

Structural performance of additive manufactured metallic material and cross-sections

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Abstract

Additive manufacturing, a common example of which is 3D printing, has become more prevalent in recent years with it now being possible to form metallic structural elements in this way. There are, however, limited available experimental data on the material behaviour of powder bed fusion (PBF) additive manufactured metallic structural elements and no existing data at the cross-section level; this is addressed in the present paper through a series of tests on additive manufactured stainless steel material and cross-sections. Tensile and compressive coupon tests were used to assess anisotropy, symmetry of stress-strain behaviour and the influence of building direction on the material properties. The yield and ultimate tensile strengths were seen to generally decrease in magnitude with increasing build angle, while a reduction in ductility was observed in some building orientations, and the Young's moduli were typically insensitive to the build angle. The structural behaviour of PBF additive manufactured cross-sections was investigated through a series of square hollow section (SHS) stub column tests, and the results compared with conventionally produced stainless steel SHS. The generated test results have been used to evaluate the applicability of existing design guidance for conventionally produced sections to additive manufactured sections.

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1. Introduction

Additive manufacturing is the overarching name for any form of manufacturing where an object is produced in an additive manner, whether this be through the laying down of material, melting and binding of material, selective curing
5 of a liquid or the adhering of existing layers. ‘3D printing’ is a term that generates tremendous excitement in society, although strictly applies only to methods which lay down material, and is itself a type of additive manufacturing. Additive manufacturing first emerged in the 1980s with rapid prototyping techniques, initially through stereolithography, which is the process of solidifying
10 ultraviolet sensitive liquid polymer with a laser [1]. Significant advancements have been made since then with a wide range of materials able to be utilised including ceramics, chemicals, composites, concrete, foodstuffs, metallic materials (including aluminium, cobalt-chrome, copper, gold, iron alloys (including stainless steels), magnesium, nickel based alloys, titanium and tungsten), paper, plastics,
15 sandstone, silicones, wax and wood [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. The end products are equally varied from customised sports footwear [11] to building plastic tools on the International Space Station [12], the production of titanium rocket nozzle components [13] and even personalised chocolate confectionary [7].

1.1. *Metallic additive manufacturing*

20 Metal additive manufacturing is increasingly popular in the aerospace, automotive, defence and medical industries [14, 15] due to its many advantages over traditional manufacturing techniques, such as casting, fabrication, machining, rolling and stamping. Conventionally manufactured objects often have simple geometries to aid manufacturing [4] whereas with new production techniques
25 this need not be the case. Additive manufacturing enables automated and repeatable rapid prototyping or small production runs of objects with complex

geometries and shapes that would otherwise be time and cost prohibitive, or even impossible with other manufacturing methods. Structural components can take highly optimised lightweight forms to carry loads more efficiently, including the possibility of internal stiffening structures and specific weight-saving porosities with parts as thin as 100 microns [16]. There are also a number of wider benefits including reduced material waste, reduced energy input and rapid incorporation of design changes. Parts can be built essentially anywhere, just-in-time if required and with the same processing parameters, predictably and reliably. Additive manufacturing techniques can even be used to repair worn and damaged metallic components [4, 15]. This new manufacturing process has also been found to yield advantageous mechanical properties due to the rapid cooling over conventionally produced metallic materials [17]; this has been observed in the material tests undertaken in this study.

To date, compared with plastic additive manufacturing, which has benefited from the introduction of low cost production equipment in the late 1990s [18], equipment suitable for use with metallic materials has been prohibitively expensive [19]. Currently, production time can be excessively lengthy since, with some building methods, objects are built up using individual layers that are tens of microns thick. Support structures are typically required to mechanically restrain the part being manufactured to the rigid building platform, in order to reduce the distortion arising from the residual stresses [20], and these need to be later manually removed. The surface finish is different from conventionally produced metallic objects which, for some applications, may necessitate additional finishing processes, such as sanding or bead blasting, and consequently parts may need to be manufactured slightly oversized. Significant design times within computer aided design (CAD) software packages can also be required. The maximum dimensions of a single part are limited by the build envelope of the equipment which, for powder bed fusion, is typically a 250 mm cube, while some direct energy deposition methods allow a single dimension up to 5 m. These size limitations will be overcome in time; Big Area Additive Manufacturing (BAAM) is being

developed with the intention to build components as large as aircraft wings that are 30 m in length [21]. While additive manufactured metallic materials exhibit some beneficial mechanical properties over conventionally produced materials, they can also exhibit anisotropy [17, 22, 23, 24, 25, 26, 27, 28, 29] which for some materials can be partially remediated through heat treatment [26, 27, 28, 30, 31, 32], and high residual stresses [3, 33].

ISO/ASTM 52900 [34] provides an outline of metallic single-step additive manufacturing methods, where the key process categories are: i) directed energy deposition, ii) powder bed fusion and iii) sheet lamination. Directed energy deposition (DED) relies on the selective depositing of melted material, which can be either a laser or electron beam melted powder or a filament/wire material, akin to welding. Powder bed fusion (PBF) is where material within a powder bed is selectively fused together using thermal energy from a laser or electron beam. The third category is sheet lamination, where individual cut out cross-sections can be laminated together using ultrasound. Beyond single-step processing, there is multi-step processing where the first step provides the geometric shape and the second provides the material properties, and this process can also involve adhering dissimilar materials together. The proprietary nature of the manufacturing equipment and metallic powders has resulted in a variety of names for similar processes. ISO/ASTM 52900 [34], and its predecessor ASTM F2792-12a [35], have attempted to standardise the terminology, but this has only recently been adopted in the literature; for example, PBF includes selective laser melting (SLM), selective laser sintering (SLS), direct metal laser sintering (DMLS) and electron beam melting (EBM) among others [1], while DED includes laser engineered net shaping (LENS).

Over the past twenty years there has been significant research into metallic additive manufacturing processes and applications. Tensile coupon tests have been undertaken on PBF 316L stainless steel to investigate anisotropy arising from different building orientations [22, 23, 25, 26, 29], the influence of the laser

power [3], powder particle size [25] and building layer thickness [25, 29] on the
 90 material properties, the fatigue performance [26, 36] and residual stresses [33, 37].
 Corrosion resistance has also been assessed and, it has been found that provided
 full relative density is attained, the resistance is similar to conventionally formed
 material [38]. Coupon tests have been performed on PH1/15-5PH martensitic
 stainless steel to study the tensile behaviour in different build orientations [20]
 95 and to examine the fatigue behaviour [20, 36]. Research has also been carried
 out into DED 316L [39], the processing parameters for PBF [40] and DED [41]
 304 stainless steel, the anisotropy [26, 28] and heat treatment [28, 30] of PBF
 aluminium alloys, the anisotropy [17] and heat treatment [31, 32] of PBF titanium
 alloys, the mechanical properties of DED titanium alloys [42, 43], the structural
 100 integrity of post-processed bronze-nickel alloys [44] and directionality at differing
 temperatures of a nickel based superalloy [45]. Studies into the structural
 applications of PBF metallic materials have included examining 316L stainless
 steel open cellular lattice structures [16, 46, 46, 47] and negative Poisson's ratio
 structures [48]. The applications of DED MX3D gas metal arc welding (GMAW)
 105 in structural engineering have also been explored [49].

1.2. Additive manufacturing in construction

Additive manufacturing offers many potential benefits in construction, such
 as the ability to produce bespoke individual components, reduced waste, time
 110 and material savings, more optimised structural forms and easier integration
 with building information modelling (BIM) [9, 50]. Current constructional
 additive manufacturing research has focussed mainly upon cementitious materials.
 Contour crafting, which utilises a cement-based paste against a trowel can be
 used to produce a 200 m² single-storey building within a day [50, 51], concrete
 115 printing involves extrusion of cement mortar [9] and the D-shape process involves
 producing a material similar to sandstone by combining adhesives and a sand-like
 material [6, 9, 50, 52]. In 2014 construction started on the 3D Print Canal House
 in Amsterdam, Netherlands which is an additive manufactured house made

by joining individual plastic blocks [50, 53]. Construction has started, again
 120 in Amsterdam, on the MX3D bridge, a stainless steel DED GMAW structure
 that will eventually span an 8 m wide canal [49]. Arup recently redesigned a
 node detail to be built using PBF and found that while currently it would cost
 roughly three times that of a conventionally produced node, it is expected to be
 cheaper through manufacturing developments within five years [54]. It has been
 125 estimated that in the future, additive manufacturing technologies may decrease
 construction costs by 30% through automation and reduced labour requirements
 [55]. Additive manufacturing techniques have also been proposed to aid in the
 rapid construction of shelters in disaster hit areas [51].

130 It is clear from the existing research into metallic additive manufacturing that
 extensive work has been carried out on the production processes and basic
 material properties, but there has been very limited research to date into
 potential structural engineering applications. The aim of this paper is to further
 investigate the directionality of powder bed fusion stainless steels in both tension
 135 and compression and to undertake cross-sectional tests to provide experimental
 data to appraise the applicability of existing design methods to sections produced
 through this novel manufacturing route.

2. Experimental investigation

140 The experimental investigation consisted of tensile and compressive material
 coupon tests and compressive tests on square hollow section (SHS) stub columns.
 Two different stainless steel grades were studied - a precipitation hardening
 martensitic grade PH1 (also known as 15-5 PH, EN 1.4540 and X4CrNiCuNb164),
 commonly used for aerospace components and parts for corrosive high pressure
 145 environments [20, 56], and an austenitic grade 316L (also referred to as EN
 1.4404 and X2CrNiMo17-12-2), which is widely used for aerospace, automotive,
 chemical, construction, consumer and nuclear applications [57]. Tensile material

properties in a variety of building orientations were determined for both stainless steel grades, with compressive material properties measured for the austenitic 316L grade only. The cross-sections were built vertically, with their longitudinal axis perpendicular to the building layers. The cross-sectional behaviour was examined for the 316L material as this is a common grade of stainless steel used in structural engineering and is included in the European stainless steel design standard EN 1993-1-4 [58]. The chemical composition of the metallic powders from the manufacturer’s datasheet [56, 57] are provided in Table 1. The tensile and compressive coupons were produced at Lappeenranta University of Technology (LUT) and the Fraunhofer Institute for Laser Technology (ILT) and the stub columns were manufactured by EOS Finland, while the experiments were undertaken at Imperial College London (ICL). The manufacturing method, including processing parameters, and the experiments are described in this section.

2.1. Powder bed fusion manufacturing

The tension coupons and stub columns were built using powder bed fusion (PBF), with equipment and powder from EOS who market their manufacturing process as direct metal laser sintering (DMLS). Development of PBF methods started in the late 1980s [59] and accelerated during the late 1990s in Germany [23, 31] with the first patent to turn metal powder into metal components filed in 1997 [4]. The first attempts at stainless steel PBF, which used 316L grade powder, were unsuccessful due to balling effects [5]; however, by 2010 the process had advanced such that 316L PBF had reached relative densities approaching 100% [22].

The general laser PBF manufacturing process is outlined in Figure 1. First, the part is drawn in CAD software as a three-dimensional solid model; it is then converted into an STL model, which describes the surface geometry using tessellated triangles; and finally it is turned into two-dimensional slices that

	Material	Cr (%)	Ni (%)	Cu (%)	Mn (%)	Si (%)	C (%)	Mo (%)	Nb (%)	P (%)	S (%)	N (%)	Fe (%)
∞	PH1	14.0 -15.5	3.5 - 5.5	2.5 - 4.5	≤ 1.00	≤ 1.00	≤ 0.07	≤ 0.50	0.15 - 0.45	-	-	-	Balance
	316L	17.0 -19.0	13.0 -15.0	0.5	2	0.75	0.03	2.25 - 3.00	-	0.025	0.01	0.1	Balance

Table 1: Chemical composition from manufacturer's data sheet

represent the individual layers to be built. The components tested in this study were initially drawn and converted to an STL model in SolidWorks CAD software with the two-dimensional slicing undertaken using Netfabb software. These layers are then sent to the PBF machine with appropriate processing parameters and the building process can begin. The recoating mechanism spreads powder across the building platform and then a laser beam scans the two-dimensional sliced cross-section (shown in Figure 2) selectively melting and fusing together the first layer of powder to the building platform. The building platform then lowers by the layer thickness and the build cycle repeats until the part has been built layer by layer. The unused powder is removed and sieved to be used in the next build job. The build platform, with built parts still attached, can be taken out of the machine (Figures 3 and 4), the parts heat treated if required and then detached from the building plate.

