.9%. For the three-point bending specimens, an approximately 11.5% increase in mass resulted in up to 25.8%, 47.6% and 22.4% increases in M_u , $M_{5\%}$ and K respectively.

The observed disproportionate increases in the resistance and initial stiffness of the specimens, relative to the increases in mass, indicate that the deposited WAAM material, owing primarily to its strategic positioning, is more efficient in terms of resisting the external loads, in comparison with the material in the base I-sections. Here, a normalised efficiency factor, $\mu_{WAAM,X}$:

$$\mu_{WAAM,X} = \frac{[(X_s - X_b)/m_W]}{(X_b/m_{I,b})}, \quad (5)$$

which quantifies the relative contributions to the attribute of interest X , per unit mass of WAAM and I-section material, is used to define the efficiency of the WAAM material relative to that of the base material.

The calculated normalised efficiency indices of the WAAM material, $\mu_{WAAM,X}$, are shown in Fig. 34(a) and (b) for the four-point bending and the three-point bending specimens respectively, together with the m_W/m_I values. Contrary to the findings from Fig. 33, a decreasing trend in $\mu_{WAAM,X}$, in terms of both resistance and stiffness, is found for Specimens B-1-4PB to B-3-4PB, with the highest $\mu_{WAAM,X}$ value observed in the specimen with the least amount of additional WAAM material. For both the four-point bending and the three-point bending specimens, relatively high normalised material efficiencies can be observed in the specimens with optimised arrangements of WAAM material. It is also found that the 'SS' type of cross-sectional material arrangement demonstrates the lowest efficiency in enhancing the initial stiffness, as evidenced by Specimens B-7-4PB and B-10-3PB, where the values of $\mu_{WAAM,K}$ are less than 1.

In addition to ϕ_X and $\mu_{WAAM,X}$, another index, μ_X , is defined to evaluate the overall performance of the hybrid WAAM-strengthened specimens relative to the bare hot-rolled I-section beams:

$$\mu_X = \frac{X_s}{X_{eq}}, \quad (6)$$

where X is the attribute to be examined, the subscript 's' denotes the strengthened specimen itself, and the subscript 'eq' represents an equivalent bare I-section beam with the same mass as the strengthened specimen, achieved by proportionally increasing the thickness of the web and the flange of the I-section. The values of the studied attributes X_{eq} of the equivalent I-sections were obtained through finite element analysis. The μ_X values for the four-point bending specimens and the three-point bending specimens, evaluated for $M_{1\%}$, $M_{5\%}$ and K , are

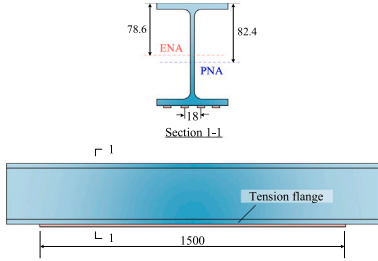
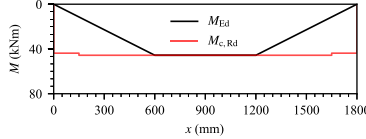
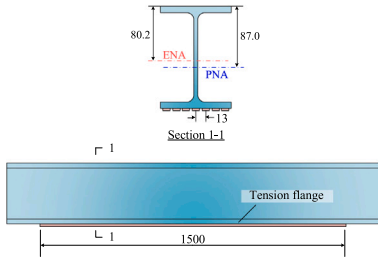
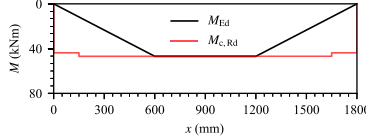
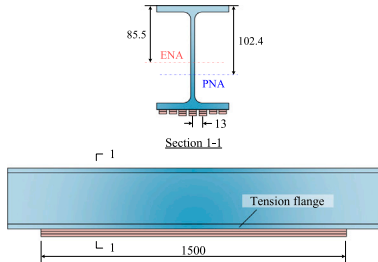
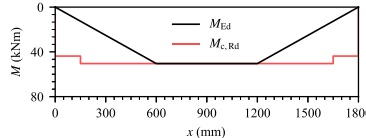
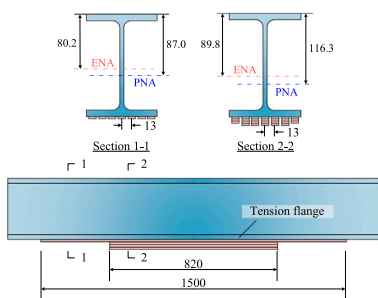
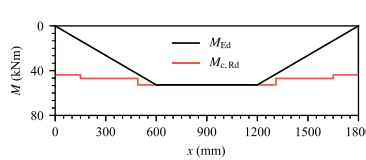
shown in Fig. 35(a) and (b) respectively. In general, it can be observed that, with the same mass, superior performances can be found in the hybrid specimens over their equivalent bare I-section counterparts.

