FFI-RAPPORT

18/00586

Characterization of in-field additively manufactured polymer composites

– hot and dusty environment

Tom Thorvaldsen
Torbjørn Olsen
Bernt Brønmo Johnsen

Characterization of in-field additively manufactured polymer composites
– hot and dusty environment

Tom Thorvaldsen
Torbjørn Olsen
Bernt Brønmo Johnsen

Norwegian Defence Research Establishment (FFI) 9 May 2018

Keywords

Additiv produksjon
Materialteknologi
Materialprøving
Materialer

FFI-rapport

FFI-RAPPORT 18/00586

Prosjektnummer

527301

ISBN

P: 978-82-464-3048-5
E: 978-82-464-3049-2

Approved by

Ole Fretheim, *Research Manager*
Jan Erik Torp, *Chief of Staff*

Summary

As part of the European Defence Agency (EDA) Operational Budget (OB) study "Additive Manufacturing Feasibility Study & Technology Demonstration" (EDA contract no. 16.ESI.OP.144), in-field 3D printing of objects, i.e. using additive manufacturing, has been demonstrated. The two contractors are Fundación Prodintec (Spain) and MBDA (France).

A (self-sustained) container, containing different printers, as well as tools for design, pre- and post-processing of the printed objects has been established and transported (on land) to an air base in Zaragoza, Spain. Moreover, the container has been put onto a transport aircraft, airborne, and finally brought back to the same air base. The demonstration aims to show military personnel, in particular, the possibilities and current capabilities of in-field production of spare parts and objects using additive manufacturing (AM). A more detailed presentation of the project and its different strands (state of the art, demonstration and AM exhibition/conference), including more details about the experiences from the demonstration, as well as recommendations for further research and development within this area, can be found in the reports from the project.

Part of the AM demonstration is related to the material properties of the objects when printed outside the regular (and stationary) factory or workshop. The printing conditions in field, such as temperature, humidity and sand/dust/particles will typically be different from factory/workshop conditions, and may not be possible to control or set. Such factors may influence the quality and properties of the printed objects, which will influence on the object's performance and area of use.

In this study performed by FFI, which supported the work done in the current EDA study on AM, the mechanical properties of standardized test specimens manufactured in the workshop/factory and in field have been characterized. In total, eight types of test specimens were produced by Prodintec. Four types of standardized test specimens were produced at Prodintec facilities in May 2017 in factory/workshop conditions. The same four types of test specimens were printed in the container in field during the exercise "European Advanced Airlift Tactics Training Course for 2017" (EAATTC17-3) in Zaragoza, Spain, in June 2017.

As an overall conclusion, based on the test results from this study, no significant reduction or change in mechanical properties are experienced for the objects printed in field compared to those printed in more controlled workshop/factory conditions. It should, however, be noted that the produced specimens are not fully dense; the specimens have a cell-like internal structure. As the real cross-sectional area of the fracture surface is challenging to measure, the cross-sectional area of a dense specimen is applied in the calculations. Again, as a result of this, the obtained parameter values included in the study for the specimen sets are much lower than what is reported by the material manufacturer and in other studies. Still, a comparison of printing under different conditions and locations, i.e. factory versus in-field, is relevant, and the overall conclusion is still valid.

Sammendrag

Som en del av European Defence Agencys (EDAs) Operational Budget (OB) studie "Additive Manufacturing Feasibility Study & Technology Demonstration" (EDA contract no. 16.ESI.OP.144), har 3D printing av komponenter i felt blitt demonstrert. Studien gjennomføres av Fundación Prodintec (Spania) og MBDA (Frankrike).

En container med ulike printere, så vel som utstyr og verktøy for design, pre- og postprosessering av de produserte komponentene, har blitt etablert. Denne har deretter blitt transportert til en militær flybase i Zaragoza, Spania. Videre har containeren blitt lastet inn i et militært transportfly og fløyet en runde rundt flybasen, før den ble brakt tilbake til flybasen. Formålet med demonstrasjonen er primært å vise militært personell hva som er mulighetene for additiv produksjon av reservedeler og andre komponenter i felt. En mer detaljert beskrivelse av de tre hoveddelene av prosjektet (status innen forskningen, selve demonstrasjonen og gjennomføringen av en konferanse) er gitt i rapportene fra prosjektet. Rapportene gir også flere detaljer og erfaringer fra selve demonstrasjonen, samt anbefalinger for videre forskning og utvikling innen dette feltet.

Deler av demonstrasjonen av additiv produksjon i felt er knyttet til materialegenskapene til de objektene som produseres utenfor fabrikker og mer permanente produksjonslokaler. Forholdene i felt, som temperatur, fuktighet og sand/støv/partikler vil typisk være annerledes i forhold til forholdene i en fabrikk. Slike produksjonsparametere kan være vanskelig å kontrollere, og de kan påvirke kvaliteten og egenskapene til de produserte komponentene. Endrede egenskaper kan videre påvirke yteevnen og bruksområdet for komponenten.