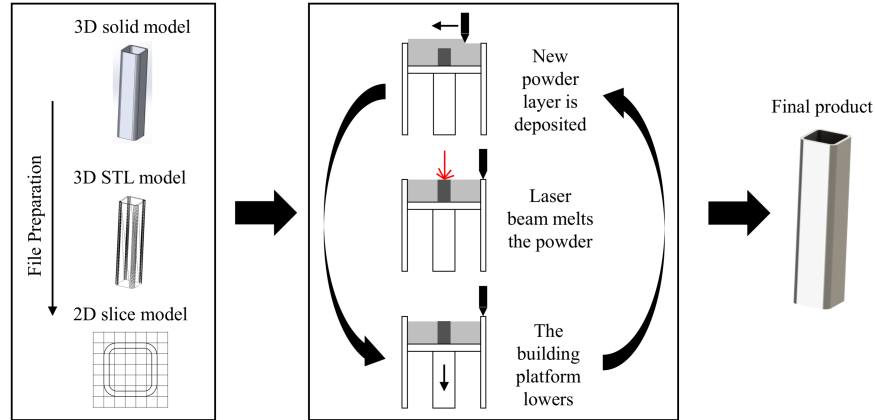


Figure 1: Overview of the PBF process from computer model to final product

Support structures, such as those shown in Figure 5, are required when building objects with cantilevering elements (both horizontal and below 45°), for mechanical stability [30] and to dissipate heat into the building platform, due to the

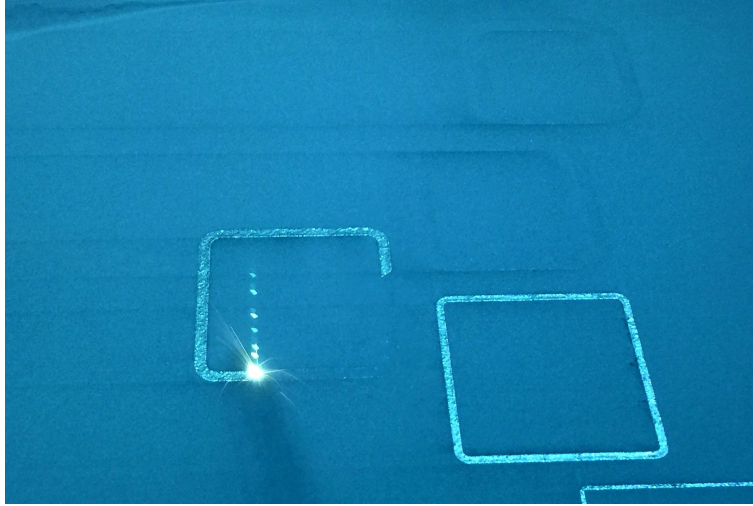


Figure 2: 316L stub columns during building

195 unmelted powder's poor heat conductivity, and for slender vertical elements that, if distorted, could be damaged by the recoating mechanism. These structures were automatically produced using Magics software, based upon inputted acceptable cantilevering build angles and the building material.

200 The PH1 tensile coupons were built from EOS PH1 powder at the LUT Laser facilities in Lappeenranta, Finland using a modified research EOS M270 machine. The 316L tensile and compressive coupons were manufactured using EOS 316L powder in an EOS M270 machine at the Fraunhofer Institute for Laser Technology (ILT) in Aachen, Germany, while the stub columns were built by EOS Finland
 205 using an EOS M280 machine. The particle size of both powders was within the 21-53 μm range. The processing parameters used were those recommended by the manufacturer, which are optimised for the powder and testing machines. The power of the ytterbium fibre laser, laser spot size on the building surface, scanning velocity (laser spot velocity), layer thickness, hatch distance (distance
 210 between adjacent scanning tracks), preheated temperature of the build platform, to minimise the residual stresses close to the building platform [31], and the

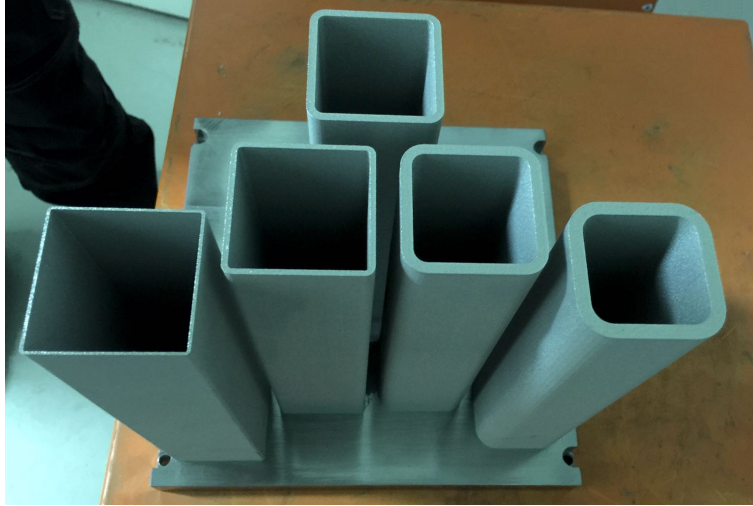


Figure 3: 316L stub columns after building, still attached to the building plate

protective gas, to prevent melt pool oxidation and the formation of nitridic phases [29, 31], employed are listed in Table 2. The scanning strategy (i.e. how the laser spot traverses the build surface) rotated by 45° with each layer to
 215 minimise the internal defects [60] and increase the relative density. The coupons and stub columns were all built at the same time within their respective groups, i.e. all of the 316L tensile coupons were built at the same time on the same build platform. The build time was roughly 40 hours for the tensile and compressive coupons and 140 hours for the stub columns with an approximate volumetric
 220 build rate of $2 \text{ mm}^3/\text{s}$. No post building surface treatment was undertaken, apart from removal using a band saw from the building platform, grinding off the support structures and machining of the stub column ends.

Prior to testing, the PH1 tensile coupons were X-ray imaged to check for obvious
 225 internal imperfections, such as large pores. No obvious imperfections were found and this process was not repeated for the 316L components since the building processes were deemed successful and no defects were expected in the test pieces. The built relative density was not measured, although by following

Material	Laser power (W)	Laser spot size (μm)	Scanning velocity (mm/s)	Layer thickness (μm)	Hatch distance (mm)	Preheated build platform ($^{\circ}\text{C}$)	Preheated powder	Protective gas
PH1	200	100	1000	20	0.1	80	No	Nitrogen
316L	200	100	1000	20	0.1	80	No	Argon

Table 2: Summary of adopted processing parameters

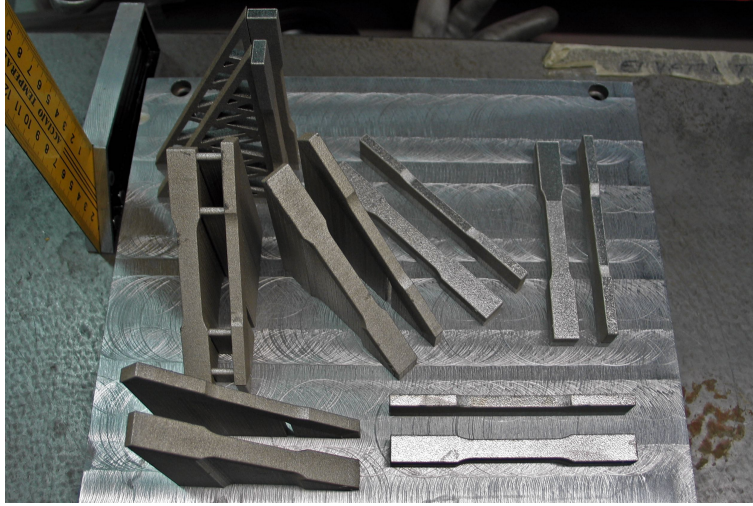


Figure 4: PH1 tensile coupons after building, still attached to the build platform

the manufacturer’s recommended processing parameters, it is expected to have
 230 approached 100%.

2.2. Tensile coupon tests

Tensile coupon tests were undertaken to ascertain the tensile engineering stress-strain properties of the material, and to observe any directionality effects arising
 235 from the manufacturing method. Fourteen coupons were built in a range of building orientations using PBF with both PH1 and 316L powder (leading to 28 coupons in total). One coupon for each orientation built from PH1 and 316L stainless steel powder was tested. The coupons had the traditional dog bone shape and had the nominal dimensions shown in Figure 6.

240

The building orientation angles of the tensile coupons are defined in Figure 7, similar to Luecke and Slotwinski [27], where θ is the angle measured from the horizontal building plane to the longitudinal axis of the coupon (i.e. $\theta = 0^\circ$ is a coupon parallel to the building plane and $\theta = 90^\circ$ is a vertical coupon), ψ
 245 is the angle between the recoating direction and the longitudinal axis of the

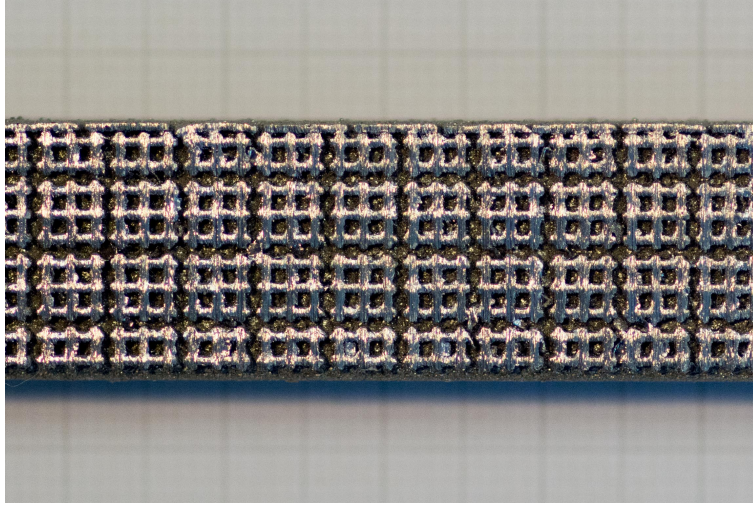


Figure 5: A cross-section through a typical support structure for a compression coupon

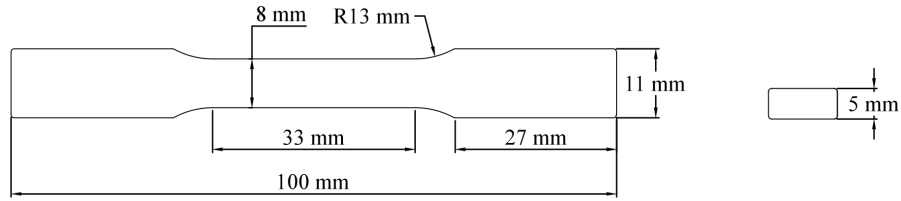


Figure 6: Nominal dimensions of the PH1 and 316L tensile coupons

coupon (i.e. $\psi = 0^\circ$ is aligned with the recoating direction and $\psi = 90^\circ$ is perpendicular to the recoating direction) and ϕ is the angle between the long face of the cross-section and the building plane (i.e. $\phi = 0^\circ$ is a coupon with its long face parallel to the building plane and $\phi = 90^\circ$ is a coupon with its short face parallel to the building plane). For the vertical coupons ($\theta = 90^\circ$), $\phi = 0^\circ$ is a coupon with the short face of its cross-section parallel to the recoating direction and $\phi = 90^\circ$ with its long face parallel to the recoating direction.

The tensile tests were carried out at room temperature and in compliance with EN ISO 6892-1 [61] using an Instron 8802 testing machine, with the data being recorded with a proprietary in-house data logger at 2 Hz frequency. The coupons

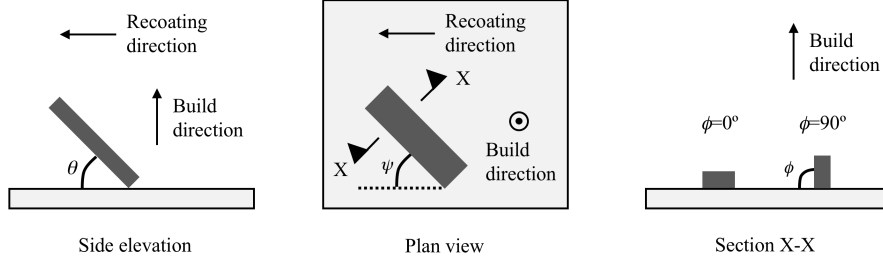


Figure 7: Building orientation angles θ , ψ and ϕ for the tensile and compressive coupons

were measured prior to testing and had the standard gauge lengths ($5.65\sqrt{S_0}$ where S_0 is the original cross-sectional area of the parallel length [61]) marked upon their surface. The instrumentation consisted of two electrical resistance strain gauges, attached to the side faces of the coupons at mid-height to measure strains until shortly after material yielding and a video extensometer to monitor the position of two dots painted onto the front face of the coupon to measure post yielding strains. The applied tensile load was measured directly from a load cell in the testing machine. As recommended in EN ISO 6892-1 [61], two crosshead separation rates were used before and post material yielding, dependent upon the parallel length of the necked region, with a gradual ramp between the two rates. The PH1-9 coupon was tested first and fractured immediately following the programmed ramp; as a precaution only the slower rate was used for the remaining PH1 coupons. The low failure strain and sudden fracture is an inherent property of some PBF metallic materials. The two separation rates with a gradual ramp were used for the 316L coupons. Further investigation into the effect of strain rate on the fracture behaviour of additively manufactured PBF stainless steel is required, along with consideration of other mechanical characteristics such as the shear properties and the Poisson's ratio.