7. Conclusions

In the present study, an experimental investigation was conducted to examine the major-axis flexural behaviour of 10 hot-rolled I-section beams, strengthened by the addition of material through WAAM, where seven and three specimens were tested under four-point bending and three-point bending conditions respectively. The results showed that for increases in mass of between 2.63% and 12.26%, increases of 11.5%–33.2% in M_u , 9.4%–38.5% in $M_{1\%}$, and 8.7%–35.9% in K , were achieved for the four-point bending specimens. For the three-point bending specimens, an approximately 11.5% increase in mass yielded up to 25.8%, 47.6% and 22.4% increases in M_u , $M_{5\%}$ and K respectively. Overall, the specimens with 'T-F' and 'T-OF' types of material arrangement (i.e., with WAAM additions primarily on the tension flange) achieved high levels of pre-cambering (a pre-camber of approximately $L/200$ with only 2.63% increase in mass), but also exhibited reduced rotation capacities, while the specimens with a 'TS-OF' type of material arrangement (i.e., with WAAM material across the tension flange and on the tips of compression flange) demonstrated a good balance between the pre-camber, the rotation capacity and the enhancements in resistance and stiffness. The 'SS' type of material arrangement (i.e., with WAAM material on the tips of both the tension and compression flanges) was shown to be capable of achieving substantial enhancements in resistance while retaining good rotation capacity; however, improvements in initial stiffness were found to be less significant. The enhancements in resistance and initial stiffness of the strengthened specimens were evaluated using several metrics, including the overall strengthening outcome – ϕ_X , the normalised efficiency of the WAAM material – $\mu_{WAAM,X}$ and the normalised efficiency of overall material – μ_X . It has been shown that the hybrid WAAM-hot-rolled steel beams demonstrate superior material efficiency when the additional WAAM material is carefully arranged in optimised patterns, with the overall material efficiency being 15% higher than that of the equivalent hot-rolled I-section beams, and the efficiency of the WAAM material itself being three to four times higher than that of the base material. These experimental findings validated the potential for using WAAM in strengthening steel flexural members, or in the manufacture of hybrid steel members with enhanced flexural behaviour in new

Table A.1

Details of the WAAM-strengthened beam specimens (dimensions in mm, not to scale), ENA = elastic neutral axis and PNA = plastic neutral axis.

Beam ID	Profile	Moment diagrams	Material arrangement	Load(s) P (kN)	Nominal $V_{W.o}/V_{L.o}$ (%)
B-1-4PB			'T-F'	76.05	2.63
B-2-4PB			'T-F'	78.17	4.60
B-3-4PB			'T-F'	84.12	11.17
B-4-4PB			'T-OF'	87.88	11.42

(continued on next page)

Table A.1 (continued).

Beam ID	Profile	Moment diagrams	Material arrangement	Load(s) P (kN)	Nominal $V_{w,n}/V_{Ln}$ (%)
B-6-4PB			'TS-OF'	92.05	11.75
B-7-4PB			'SS-O'	93.58	12.19
B-8-3PB			'T-F'	112.16	11.17
B-10-3PB			'SS-O'	142.89	11.38