I denne FFI-studien, som har støttet arbeidet som er gjort i EDA-prosjektet, er de mekaniske egenskapene til standardiserte prøvestykker produsert i fabrikk og i felt sammenliknet og vurdert. Totalt produserte Prodintec åtte ulike prøvestykker. Fire typer prøvestykker ble produsert i Prodintec sin fabrikk i mai 2017. De samme fire typene prøvestykker ble produsert i containeren under øvelsen "European Advanced Airlift Tactics Training Course for 2017" (EAATTC17-3) i Zaragoza, Spania, i juni 2017.

Som en overordnet konklusjon, basert på resultatene fra denne FFI-studien, er det ingen signifikant reduksjon av yteevne eller endring av mekaniske egenskaper ved produksjon i felt sammenliknet med produksjon i fabrikk. Det skal derimot bemerkes at prøvestykkene i denne studien ikke har høy tetthet; prøvene har en indre cellestruktur. Ettersom det er utfordrende å måle det virkelige tverrsnittsarealet, er tverrsnittsarealet til et prøvestykke med 100 % tetthet benyttet i beregningene. Som en følge av dette er de rapporterte verdiene lavere enn hva som er rapportert andre steder. En sammenlikning er likevel relevant ettersom de samme parameterne, betingelsene og prosedyrene for produksjonen ble benyttet i begge tilfeller. Konklusjonen er derfor fremdeles gyldig.

Content

1 Introduction

As part of the European Defence Agency (EDA) Operational Budget (OB) study “Additive Manufacturing Feasibility Study & Technology Demonstration” (EDA contract no. 16.ESI.OP.144), in-field 3D printing of objects, i.e. using additive manufacturing, has been demonstrated. The two contractors are Fundación Prodintec (Spain) and MBDA (Frankrike).

A (self-sustained) container, containing different printers, as well as tools for design, pre- and post-processing of the printed objects has been established and transported (on land) to an air base in Zaragoza, Spain. Moreover, the container has been put onto a transport aircraft, airborne (see Figure 1.1), and finally brought back to the same air base. The demonstration aims to show military personnel, in particular, the possibilities and current capabilities of in-field production of spare parts and objects using additive manufacturing (AM). A more detailed presentation of the project and its different strands (state of the art, demonstration and AM exhibition/conference), including more details about the experiences from the demonstration, as well as recommendations for further research and development within this area, can be found in the reports from the project [1] [2].

Figure 1.1 The EDA AM container is being put on a transport aircraft at the airbase in Zaragoza, Spain, and then airborne, to demonstrate the capabilities of in-field additive manufacturing. EDA ©. Source: European Defence Agency project on Additive Manufacturing (16.EDA.OP.144) lead by Fundación Prodintec.

Part of the AM demonstration is related to the material properties of the objects when printed outside the regular (and stationary) factory or workshop. The printing conditions in field, such as temperature, humidity and sand/dust/particles will typically be different from factory/workshop conditions, and may not be possible to control or set. Such factors may influence the quality and properties of the printed objects, which will influence on the object's performance and area of use.

In this study performed by FFI, which supported the work done in the current EDA study on AM, the mechanical properties of standardized test specimens manufactured in field will be characterized and compared to the test specimens produced in factory conditions.

2 Production of the test specimens

Four types of standardized test specimens were produced at Prodintec facilities in May 2017 in factory/workshop conditions. The same four types of test specimens were printed in the container, in in-field conditions, during the exercise "European Advanced Airlift Tactics Training Course for 2017" (EAATTC17-3) in Zaragoza, Spain, in June 2017. In total, eight types of test specimens were produced by Prodintec. The printers in the container, as well as some of the tools for pre- and post-processing, are displayed in Figure 2.1. As also shown in the picture, an air condition system was implemented to keep the temperature around 24°C. No other equipment was implemented to control the temperature or the humidity during printing.

Figure 2.1 The EDA AM container for in-field printing. EDA ©. Source: European Defence Agency project on Additive Manufacturing (16.EDA.OP.144) lead by Fundación Prodintec.

2.1 Test specimens standards

Dumbbell shaped test specimens were produced according to ISO standard ISO-527-2 [3], using the type 1BA (small) specimen geometry, as shown and defined in Figure 2.2 and Table 2.1. The print orientations were chosen according to ASTM F2971-13 [4], see Figure 2.3. As a result of the print orientation, four different specimen types were made.