275

The Young's modulus E , 0.2% proof stress $\sigma_{0.2}$, 1.0% proof stress $\sigma_{1.0}$, ultimate tensile stress σ_u , strain at the ultimate tensile stress ε_u , fracture strain measured over the marked standard gauge length ε_f , area reduction at fracture A_f , the

Ramberg-Osgood (R-O) parameter n [62] and the extended R-O parameters
 280 $n'_{0.2,1,0}$ and $n'_{0.2,u}$ [63, 64, 65] determined from the coupon tests are reported in
 Tables 3 and 4 for the PH1 and 316L coupons respectively. The average material
 properties are also reported for the horizontal ($\theta = 0^\circ$), vertical ($\theta = 90^\circ$) and
 inclined ($\theta = 45^\circ$) coupons; average values for all orientations are also presented.
 Typical material properties from the manufacturer's datasheets [56, 57] are
 285 provided in Table 5, which, it should be noted, are not guaranteed minimum
 values[27]. The stress-strain curves for all the tested tensile coupons are shown
 in Figures 8 and 9. The variation of Young's modulus E , 0.2% proof stress
 $\sigma_{0.2}$, ultimate tensile stress σ_u and fracture strain ε_f with coupon building
 orientation θ is plotted in Figures 10-13 for the PH1 coupons, together with
 290 existing heat-treated PH1 tensile coupon data [20], and Figures 14-17 for the
 316L coupons, alongside existing 316L tensile coupon results [22, 23, 25, 26, 29].
 The plotted tensile material properties have been normalised by the average
 of the respective dataset. Note that PH1-14 was a replacement coupon that
 was built several months later than the original PH1 coupons and exhibits a
 295 significantly lower Young's modulus E and 0.2% proof stress $\sigma_{0.2}$ compared with
 the other inclined coupons, and as a result has been omitted from Figures 10-13.

The tested PH1 tensile coupons show fairly consistent values of the Young's
 modulus E , varying $\pm 3\%$, with a very slight reduction as the building angle θ
 300 increases as seen in Figure 10. Likewise, the 0.2% proof stress $\sigma_{0.2}$ shows minimal
 variation with the building angle (see Figure 11), while the existing heat-treated
 data [20] has a significantly lower yield stress for the vertical ($\theta = 90^\circ$) coupon.
 There is a clear trend with both the ultimate tensile stress σ_u and fracture strain
 ε_f of decreasing magnitude with increasing building angle (see Figures 12 and 13
 305 respectively), the latter quite dramatically, particularly for the vertical coupons
 ($\theta = 90^\circ$) and those inclined in the recoating direction ($\theta = 45^\circ$, $\psi = 0^\circ$), which
 exhibited negligible necking before failure. For the existing data [20] there is
 no clear influence of building orientation on the ultimate tensile stress σ_u and
 fracture strain ε_f indicating that heat treatment reduces the inherent material

Coupon	θ (deg)	ψ (deg)	ϕ (deg)	E (N/mm ²)	$\sigma_{0.2}$ (N/mm ²)	$\sigma_{1.0}$ (N/mm ²)	σ_u (N/mm ²)	ε_u (%)	ε_f (%)	A_f (%)	n	$n'_{0.2,1.0}$	$n'_{0.2,u}$
PH1-1	0	0	0	194900	870	1045	1273	10	13.4	37.5	7.5	2.5	2.6
PH1-2	0	0	90	191100	816	1022	1252	7.2	14.1	39.8	8.3	2.5	2.6
PH1-3	0	90	0	197300	883	1062	1280	8.3	15.1	41.5	7.3	2.5	2.5
PH1-4	0	90	90	194600	815	1030	1262	8.1	16.4	40.8	8.1	2.5	3.4
PH1-5	0	45	0	192800	879	1055	1255	7.8	15.3	35.9	6.5	2.4	2.5
PH1-6	0	45	90	189500	826	1031	1248	7.8	15.7	45.1	8.4	2.5	2.7
PH1-7	90	-	0	188700	850	1111	1216	4.6	5.4	7.2	5.1	2.4	2.6
PH1-8	90	-	90	187700	858	1113	1178	2.6	4.3	10.8	5.3	1.8	2.5
PH1-9	45	0	0	187500	800	1072	1232	4.7	3.6	9.9	5.0	2.5	3.4
PH1-10	45	0	90	193000	822	1074	1203	3.4	4.6	13.0	5.6	2.5	2.5
PH1-11	45	90	0	188400	810	1074	1238	6.5	12.5	30.5	5.4	2.5	3.5
PH1-12	45	90	90	198200	819	1078	1234	4.9	11.1	46.4	5.3	2.5	2.6
PH1-13	45	45	0	196900	803	1084	1257	6.7	11.4	33.0	4.9	2.5	3.5
PH1-14	45	45	90	180600	710	1012	1245	7.2	7.7	14.6	6.1	3.5	4.6
Average (horizontal)	0	-	-	193400	848	1041	1262	8.2	15.0	40.1	7.7	2.5	2.7
Average (vertical)	90	-	-	188200	854	1112	1197	3.6	4.9	9.0	5.2	2.1	2.5
Average (inclined)	45	-	-	190800	794	1066	1235	5.6	8.5	24.6	5.4	2.7	3.4
Average (all)	-	-	-	191500	826	1062	1241	6.4	10.8	29.0	6.3	2.5	3.0

Table 3: Summary of the PH1 measured tensile coupon material properties

Coupon	θ (deg)	ψ (deg)	ϕ (deg)	E (N/mm ²)	$\sigma_{0.2}$ (N/mm ²)	$\sigma_{1.0}$ (N/mm ²)	σ_u (N/mm ²)	ε_u (%)	ε_f (%)	A_f (%)	n	$n'_{0.2,1.0}$	$n'_{0.2,u}$
316L-15	0	0	0	179200	486	530	626	24.3	28.9	33.6	10.7	1.6	2.5
316L-16	0	0	90	171900	492	533	637	27.0	37.7	35.6	13.5	1.8	2.5
316L-17	0	90	0	167300	480	510	616	23.9	29.5	25.6	14.0	1.6	1.9
316L-18	0	90	90	167500	488	529	634	27.2	34.7	40.2	12.6	1.8	2.5
316L-19	0	45	0	172000	511	551	659	30.8	41.0	38.3	10.4	1.8	2.5
316L-20	0	45	90	170500	499	542	645	27.4	38.7	46.7	11.6	1.6	2.5
316L-21	90	-	0	183700	391	469	552	24.5	28.0	34.2	2.5	2.5	3.6
316L-22	90	-	90	180300	428	488	576	37.2	50.3	67.7	3.3	2.4	3.5
316L-23	45	0	0	177800	502	538	658	46.6	59.5	53.8	5.5	2.4	2.5
316L-24	45	0	90	180000	466	526	637	40.9	51.5	55.3	3.5	2.5	3.3
316L-25	45	90	0	180900	468	513	631	44.8	57.8	44.6	4.2	2.4	2.7
316L-26	45	90	90	202900	486	536	660	42.6	56.6	49.1	4.4	2.5	2.7
316L-27	45	45	0	195600	477	524	645	44.2	56.5	48.9	3.4	2.4	2.7
316L-28	45	45	90	179100	482	524	649	44.2	52.9	45.2	4.8	2.4	2.6
Average (horizontal)	0	-	-	171400	493	533	636	26.8	35.1	36.7	12.1	1.7	2.4
Average (vertical)	90	-	-	182000	409	478	564	30.9	39.2	51.0	2.9	2.5	3.5
Average (inclined)	45	-	-	186100	480	527	647	43.9	55.8	49.5	4.3	2.4	2.7
Average (all)	-	-	-	179200	475	522	630	34.7	44.5	44.2	7.5	2.1	2.7

Table 4: Summary of the 316L measured tensile coupon material properties

Material	Source	θ (deg)	ψ (deg)	ϕ (deg)	E (N/mm ²)	$\sigma_{0.2}$ (N/mm ²)	σ_u (N/mm ²)	ε_f (%)
PH1 ^a	Datasheet [56]	0	0-90	-	- ^b	950-1100	1150-1250	13-21
PH1 ^a	Datasheet [56]	90	-	0-90	- ^b	865-1015	1150-1250	10-18
316L ^a	Datasheet [57]	0	0-90	-	185000	470-590	590-690	25-55
316L ^a	Datasheet [57]	90	-	0-90	180000	380-560	485-595	30-70
316L	EN 1993-1-4 [58]	-	-	-	200000	200-240	500-530	- ^b
316L	EN 10088-2 [66]	-	-	-	- ^b	220-240	520-680	40-45

Table 5: Summary of typical PH1 and 316L material properties

^aAs manufactured without heat treatment

^b Not provided

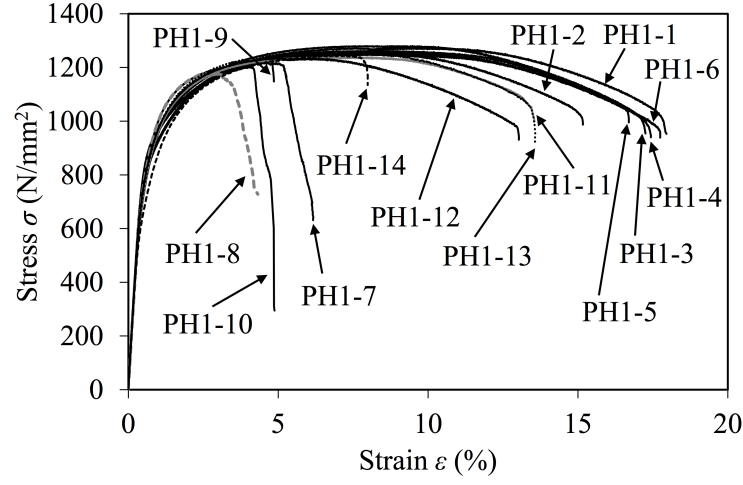


Figure 8: Measured stress-strain curves from the tensile PH1 coupons

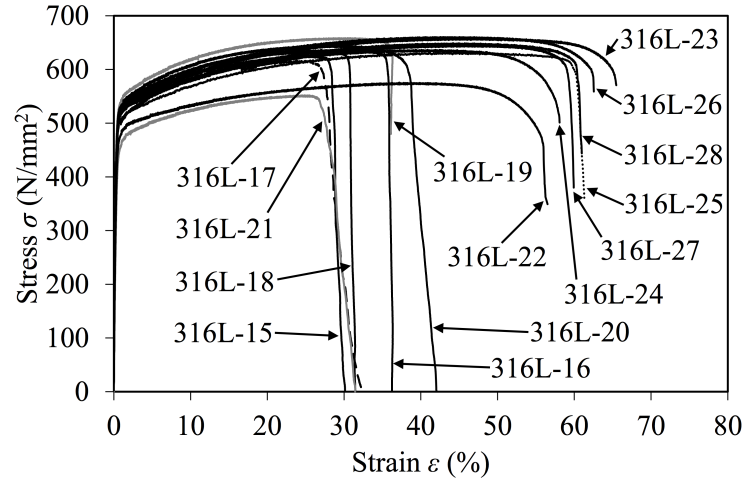


Figure 9: Measured stress-strain curves from the tensile 316L coupons

310 anisotropy. The angle of the failure surfaces on the tested vertical ($\theta = 90^\circ$) and inclined ($\theta = 45^\circ$) PH1 coupons were clearly aligned with the building plane, indicating that the building plane is a weaker plane. It should be noted that Khalid Rafi et al. [20] carried out the tensile coupon tests in accordance with ASTM E8M [67], which utilises a different gauge length to EN ISO 6892-1 [61].