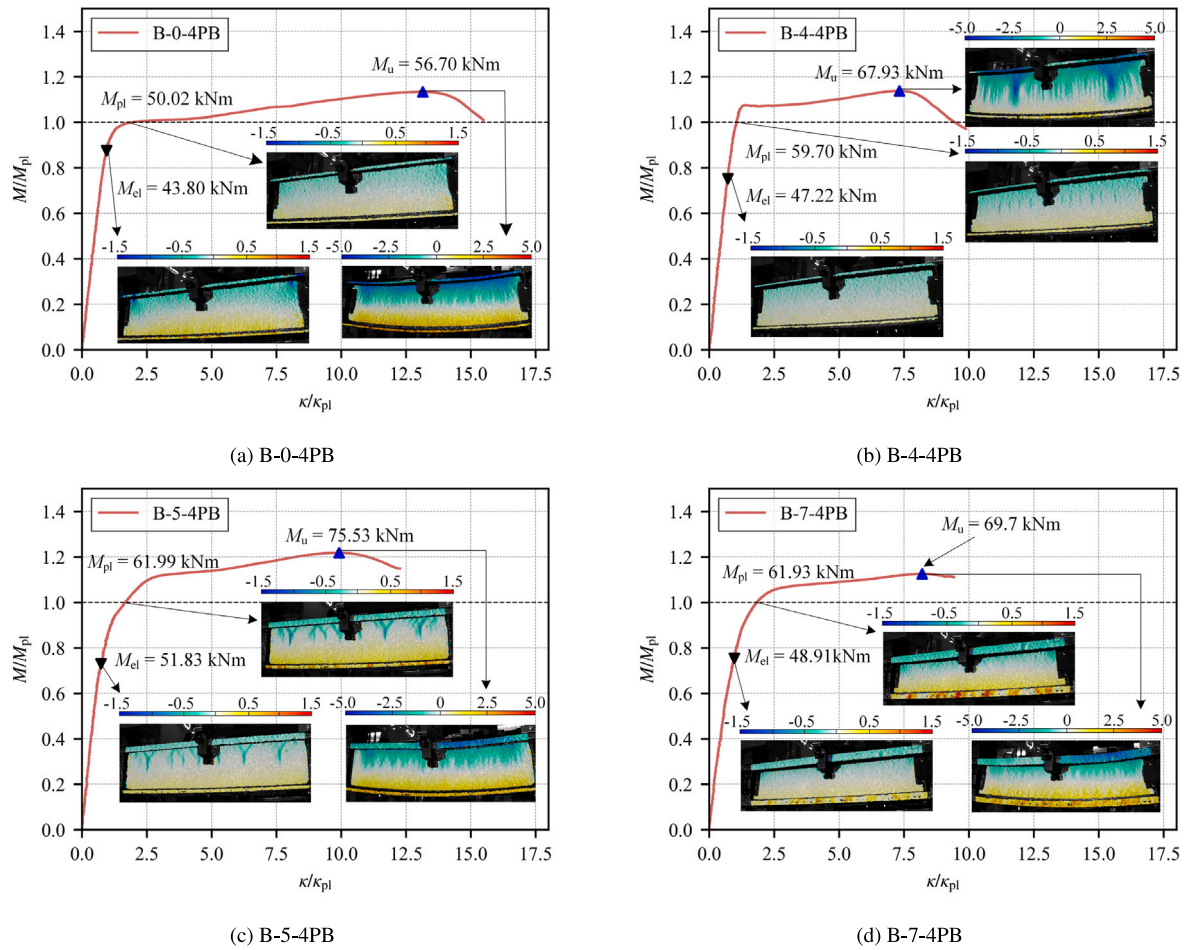


Fig. B.1. Graphs of normalised bending moment versus curvature within the flexural span and longitudinal strain fields at key bending moment levels obtained from DIC for some typical four-point bending specimens (a) B-0-4PB, (b) B-4-4PB (c) B-5-4PB and (d) B-7-4PB. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

construction. Further studies will focus on the residual stresses in the strengthened specimens due to the thermal prestressing effect, and the finite element modelling and design of WAAM-strengthened I-section beams. It should be mentioned that the application of WAAM for in-situ strengthening of existing structures may be constrained by the limitations of welding equipment and robotic operations. Additionally, while the present study has provided some typical WAAM material arrangements for specific major-axis bending conditions, other loading conditions and their corresponding WAAM material arrangements and strengthening effects should be explored in further research.

CRediT authorship contribution statement

Jiachi Yang: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis. **M. Ahmer Wadee:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Leroy Gardner:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Design of the WAAM-strengthened beam specimens

See [Table A.1](#).