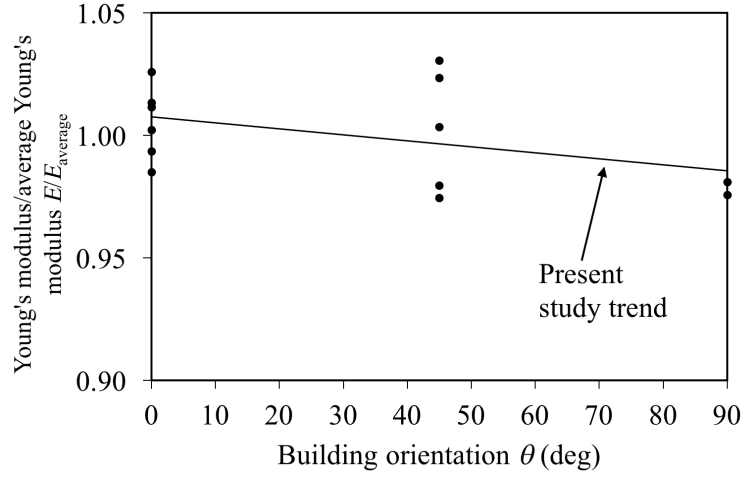


Figure 10: Normalised Young's moduli varying with building orientation for tensile PH1 coupons

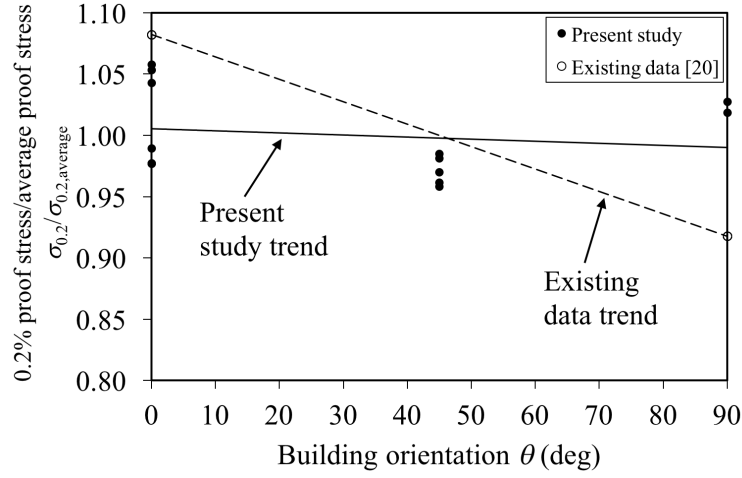


Figure 11: Normalised 0.2% proof stress varying with building orientation for tensile PH1 coupons

315

The Young's moduli E for the 316L tensile coupons show minimal variation with building angle θ , which is in line with previous stress relieved coupon results [26], as can be seen from Figure 14. For the 0.2% proof stress $\sigma_{0.2}$

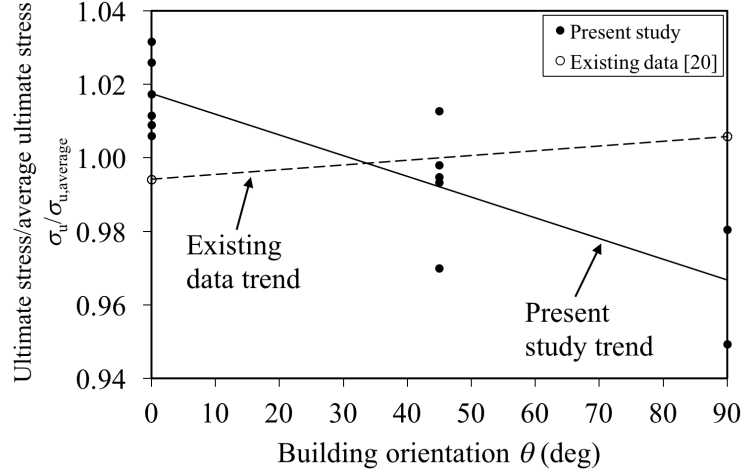


Figure 12: Normalised ultimate stress varying with building orientation for tensile PH1 coupons

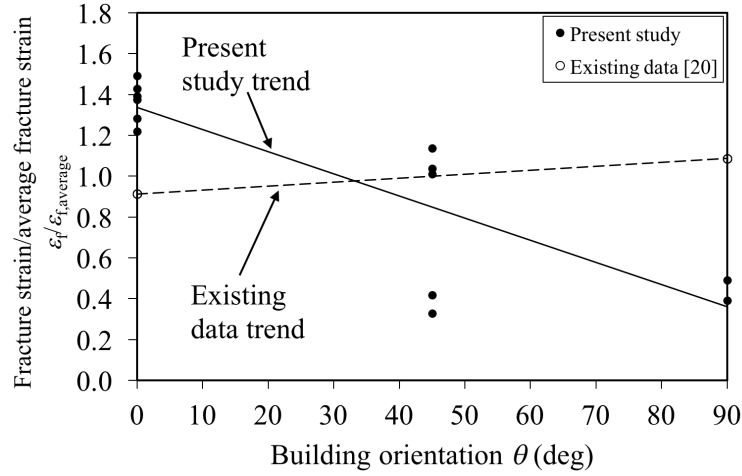


Figure 13: Normalised fracture strain varying with building orientation for tensile PH1 coupons

and ultimate tensile stress σ_u there is a clear reduction in magnitude with a greater building orientation, as seen in Figures 15 and 16 respectively, which is also apparent from the existing 316L tension coupon tests from the literature [22, 23, 25, 26, 20, 29]; this is attributed to elongated grains in the vertical direction leading to a lower yield stress when loaded in this orientation [23]. In

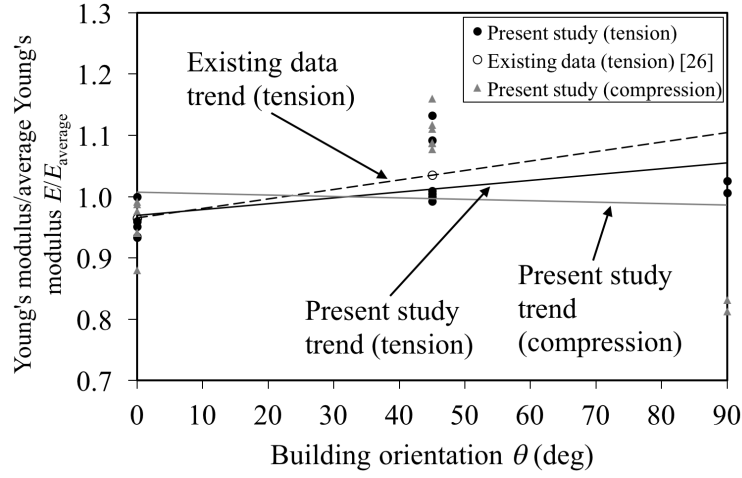


Figure 14: Normalised Young's moduli varying with building orientation for tensile 316L coupons

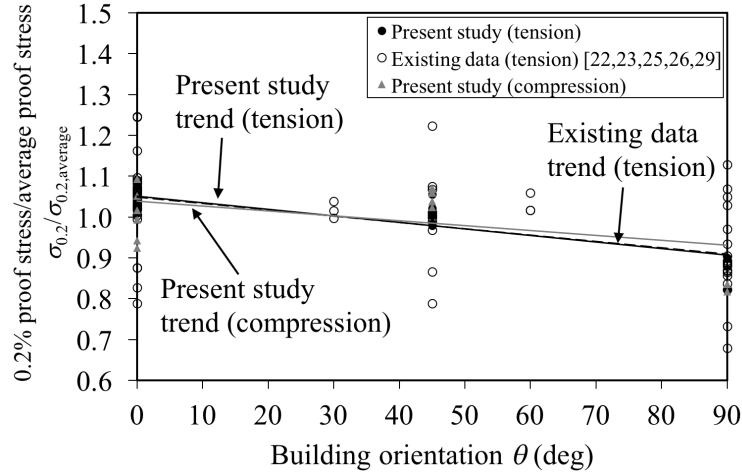


Figure 15: Normalised 0.2% proof stress varying with building orientation for tensile 316L coupons

both Figures 15 and 16 the linear regression trend line for the present study is very close to that from the literature. There is substantial variation in fracture strain ε_f , but no clear trend with building orientation for both the generated and existing data sets, as seen in Figure 17. Meier and Haberland [29], Spierings

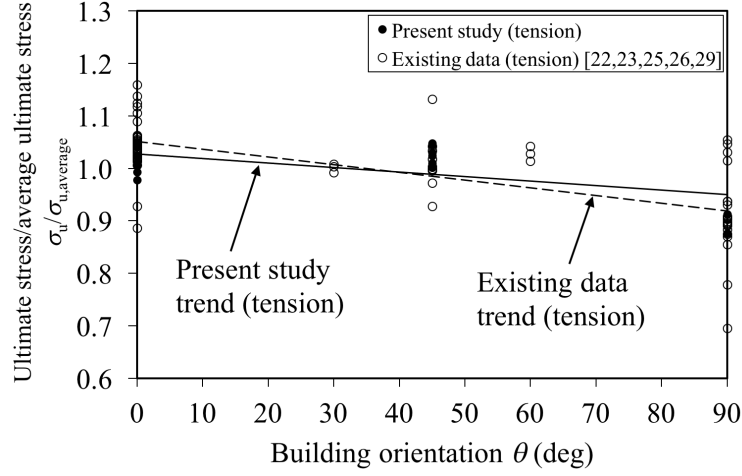


Figure 16: Normalised ultimate stress varying with building orientation for tensile 316L coupons

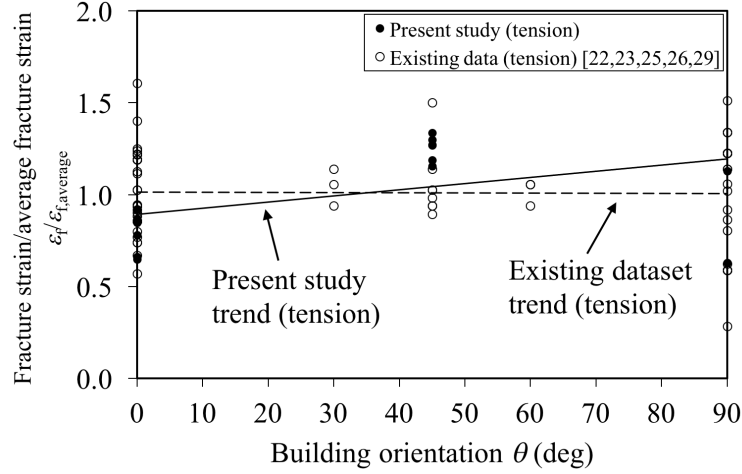


Figure 17: Normalised fracture strain varying with building orientation for tensile 316L coupons

et al. [25] and Mertens et al. [23] observed their vertical coupons fracturing at the lowest strain of all orientations, as low as 8% due to ‘lack of melting’ defects that were observed on the fracture surface; in comparison, the two 316L vertical coupons tested in this study reached 28% and 50% strains at fracture

and Tolosa et al. [22] noted that the vertical coupons exhibited the largest fracture strains (42-44% on average). It should however be highlighted that only two of the existing studies [23, 25] state that they undertook their tensile coupon tests in accordance with EN ISO 6892-1 [61], while the other studies
335 [22, 26, 29] make no mention of adhering to a particular standard, and hence may have used different gauge lengths in their calculation of the fracture strain ε_f .

An observation during testing was that the less ductile 316L coupons (i.e. the horizontally orientated coupons ($\theta = 0^\circ$) and one vertical coupon (316L-21)),
340 did not fracture cleanly, but instead slowly and silently tore apart, whereas the remaining coupons all fractured with a characteristic ‘bang’. Additionally, unlike for the PH1 coupons, the 316L tensile coupon failure surfaces did not obviously align with the building plane. It is also unclear whether heat treatment can
345 remediate the anisotropy observed in PBF 316L tensile coupons. The powder datasheet [57] refers to stress relieving heat treatment, but does not refer to changes to the mechanical properties. Mower and Long [26] tested horizontal ($\theta = 0^\circ$) and inclined ($\theta = 45^\circ$) thermally stress relieved 316L coupons and observed similar properties, but did not test vertically ($\theta = 90^\circ$) built coupons
350 or non heat-treated coupons. Yadollahi et al. [39] tested heat treated DED 316L stainless steel tensile coupons and observed effects similar to annealing, with an increased and more consistent fracture strain and reduced yield and ultimate strengths.

Comparison can also be made with typical horizontal ($\theta = 0^\circ$) and vertical
355 ($\theta = 90^\circ$) mechanical properties from the powder datasheets EOS [56, 57] given in Table 5. For the PH1 coupons, the yield stress was lower than expected, while the ultimate stresses and fracture strain for $\theta = 0^\circ$ were generally within the stated range, although the fracture strain for $\theta = 90^\circ$ was significantly below
360 that expected. By contrast the 316L material properties were all within the expected range, apart from the horizontal Young’s moduli, which were lower than expected. The PBF 316L properties can also be compared with those of

conventionally formed 316L stainless steel from EN 1993-1-4 [58] and EN 10088-2 [66], as presented in Table 5. It is apparent from the results that PBF 316L stainless steel has a slightly lower Young’s modulus, but a significantly higher yield stress and more variable fracture strain than conventional hot-rolled 316L material. The increase in strength has also been noted by others [22, 26, 29] and has been attributed to the very rapid cooling and solidification associated with PBF manufactured material leading to a very fine crystalline structure. This highlights that the mechanical properties are not just dependent upon the composition of the material, but also strongly influenced by the adopted manufacturing processes [22].

2.3. Compressive coupon tests

Compressive coupon tests were carried out to measure the compressive stress-strain response of the material, to determine if the directionality effects also exist in compression and to compare the tensile and compressive properties. Compression coupons were only built with the 316L powder, with fourteen coupons manufactured in the same orientations as those used for the tensile coupons (defined in Figure 7), with one coupon tested per building orientation. The coupons were built in a cuboidal shape with constant cross-sectional area, with the nominal dimensions shown in Figure 18.

All of the as-built compression coupons had their ends machined to ensure that they were flat and parallel. An Instron 8802 testing machine was again used, with metallic dowels inserted into the jaws to apply the compressive load to the coupons ends. The geometry of the coupons was measured prior to testing and two electrical resistance strain gauges were affixed at mid-height on opposite faces. The applied load, measured by means of a load cell within the testing machine, and strain gauge data was recorded at 2 Hz frequency. To prevent minor axis buckling the compression coupons were held within a restraining jig, as shown in Figure 18 with the sides of the coupon in contact with the jig

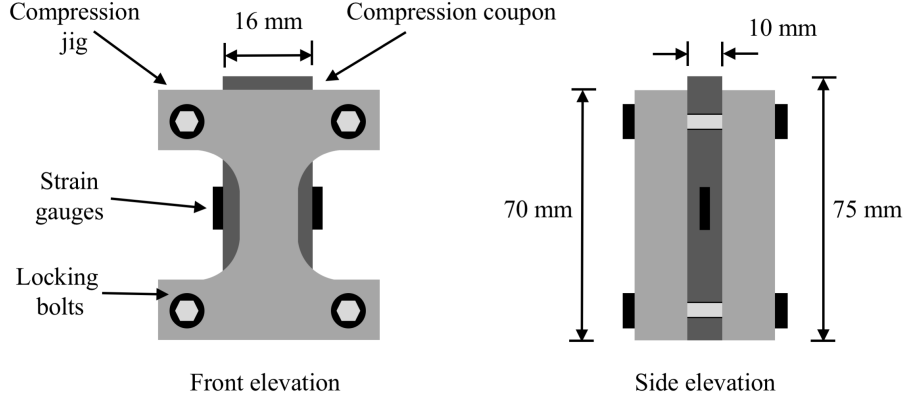


Figure 18: Compression coupon setup with nominal coupon dimensions

covered in a thin layer of lubricating grease to reduce friction effects, with the locking bolts finger tight such that buckling was restrained but Poisson's ratio
 395 effect expansion can still occur. This type of setup has been used successfully in previous studies [68, 69, 70, 71]. A constant compression rate of 0.067 mm/min was used, with the test stopped as the metallic dowel was about to touch the top face of the compression jig.

400 The compressive Young's modulus E_c , 0.2% proof stress $\sigma_{0.2,c}$, 1.0% proof stress $\sigma_{1.0,c}$ and Ramberg-Osgood parameter n_c [62], along with ratios of the compressive to tensile Young's moduli E_c/E , 0.2% proof stresses $\sigma_{0.2,c}/\sigma_{0.2}$ and 1.0% proof stresses $\sigma_{1.0,c}/\sigma_{1.0}$ are reported in Table 6. The average material properties are again also reported for the horizontal ($\theta = 0^\circ$), vertical ($\theta = 90^\circ$)
 405 and inclined ($\theta = 45^\circ$) coupons and averaged values for all orientations. The full stress-strain curves for all the tested austenitic 316L compressive coupons are shown in Figure 19 to provide an indication of the range of stress-strain responses; a sample of these curves have been labelled. The variation of Young's modulus E and 0.2% proof stress $\sigma_{0.2}$ with the coupon longitudinal axis building

orientation θ is plotted in Figures 14 and 15 respectively for the compressive coupons along with the new and existing [22, 23, 25, 26, 29] 316L tensile coupons. The plotted compressive material properties have been normalised by the average of all the compressive results.

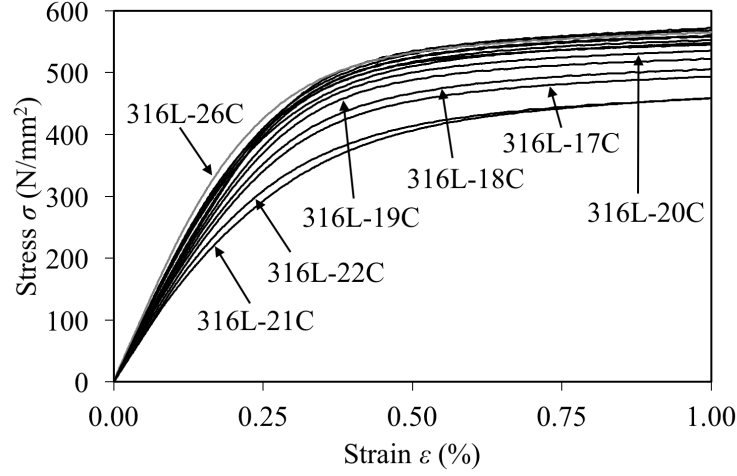


Figure 19: Measured stress-strain curves from the compressive 316L coupons

Plotting the compression coupon Young's moduli E against the building angle θ , in Figure 14, shows that the relationship between the magnitude and building angle is relatively inconsistent - the inclined coupons ($\theta = 45^\circ$) have the largest Young's moduli values, while the vertical coupons ($\theta = 90^\circ$) have the lowest values. The value of the 0.2% proof stress $\sigma_{0.2}$ typically decreases with increasing building angle θ , similar to the behaviour and magnitudes seen in tension, as apparent from Figure 15. As observed for the Young's modulus, on average the inclined coupons ($\theta = 45^\circ$) have the largest 0.2% proof stress $\sigma_{0.2}$ of all the studied building orientations (see Table 6).

Gardner and Nethercot [70] compared the material behaviour of conventionally produced tensile and compressive coupons and noted that on average (considering 54 tensile and 56 compressive results) the Young's modulus E and 1.0% proof

Coupon	θ (deg)	ψ (deg)	ϕ (deg)	E_c (N/mm ²)	$\sigma_{0.2,c}$ (N/mm ²)	$\sigma_{1.0,c}$ (N/mm ²)	n_c	E_c/E	$\sigma_{0.2,c}/\sigma_{0.2}$	$\sigma_{1.0,c}/\sigma_{1.0}$
316L-15C	0	0	0	181200	512	553	8.5	1.01	1.05	1.04
316L-16C	0	0	90	181900	533	599	8.5	1.06	1.08	1.12
316L-17C	0	90	0	161400	450	504	6.3	0.96	0.94	0.99
316L-18C	0	90	90	172500	459	515	5.8	1.03	0.94	0.97
316L-19C	0	45	0	172700	484	530	7.2	1.00	0.95	0.96
316L-20C	0	45	90	179100	496	545	7.1	1.05	0.99	1.01
316L-21C	90	-	0	149100	398	472	4.3	0.81	1.02	1.01
316L-22C	90	-	90	152600	407	472	5.4	0.85	0.95	0.97
316L-23C	45	0	0	197800	517	565	6.3	1.11	1.03	1.05
316L-24C	45	0	90	199500	499	555	5.8	1.11	1.07	1.06
316L-25C	45	90	0	205000	521	580	5.9	1.13	1.11	1.13
316L-26C	45	90	90	212800	522	574	7.1	1.05	1.07	1.07
316L-27C	45	45	0	199500	516	566	6.1	1.02	1.08	1.08
316L-28C	45	45	90	203800	506	560	6.4	1.14	1.05	1.07
Average (horizontal)	0	-	-	174800	489	541	7.2	1.02	0.99	1.02
Average (vertical)	90	-	-	150800	403	472	4.8	0.83	0.99	0.99
Average (inclined)	45	-	-	203100	513	567	6.2	1.09	1.07	1.08
Average (all)	-	-	-	183500	487	542	6.5	1.02	1.02	1.04

Table 6: Summary of the 316L compressive coupon measured material properties

stress $\sigma_{1.0}$ were 1% and 4% higher respectively for the tested compressive coupons than the corresponding tensile coupons, while the 0.2% proof stress $\sigma_{0.2}$ was 5%
430 lower on average in compression than in tension. The additive manufactured 316L austenitic stainless steel coupons tested here also generally show slightly non-symmetric stress-strain responses on average. The Young's modulus E and 0.2% proof stress $\sigma_{0.2}$ were both observed to be 2% higher on average in compression than tension, while the 1.0% proof stress $\sigma_{1.0}$ was found to be
435 4% higher on average in compression. The only major deviation amongst the building orientation averages is that for the vertical coupons the average tensile Young's modulus is greater than the equivalent compression values, as seen in Table 6. Gardner and Nethercot [70] also observed that the compressive coupons tended to have a more rounded stress-strain response than their tensile
440 equivalents, with a lower Ramberg-Osgood parameter n [72], which can also be observed here from the averaged values in Tables 4 and 6. It is apparent from Table 6 that while the ratio of the compressive property to the tensile property is reasonably consistent for the Young's modulus E and 1.0% proof stress $\sigma_{1.0}$, there is more variation for the 0.2% proof stress $\sigma_{0.2}$.

445 Comparison with the manufacturer's powder datasheet [57] in Table 5 shows that the horizontal compression coupons ($\theta = 0^\circ$) have 0.2% proof stresses $\sigma_{0.2}$ that typically lie within the expected range, although two results are slightly lower, while the vertical coupon ($\theta = 90^\circ$) results all lie within the stated
450 range. For both building orientations, the Young's modulus E is lower than that expected from the datasheet. Comparison with the stated Young's moduli for conventionally formed 316L stainless steel from EN 1993-1-4 [58] and EN 10088-2 [66] shows that, similar to the tension observations, the measured Young's moduli are lower than typically expected for conventionally produced material, though
455 the 0.2% proof stresses $\sigma_{0.2}$ are higher than the quoted minimum specified values [58, 66].

2.4. Stub column geometric properties

The stub columns had nominal 50×50 mm outer dimensions with wall thicknesses
460 varying from 1 mm to 5 mm in order to examine a wide range of local cross-
section slendernesses. The geometric properties of the stub column specimens
were carefully measured before testing, following the recommendations laid out
in EN 10219 [73]. The outer breadth B and height H were measured across the
four faces at five equally spaced locations along the column length using digital
465 callipers. The average wall thickness t was calculated from the wall thicknesses
measured at three locations along each face at both ends of the stub columns.
The average column length L could similarly be determined by measuring the
length of each face of the stub column, again using callipers. The average inner
and outer corner radii, r_i and r_e respectively, were measured at both ends by
470 scanning the specimen ends, with an object of known size, and fitting circles
using AutoCAD; EN 10219 [73] suggests using a radius gauge but due to the
small radii and discrete gauges this was found to be less accurate.

The local geometric imperfections of the stub columns were measured prior to
475 testing. A potentiometer was used to measure the surface profile while the stub
column moved on a milling bed, with the horizontal position recorded with a
string potentiometer, similar to previous studies [74]. Measurements were taken
along three equally spaced longitudinal lines on each face, with the maximum
local imperfection ω_0 defined as the maximum deviation from a linear regression
480 line fitted to the measured surface profile. The largest and smallest profile
imperfections are shown in Figures 20 and 21. The average geometric properties,
along with the nominal inner and outer corner radii, $r_{i,nom}$ and $r_{e,nom}$, and
calculated cross-sectional area A of the SHS stub columns are summarised in
Table 7.