Appendix B. Strain development of the WAAM-strengthened beam specimens obtained through DIC

See [Figs. B.1](#) and [B.2](#).

Data availability

Data will be made available on request.

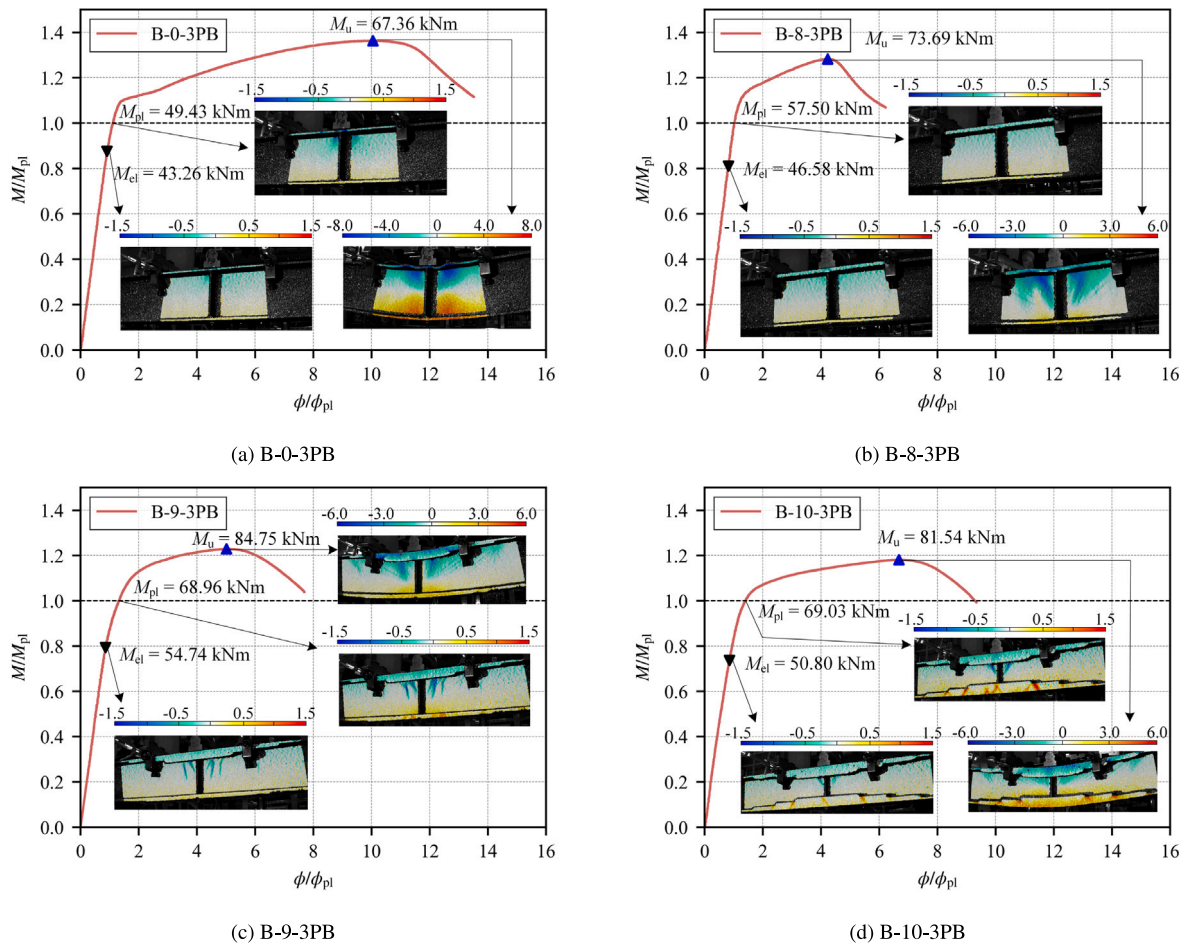


Fig. B.2. Graphs of normalised bending moment versus curvature within the flexural span and longitudinal strain fields at key bending moment levels obtained from DIC for some typical three-point bending specimens (a) B-0-3PB, (b) B-8-3PB (c) B-9-3PB and (d) B-10-3PB.

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