485

Specimen	B (mm)	H (mm)	t (mm)	L (mm)	$r_{e,nom}$ (mm)	r_e (mm)	$r_{i,nom}$ (mm)	r_i (mm)	ω_0 (mm)	A (mm ²)
50×50×1	50.17	50	1.05	204.34	1.6	1.32	0.6	0.65	0.26	204.1
50×50×2	50.03	50.02	2.03	204.22	3.6	3.10	1.6	1.26	0.11	381.8
50×50×3	49.99	50.03	3.05	204.33	6.0	5.56	3.0	2.60	0.13	549.9
50×50×4	49.99	50	4.03	203.76	8.8	8.39	4.8	4.32	0.05	697.5
50×50×5	50.03	50.03	5.02	204.43	12.0	11.52	7.0	6.72	0.09	816.7

Table 7: Summary of the geometric properties of the stub columns

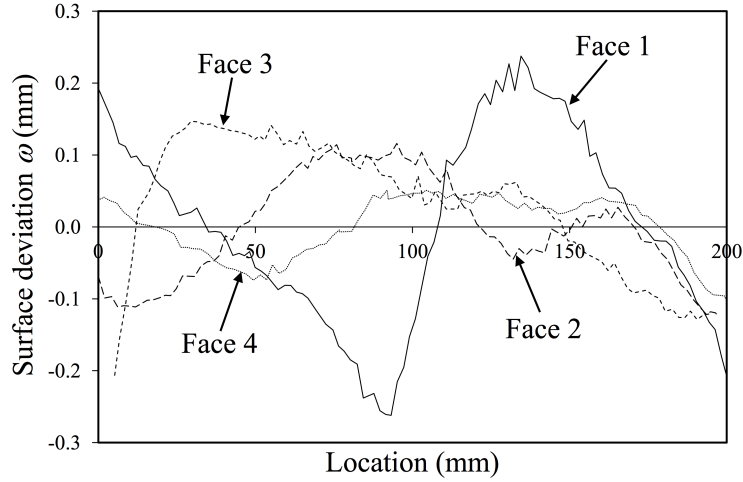


Figure 20: Longitudinal imperfection profiles for SHS 50×50×1 specimen

2.5. Stub column testing

Stub column tests were undertaken to determine the load carrying capacity and general cross-sectional response under pure compression. The stub columns had a 200 mm nominal length which is sufficiently short to prevent global buckling, but expected to be long enough to contain a representative pattern of residual stress and imperfections [75]. The testing setup is shown in Figure 22. The end plates provide fixed-end conditions, and although the column ends were machined to be flat and parallel, grout was used above the top plate to ensure full surface contact. Instron 600kN-J3D-SPL and Instron 3500kN-SPL testing machines were used for the 1 mm to 4 mm thick specimens and 5 mm thick specimen respectively. The instrumentation consisted of four electrical resistance strain gauges attached at mid-height, at a distance of $3t$ from the edges of two opposite faces. Four potentiometers recorded the vertical movement of the top platen [76, 77, 78, 79, 80] and the applied load was measured using a load cell within the testing machine. Data were again recorded using a proprietary in-house developed datalogger and software at a frequency of 2 Hz. The tests were displacement controlled, with the top platen moving downwards at a displacement rate of 0.1 mm/min, achieving a similar compressive strain rate as other stainless

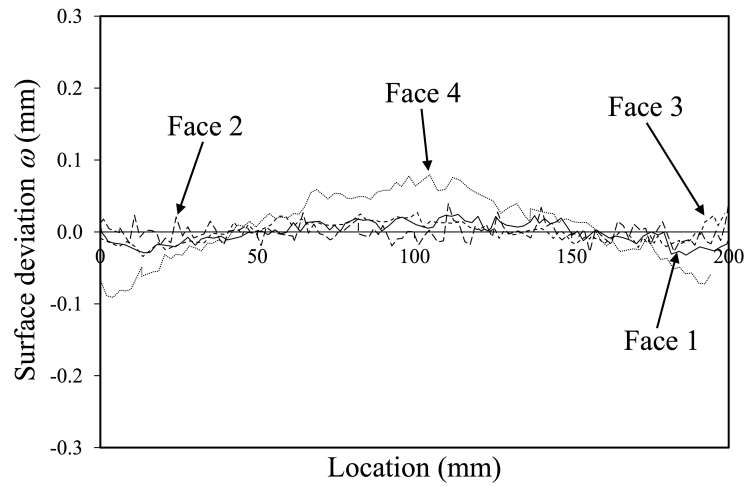


Figure 21: Longitudinal imperfection profiles for SHS 50×50×5 specimen

steel SHS stub columns tests [76, 79, 80, 81, 82], with the tests continued beyond
 505 the peak load to observe the initial unloading behaviour.

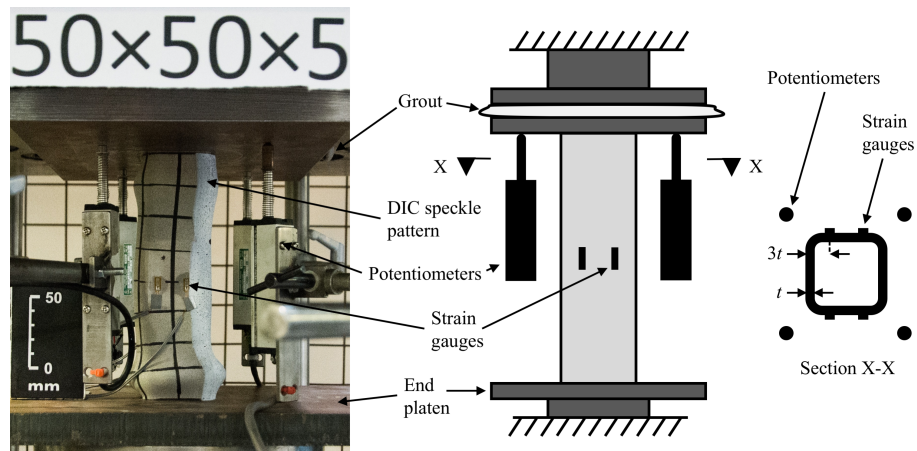


Figure 22: Stub column testing setup

Strain visualisation grids were painted onto three faces of the stub columns, although there were issues with the paint bleeding due to the high porosity of the surface (as apparent in Figure 24). StrainMaster digital image correlation

510 (DIC) hardware was also used to record the deformations in three-dimensional space by monitoring a speckle pattern that was applied to the fourth face.

The ultimate axial load N_u and corresponding true end shortening at the ultimate load δ_u , accounting for the deformation of the end platens [83], are reported
 515 in Table 8 and the load-end shortening curves and deformed specimens are presented in Figures 23 and 24 respectively. The curves show that the $50 \times 50 \times 3$, $50 \times 50 \times 4$ and $50 \times 50 \times 5$ stub columns undergo significant strain hardening before reaching their peak load. The failure mode of the $50 \times 50 \times 1$ column was the classic ‘in-out’ local buckling at mid-height; a similar mode was observed for
 520 the $50 \times 50 \times 2$ and $50 \times 50 \times 3$ specimens, but close to one end. The $50 \times 50 \times 4$ and $50 \times 50 \times 5$ column developed an ‘elephant’s foot’ type local buckling close to both ends, followed by global buckling beyond the peak load, as shown in Figures 22 and 24.

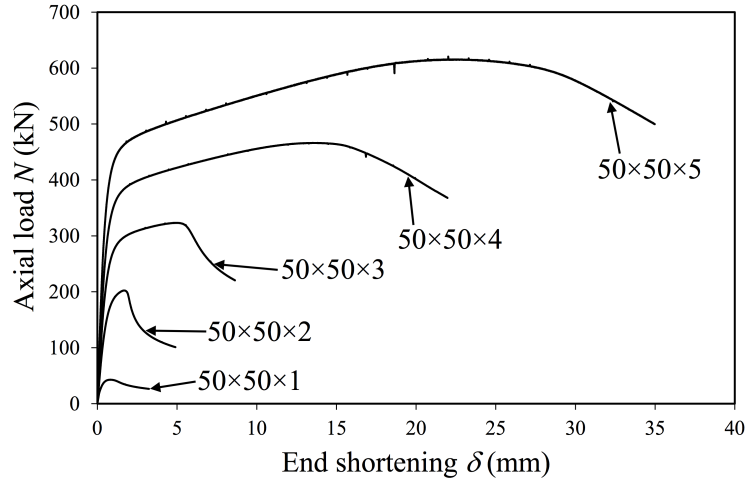


Figure 23: Load end-shortening curves

Specimen	N_u (kN)	δ_u (mm)	EN 1993-1-4 compression class	$c/t\varepsilon$	Local slenderness $\bar{\lambda}_p$	$N_u/A\sigma_{0.2}$	$N_u/N_{u,EC3}$	$N_u/N_{u,csm}$
50×50×1	42.8	0.81	4	63.9	1.12	0.51	0.87	-
50×50×2	202.3	1.66	1	30.5	0.54	1.29	1.29	1.26
50×50×3	323.4	5.01	1	18.1	0.32	1.44	1.44	1.17
50×50×4	466.2	13.54	1	11.7	0.21	1.63	1.63	1.33
50×50×5	620.7	22.02	1	7.6	0.13	1.86	1.86	1.51
						Average	1.42	1.32
						COV	0.26	0.11

Table 8: Summary of stub column tests results and comparisons with existing design methods



Figure 24: Deformed SHS stub columns, with increasing wall thickness from left to right

3. Comparison with existing design methods

In this section, the applicability of existing structural design methods to PBF manufactured stainless steel SHS stub columns is appraised. In the comparisons presented, the material properties are taken as the average of the vertical 316L tensile coupons (316L-21 and 316L-22) and all safety factors are set equal to unity.

530

3.1. Comparisons with EN 1993-1-4 and CSM design provisions

The EN 1993-1-4 [58] guidance for the compression resistance of stainless steel cross-sections is based upon the same approach as for structural steel in EN 1993-1-1 [84]. The following are presented in Table 8 - the EN 1993-1-4 [58] local slenderness parameter $c/t\varepsilon$, where c is the element width, t is the thickness and $\varepsilon = [(235/\sigma_{0.2}) (E/210000)]^{0.5}$, the cross-section class and the ultimate load normalised by the yield load $N_u/A\sigma_{0.2}$. $N_u/A\sigma_{0.2}$ is also plotted against the slenderness parameter $c/t\varepsilon$ in Figure 25 along with a linear regression line. The class 3 limit of $c/t\varepsilon = 37$ in EN 1993-1-4 [58] is the slenderness limit up to which the cross-section is considered to be fully effective in compression, i.e. the

540

cross-section can attain the yield load $A\sigma_{0.2}$. Beyond this limit the cross-section capacity is reduced to allow for the occurrence of failure local buckling prior to reaching the yield load. This limit, and the slightly modified CSM yield slenderness limit of $c/t\varepsilon = 38.6$ [85], may be seen to be generally applicable to

545 PBF manufactured stainless steel SHS.

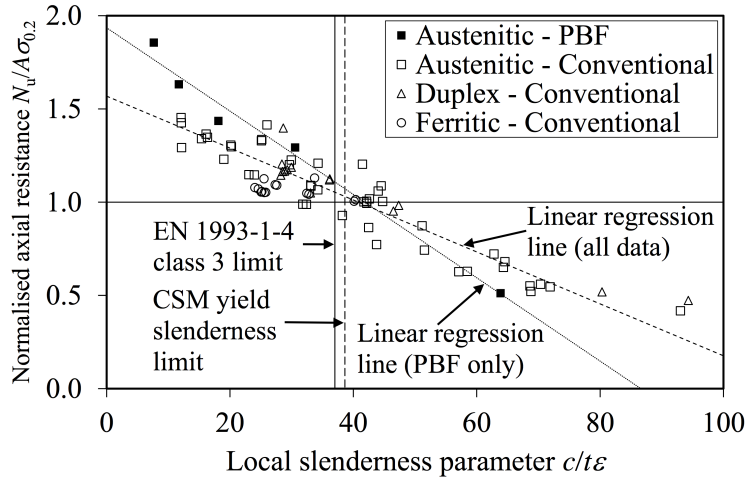


Figure 25: Normalised ultimate axial resistance varying with local slenderness

The PBF stub column results have also been compared with existing, conventionally formed austenitic [76, 78, 81, 70, 86, 69, 87, 88, 89], duplex [77, 78, 81, 89] and ferritic [79, 82, 90, 91, 92] SHS stub column data, as shown in Figure 25.

550 For the existing SHS dataset, $\sigma_{0.2}$ is taken as the weighted average 0.2% proof stress to account for the increased strength in the cold worked corner regions, where corner material properties are reported. Where corner properties have not been reported, the predictive model of Rossi et al. [93] has been employed.

The non-slender class 1 PBF stub columns all lie towards the upper end of

555 the $N_u/A\sigma_{0.2}$ range relative to the existing data, while the slender class 4 stub column lies slightly below the existing test data of comparable slenderness, this may be the result of internal defects or residual stresses from the manufacturing method; these will be measured in a future study. By fitting a linear regression

line to the full stainless steel SHS dataset it can be seen that the current class 3
560 limit is generally appropriate.

The EN 1993-1-4 [58] cross-sectional resistance can also be calculated, which for
non-slender class 1 cross-sections is the product of the gross cross-sectional area A
and the 0.2% proof stress $\sigma_{0.2}$, while for slender class 4 cross-sections the effective
565 area A_{eff} is employed. The ultimate load normalised by the EN 1993-1-4 [58]
prediction $N_u/N_{u,EC3}$ is reported in Table 8 and it can be seen that the class
1 predictions are very conservative showing that there is additional structural
efficiency to be sought, although the class 4 prediction is slightly unconservative.
Overall, EN 1993-1-4 [58] can be observed to be safe, if inefficient, for non-slender
570 PBF SHS design, although further investigation is required for slender cross-
sections.

Comparisons with the resistance predictions $N_u/N_{u,csm}$ of the deformation
based continuous strength method (CSM) [85, 94] are also presented in Table 8.
575 The CSM allows for material strain hardening and thus, as expected, yields
significantly more accurate predictions.

4. Conclusions

An experimental programme has been undertaken to investigate the behaviour
580 of additive manufactured metallic material and cross-sections, and to assess the
applicability of existing metallic design methods. Stainless steel PH1 and 316L
tensile coupons and 316L compression coupons, built using powder bed fusion
(PBF), have been tested in a range of building orientations. For the 316L stainless
steel coupons it was observed that the 0.2% proof stress $\sigma_{0.2}$ (in both tension and
585 compression) and ultimate tensile stress σ_u decrease in magnitude with increasing
building orientation angle; this is attributed to elongated grains in the vertical
direction resulting in a lower strength when loaded in this orientation. The

magnitude of the measured strengths were also found to be generally higher than conventionally formed material; this is due to the rapid cooling that occurs in the thin layers of built up material. For the PH1 stainless steel coupons, the 0.2% proof stress $\sigma_{0.2}$ was seen to be fairly uniform, while the ultimate tensile stress σ_u decreased with increasing building angle. The measured Young's moduli E were found to have no discernible variation with building angle for both the PH1 and 316L stainless steel, but were lower than conventionally produced material. The fracture strain showed variation (more than conventionally produced material), but no clear trend with building angle for the 316L stainless steel, but reduced with increasing building angle for the PH1 material.

A range of additive manufactured 316L stainless steel square hollow section (SHS) stub columns with varying wall thicknesses were also tested. These are believed to be the first structural experiments on additive manufactured metallic cross-sections. The structural behaviour was broadly similar to conventionally produced stainless steel SHS with the more slender sections showing increased propensity to local buckling. The results were also compared with existing design methods, which were found to generally be applicable to PBF manufactured sections. Further research is currently underway to explore different cross-section types, the influence of heat treatment, internal defects and residual stresses. PBF additive manufacturing is a promising new manufacturing technique that while currently rather slow and expensive, with anticipated developments in manufacturing technology and further advances in understanding of the response of the resulting structural elements, could become an important part of structural engineering in the future.

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References

- [1] Wong KV, Hernandez A. A review of additive manufacturing. ISRN Mechanical Engineering 2012;2012:1–10. doi:10.5402/2012/208760.
- 625 [2] Symes M, Kitson P, Yan J, Richmond CJ, Cooper G, Bowman R, et al. Integrated 3D-printed reactionware for chemical synthesis and analysis. Nature Chemistry 2012;4(5):349–54. doi:10.1038/nchem.1313.
- [3] Niendorf T, Leuders S, Riemer A, Richard HA, Tröster T, Schwarze D. Highly anisotropic steel processed by selective laser melting. Metallurgical
 630 and Materials Transactions B: Process Metallurgy and Materials Processing Science 2013;44(4):794–6. doi:10.1007/s11663-013-9875-z.
- [4] Yap CY, Chua CK, Dong ZL, Liu ZH, Zhang DQ, Loh LE, et al. Review of selective laser melting: materials and applications. Applied Physics Reviews 2015;2(4). doi:10.1063/1.4935926.
- 635 [5] Abe F, Osakada K, Shiomi M, Uematsu K, Matsumoto M. The manufacturing of hard tools from metallic powders by selective laser melting. Journal of Materials Processing Technology 2001;111(1-3):210–3. doi:10.1016/S0924-0136(01)00522-2.
- [6] Cesaretti G, Dini E, De Kestelier X, Colla V, Pambaguian L. Building
 640 components for an outpost on the lunar soil by means of a novel 3D printing technology. Acta Astronautica 2014;93:430–50. doi:10.1016/j.actaastro.2013.07.034.

- [7] Sun J, Peng Z, Zhou W, Fuh JY, Hong GS, Chiu A. A review on 3D printing for customized food fabrication. *Procedia Manufacturing* 2015;1:308–19. doi:10.1016/j.promfg.2015.09.057.
- [8] Pearce JM, Morris Blair C, Laciak KJ, Andrews R, Nosrat A, Zelenika-Zovko I. 3-D printing of open source appropriate technologies for self-directed sustainable development. *Journal of Sustainable Development* 2010;3(4):17. doi:10.5539/jsd.v3n4p17.
- [9] Lim S, Buswell RA, Le TT, Austin SA, Gibb AGF, Thorpe T. Developments in construction-scale additive manufacturing processes. *Automation in Construction* 2012;21(1):262–8. doi:10.1016/j.autcon.2011.06.010.
- [10] Henke K, Treml S. Wood based bulk material in 3D printing processes for applications in construction. *European Journal of Wood and Wood Products* 2013;71(1):139–41. doi:10.1007/s00107-012-0658-z.
- [11] Wohlers T, Caffrey T. Additive manufacturing: going mainstream. *Manufacturing Engineering* 2013;5doi:<http://dx.doi.org/10.1108/17506200710779521>.
- [12] Snyder MP, Dunn JJ, Gonzalez EG. Effects of microgravity on extrusion based additive manufacturing. In: *AIAA SPACE 2013 Conference and Exposition*. ISBN 9781624102394 (ISBN); 2013, p. 1–6. doi:10.2514/6.2013-5439.
- [13] Song B, Zhao X, Li S, Han C, Wei Q, Wen S, et al. Differences in microstructure and properties between selective laser melting and traditional manufacturing for fabrication of metal parts: A review. *Frontiers of Mechanical Engineering* 2015;10(2):111–25. doi:10.1007/s11465-015-0341-2.
- [14] Cooper DE, Stanford M, Kibble KA, Gibbons GJ. Additive manufacturing for product improvement at Red Bull Technology. *Materials and Design* 2012;41:226–30. doi:10.1016/j.matdes.2012.05.017.

- 670 [15] Gu DD, Meiners W, Wissenbach K, Poprawe R. Laser additive manufacturing of metallic components: materials, processes and mechanisms. *International Materials Reviews* 2012;57(3):133–64. doi:10.1179/1743280411Y.0000000014.
- [16] Santorinaios M, Brooks W, Sutcliffe CJ, Mines RAW. Crush behaviour of
675 open cellular lattice structures manufactured using selective laser melting. *WIT Transactions on the Built Environment* 2006;85:481–90. doi:10.2495/HPSM06047.
- [17] Kobryn PA, Semiatin SL. Mechanical properties of laser-deposited Ti-6Al-4V. *Solid Freeform Fabrication Proceedings* 2001;:6–8.
- 680 [18] Wohlers T, Gornet T. History of additive manufacturing. Tech. Rep.; Wohlers Associates, inc.; 2011.
- [19] Anzalone GC, Wijnen B, Sanders PG, Pearce JM. A low-cost open-source metal 3-D printer. *IEEE Access* 2013;1:803–10. doi:10.1109/ACCESS.2013.2293018.
- 685 [20] Khalid Rafi H, Starr TL, Stucker BE. A comparison of the tensile, fatigue, and fracture behavior of Ti-6Al-4V and 15-5 PH stainless steel parts made by selective laser melting. *International Journal of Advanced Manufacturing Technology* 2013;69(5-8):1299–309. doi:10.1007/s00170-013-5106-7.
- [21] Holshouser C, Newell C, Palas S, Martin L, Duty C, Love L, et al. Out
690 of bounds additive manufacturing. *Advanced Materials and Processes* 2013;171(3):15–7.
- [22] Tolosa I, Garciandía F, Zubiri F, Zapirain F, Esnaola A. Study of mechanical properties of AISI 316 stainless steel processed by "selective laser melting", following different manufacturing strategies. *International Journal of Advanced Manufacturing Technology* 2010;51(5-8):639–47.
695 doi:10.1007/s00170-010-2631-5.

- [23] Mertens AI, Reginster S, Contrepois Q, Dormal T, Lemaire O, Lecomte-Beckers J. Microstructures and mechanical properties of stainless steel AISI 316L processed by selective laser melting. *Materials Science Forum* 2014;783-786(August 2015):898–903. doi:10.4028/www.scientific.net/MSF.783-786.898.
- [24] Kruth JP, Mercelis P, Vaerenbergh J, Froyen L, Rombouts M. Binding mechanisms in selective laser sintering and selective laser melting. *Rapid Prototyping Journal* 2005;11(1):26–36. doi:10.1108/13552540510573365.
- [25] Spierings AB, Herres N, Levy G. Influence of the particle size distribution on surface quality and mechanical properties in AM steel parts. *Rapid Prototyping Journal* 2011;17(3):195–202. doi:10.1108/13552541111124770. arXiv:arXiv:1011.1669v3.
- [26] Mower TM, Long MJ. Mechanical behavior of additive manufactured, powder-bed laser-fused materials. *Materials Science and Engineering A* 2016;651:198–213. doi:10.1016/j.msea.2015.10.068.
- [27] Luecke WE, Slotwinski JA. Mechanical properties of austenitic stainless steel made by additive manufacturing. *Journal of Research of the National Institute of Standards and Technology* 2014;119:398–418. doi:10.6028/jres.119.015.
- [28] Kempen K, Thijs L, Van Humbeeck J, Kruth JP. Mechanical properties of AlSi10Mg produced by selective laser melting. *Physics Procedia* 2012;39:439–46. doi:10.1016/j.phpro.2012.10.059.
- [29] Meier H, Haberland C. Experimental studies on selective laser melting of metallic parts. *Materialwissenschaft und Werkstofftechnik* 2008;39(9):665–70. doi:10.1002/mawe.200800327.
- [30] Prashanth KG, Scudino S, Klauss HJ, Surreddi KB, Löber L, Wang Z, et al. Microstructure and mechanical properties of Al-12Si produced by selective

- laser melting: Effect of heat treatment. *Materials Science and Engineering A* 2014;590(OCTOBER):153–60. doi:10.1016/j.msea.2013.10.023.
- [31] Vilaro T, Colin C, Bartout JD. As-fabricated and heat-treated microstructures of the Ti-6Al-4V alloy processed by selective laser melting. *Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science* 2011;42(10):3190–9. doi:10.1007/s11661-011-0731-y.
- [32] Facchini L, Magalini E, Robotti P, Molinari A, Höges S, Wissenbach K. Ductility of a Ti-6Al-4V alloy produced by selective laser melting of prealloyed powders. *Rapid Prototyping Journal* 2010;16(6):450–9. doi:10.1108/13552541011083371.
- [33] Wu AS, Brown DW, Kumar M, Gallegos GF, King WE. An experimental investigation into additive manufacturing-induced residual stresses in 316L stainless steel. *Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science* 2014;45(13):6260–70. doi:10.1007/s11661-014-2549-x.
- [34] ASTM International . Standard Terminology for Additive Manufacturing Technologies General Principles Terminology. Tech. Rep.; 2015. doi:10.1520/F2792-12A.2.
- [35] ASTM International . Standard Terminology for Additive Manufacturing Technologies. Tech. Rep.; 2013. doi:10.1520/F2792-12A.2.
- [36] Spierings A, Starr T, Wegener K. Fatigue performance of additive manufactured metallic parts. *Rapid Prototyping Journal* 2013;19(2):88–94. doi:10.1108/13552541311302932.
- [37] Mercelis P, Kruth JP. Residual stresses in selective laser sintering and selective laser melting. *Rapid Prototyping Journal* 2006;12(5):254–65. doi:10.1108/13552540610707013.
- [38] Sun Y, Moroz A, Alrbaey K. Sliding wear characteristics and corrosion behaviour of selective laser melted 316L stainless steel. *Journal of*

Materials Engineering and Performance 2014;23(2):518–26. doi:10.1007/
s11665-013-0784-8.

- 755 [39] Yadollahi A, Shamsaei N, Thompson SM, Seely DW. Effects of process
time interval and heat treatment on the mechanical and microstructural
properties of direct laser deposited 316L stainless steel. Materials Science
and Engineering A 2015;644:171–83. doi:10.1016/j.msea.2015.07.056.
- [40] Guan K, Wang Z, Gao M, Li X, Zeng X. Effects of processing parameters
on tensile properties of selective laser melted 304 stainless steel. Materials
760 and Design 2013;50:581–6. doi:10.1016/j.matdes.2013.03.056.
- [41] Kahlen FJ, Kar A. Tensile strengths for laser-fabricated parts and similarity
parameters for rapid manufacturing. Journal of Manufacturing Science and
Engineering 1999;123(1):38–44. doi:10.1115/1.1286472.
- [42] Mertens A, Contrepolis Q, Dormal T, Lemaire O, Lecomte-Beckers J.
765 Ti alloys processed by selective laser melting and by laser cladding:
microstructures and mechanical properties. In: 12th European Conference
on Space Structures, Materials & Environmental Testing; vol. 2012. 2012, p.
20–3.
- [43] Baufeld B, Van der Biest O, Gault R. Additive manufacturing of Ti-6Al-4V
770 components by shaped metal deposition: microstructure and mechanical
properties. Materials and Design 2010;31(SUPPL. 1):S106–11. doi:10.1016/
j.matdes.2009.11.032.
- [44] Agarwala M, Bourell D, Beaman J, Marcus H, Barlow J. Post-processing of
selective laser sintered metal parts. Rapid Prototyping Journal 1995;1(2):36–
775 44. doi:10.1108/13552549510086853.
- [45] Rickenbacher L, Etter T, Hövel S, Wegener K. High temperature ma-
terial properties of IN738LC processed by selective laser melting (SLM)
technology. Rapid Prototyping Journal 2013;19(4):282–90. doi:10.1108/
13552541311323281.

- 780 [46] Shen Y, McKown S, Tsopanos S, Sutcliffe CJ, Mines RAW, Cantwell WJ. The mechanical properties of sandwich structures based on metal lattice architectures. *Journal of Sandwich Structures & Materials* 2010;12(2):159–80. doi:Doi10.1177/1099636209104536.
- [47] Ushijima K, Cantwell W, Mines R, Tsopanos S, Smith M. An investigation
785 into the compressive properties of stainless steel micro-lattice structures. *Journal of Sandwich Structures and Materials* 2011;13:303–29. doi:10.1177/1099636210380997.
- [48] Rehme O. Selective laser melting of honeycombs with negative Poisson's
790 ratio. *Journal of Laser Micro/Nanoengineering* 2009;4(2):128–34. doi:10.2961/jlmn.2009.02.0010.
- [49] Joosten S. Printing a stainless steel bridge: An exploration of structural properties of stainless steel additive manufactures for civil engineering purposes. Ph.D. thesis; Delft University of Technology; 2015.
- [50] Perkins I, Skitmore M. Three-dimensional printing in the construction
795 industry: a review. *International Journal of Construction Management* 2015;15(1):1–9. doi:10.1080/15623599.2015.1012136.
- [51] Khoshnevis B. Automated construction by contour crafting - related robotics and information technologies. *Automation in Construction* 2004;13(1):5–19. doi:10.1016/j.autcon.2003.08.012.
- 800 [52] Tibaut A, Rebolj D, Nekrep Perc M. Interoperability requirements for automated manufacturing systems in construction. *Journal of Intelligent Manufacturing* 2014;;1–12doi:10.1007/s10845-013-0862-7.
- [53] Bogue R. 3D printing: the dawn of a new era in manufacturing? *Assembly Automation* 2013;33(4):307–11. doi:10.1108/AA-06-2013-055.
- 805 [54] Galjaard S, Hofman S, Ren S. New opportunities to optimize structural designs in metal by using additive manufacturing. In: *Advances in*

Architectural Geometry 2014. Springer International Publishing. ISBN 978-3-319-11418-7; 2014, p. 79–93. doi:10.1007/978-3-319-11418-7_6.

- 810 [55] Pegna J. Exploratory investigation of solid freeform construction. Automation in Construction 1997;5(5):427–37. doi:10.1016/S0926-5805(96)00166-5.
- [56] EOS . Material data sheet EOS StainlessSteel PH1 for EOS M 290. Tech. Rep.; Electro Optical Systems; 2015.
- [57] EOS . Material data sheet EOS StainlessSteel 316L. Tech. Rep.; Electro
815 Optical Systems; 2014.
- [58] European Committee for Standardisation (CEN) . EN 1993-1-4:2006+A1:2015 Eurocode 3 Design of steel structures Part 1-4: General rules supplementary rules for stainless steel. 2015.
- [59] Levy GN, Schindel R, Kruth J. Rapid manufacturing and rapid tooling
820 with layer manufacturing (LM) technologies, state of the art and future perspectives. CIRP Annals - Manufacturing Technology 2003;52(2):589–609. doi:10.1016/S0007-8506(07)60206-6.
- [60] Yadroitsev I, Thivillon L, Bertrand P, Smurov I. Strategy of manufacturing components with designed internal structure by selective laser melting of
825 metallic powder. Applied Surface Science 2007;254(4):980–3. doi:10.1016/j.apsusc.2007.08.046.
- [61] European Committee for Standardisation . BS EN ISO 6892-1:2009 Metallic materials - Tensile testing Part 1: Method of test at ambient temperature. Brussels: CEN; 2009.
- 830 [62] Ramberg W, Osgood WR. Description of stress-strain curves by three parameters. National Advisory Committee For Aeronautics 1943;:Technical Note No. 902.

- [63] Mirambell E, Real E. On the calculation of deflections in structural stainless steel beams: an experimental and numerical investigation. *Journal of Constructional Steel Research* 2000;54(1):109–33. doi:10.1016/S0143-974X(99)00051-6.
- [64] Rasmussen K. Full-range stress-strain curves for stainless steel alloys. *Journal of Constructional Steel Research* 2003;59(2003):47–61.
- [65] Gardner L, Ashraf M. Structural design for non-linear metallic materials. *Engineering Structures* 2006;28(6):926–34. doi:10.1016/j.engstruct.2005.11.001.
- [66] British Standards Institution . BS EN 10088-2:2014 Stainless steels Part 2: Technical delivery conditions for sheet/plate and strip of corrosion resisting steels for general purposes. Tech. Rep.; British Standards Institution; 2014.
- [67] ASTM International . E8/E8M Standard Test Methods for Tension Testing of Metallic Materials. 2016. ISBN 5935522004. doi:10.1520/E0008.
- [68] Rockey KC, Jenkins F. The behaviour of webplates of plate girders subjected to pure bending. *The Structural Engineer* 1957;35:176–89.
- [69] Rasmussen K, Hancock G. Design of cold-formed stainless steel tubular members. I: columns. *Journal of Structural Engineering ASCE* 1993;119(8):2349–67.
- [70] Gardner L, Nethercot DA. Experiments on stainless steel hollow sections - Part 1: Material and cross-sectional behaviour. *Journal of Constructional Steel Research* 2004;60(9):1291–318. doi:10.1016/j.jcsr.2003.11.006.
- [71] Foster A, Gardner L. Ultimate behaviour of steel beams with discrete lateral restraints. *Thin-Walled Structures* 2013;72:88–101. doi:10.1016/j.tws.2013.06.009.
- [72] Afshan S, Rossi B, Gardner L. Strength enhancements in cold-formed structural sections Part I: Material testing. *Journal of Constructional Steel Research* 2013;83:177–88. doi:10.1016/j.jcsr.2012.12.008.

- [73] European Committee for Standardisation C. Cold formed welded structural hollow sections of non-alloy and fine grain steels. Part 2: Tolerances, dimensions and sectional properties (EN 10219-2:2006) 2006;3.
- [74] Schafer B, Peköz T. Computational modeling of cold-formed steel: character-
865 izing geometric imperfections and residual stresses. *Journal of Constructional Steel Research* 1998;47(3):193–210. doi:10.1016/S0143-974X(98)00007-8.
- [75] Ziemian R. *Guide to Stability Design Criteria for Metal Structures*. 6th ed.; New York: John Wiley & Sons, Inc.; 2010.
- [76] Liu Y, Young B. Buckling of stainless steel square hollow section compression
870 members. *Journal of Constructional Steel Research* 2003;59(2):165–77. doi:10.1016/S0143-974X(02)00031-7.
- [77] Theofanous M, Gardner L. Testing and numerical modelling of lean duplex stainless steel hollow section columns. *Engineering Structures* 2009;31(12):3047–58. doi:10.1016/j.engstruct.2009.08.004.
- [78] Yuan HX, Wang YQ, Shi YJ, Gardner L. Stub column tests on stainless
875 steel built-up sections. *Thin-Walled Structures* 2014;83:103–14. doi:10.1016/j.tws.2014.01.007.
- [79] Zhao O, Rossi B, Gardner L, Young B. Experimental and numerical studies of ferritic stainless steel tubular cross sections under combined compression and bending. *Journal of Structural Engineering ASCE* 2015;142(2). doi:10.1061/(ASCE)ST.1943-541X.0001366.
880
- [80] Zhao O, Rossi B, Gardner L, Young B. Behaviour of structural stainless steel cross-sections under combined loading part I: experimental study. *Engineering Structures* 2015;89:236–46. doi:10.1016/j.engstruct.2014.11.014.
885
- [81] Young B, Lui WM. Behavior of cold-formed high strength stainless steel sections. *Journal of Structural Engineering ASCE* 2005;131(November):1738–45. doi:10.1061/(ASCE)0733-9445(2005)131:11(1738).

- [82] Zhao O, Gardner L, Young B. Buckling of ferritic stainless steel members
890 under combined axial compression and bending. *Journal of Constructional Steel Research* 2016;117:35–48. doi:10.1016/j.jcsr.2015.10.003.
- [83] Centre for Advanced Structural Engineering . Compression tests of stainless steel tubular columns. Investigation Report S770. Tech. Rep.; University of Sydney.; 1990.
- 895 [84] European Committee for Standardisation (CEN) . EN 1993-1-1:2005 Eurocode 3: Design of steel structures - Part 1-1: General rules and rules for buildings. 2005.
- [85] Afshan S, Gardner L. The continuous strength method for structural stainless steel design. *Thin-Walled Structures* 2013;68:42–9. doi:10.1016/j.tws.2013.02.011.
900
- [86] Talja A, Salmi P. Design of stainless steel RHS beams, columns and beam-columns. Tech. Rep.; VTT; 1995.
- [87] Kuwamura H. Local buckling of thin-walled stainless steel members. *Steel Structures* 2003;3:191–201.
- 905 [88] Gardner L, Talja a, Baddoo NR. Structural design of high-strength austenitic stainless steel. *Thin-Walled Structures* 2006;44:517–28. doi:10.1016/j.tws.2006.04.014.
- [89] Lam D, Gardner L. Structural design of stainless steel concrete filled columns. *Journal of Constructional Steel Research* 2008;64(11):1275–82.
910 doi:10.1016/j.jcsr.2008.04.012.
- [90] Afshan S, Gardner L. Experimental study of cold-formed ferritic stainless steel hollow sections. *Journal of Structural Engineering ASCE* 2013;139:717–28. doi:10.1061/(ASCE)ST.1943-541X.0000580.
- [91] Bock M, Arrayago I, Real E. Experiments on cold-formed ferritic stainless steel slender sections. *Journal of Constructional Steel Research* 2015;109:13–23. doi:10.1016/j.jcsr.2015.02.005.
915

- [92] Arrayago I, Real E. Experimental study on ferritic stainless steel RHS and SHS cross-sectional resistance under combined loading. *Structures* 2015;4:69–79. doi:10.1016/j.istruc.2015.10.003.
- 920 [93] Rossi B, Afshan S, Gardner L. Strength enhancements in cold-formed structural sections Part II: Predictive models. *Journal of Constructional Steel Research* 2013;83:189–96. doi:10.1016/j.jcsr.2012.12.007.
- [94] Zhao O, Rossi B, Gardner L, Young B. Behaviour of structural stainless steel cross-sections under combined loading part II: numerical modelling and design approach. *Engineering Structures* 2014;89:247–59. doi:10.1016/j.engstruct.2014.11.016.
- 925