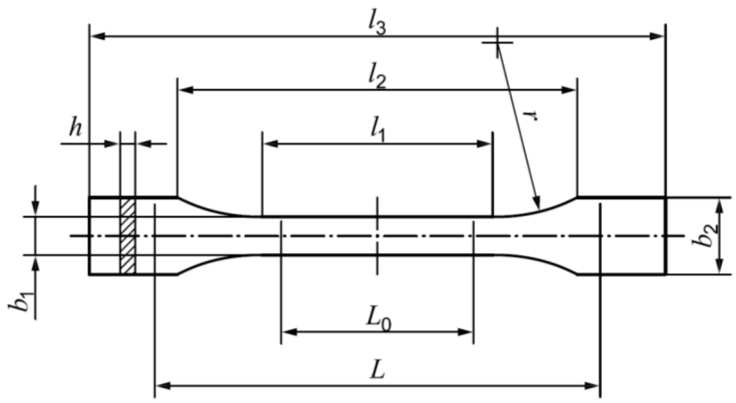


Figure 2.2 Test specimen geometry, according to ISO 527-2, type 1BA (small). See Table 2.1 for parameter values and more details.

Table 2.1 Test specimen parameter values according to ISO 527-2, type 1BA (small). See Figure 2.2 for a sketch of the test specimen.

Parameter	**Description**	**Dimensions in mm**
l_3	Overall length	100
l_1	Length of narrow parallel-sided portion	30.0 ± 0,5
r	Radius	≥30
l_2	Distance between broad parallel-sided portions	58 ± 2
b_2	Width at ends	10.0 ± 0.5
b_1	Width at narrow portion	5.0 ± 0.5
H	Thickness	≥2
L_0	Gauge length	25.0 ± 0.5
L	Initial distance between grips	--

Figure 2.3 Build platform. The different print orientations are indicated. Three in-plane print orientations are defined, as well as one out-of-plane print orientation.

2.2 Printing

For all specimen types the same Markforged Mark II printer was applied – both at the Prodintec facilities and in the container. The same printer settings were used in both environments, but variations in temperature and humidity are reported; see Section 2.2.3 for details.

2.2.1 Material

For all test specimen types the Markforged material type Onyx was applied, which is referred to as a "fusion of engineering nylon and chopped carbon fibre" [5].

2.2.2 Printer input file

MarkForged Mark II files (".mfp" format) for the standardized test specimen geometry were generated and provided by FFI. Due to (expected) different mechanical properties of the printed objects as a result of the print direction, four different orientations were included in the test program, as specified in ASTM 2971-13 [4]. One input file was made for each of the four orientations, and then sent to Prodintec. Each ".mfp" file specifies geometry, orientation, material, filament/raster control, support material and brim, as well as material filler density.

It should be noted that when using Markforged printers, the filler density will not be 100%, even if "full filler density" is specified in the input file. Hence, fully dense objects cannot be made. For the printed test specimens, this result in an inner cell-like structure which will vary depending on the print orientation. Images showing the inner structure of each specimen type are provided in Section 3.2.

2.2.3 Printer settings

Additional printer parameter settings/adjustments were set and logged by the Prodintec operator for the printing at the two different locations.

The temperature and humidity in the workshop/factory and in the container during printing were logged to make sure that the in-field printed objects experienced similar environmental conditions as the printed objects produced in the workshop/factory. The logged data are given in Table 2.2. Each specimen type has been given a unique ID.

Table 2.2 Environmental conditions (temperature and humidity) during printing of the test specimens.

Specimen type ID	Production location	Humidity (%)	Temperature (°C)
EDA-OB-1	Prodintec facilities	51.0	20.9
EDA-OB-2	Prodintec facilities	50.5	23.0
EDA-OB-3	Prodintec facilities	45.9	24.5
EDA-OB-4	Prodintec facilities	51.7	23.2
EDA-OB-5	Container Zaragoza	40.8	24.8
EDA-OB-6	Container Zaragoza	42.0	26.8
EDA-OB-7	Container Zaragoza	42.6	22.8
EDA-OB-8	Container Zaragoza	42.6	22.6

Moreover, the same routines regarding material handling and printing were followed for all specimen types:

- The printer was calibrated after transport/air lift.
- The printer nozzle was purged before printing the Onyx material to avoid humidity problems (i.e. to avoid that the material was exposed to oxygen).
- PVA based glue was used on base plate.
- The time after end of a print job and removal from the base plate was 1 minute.
- There was no pause during a print job.
- The specimens were put in plastic bags (not airtight) after printing.

2.3 Specimen type summary

Table 2.3 provides an overview of the eight types of 3D printed test specimens. As also explained above, four types were produced at Prodintec facilities, and the same four types were produced in the container in field during the airlift exercise in Zaragoza. The print orientation is varied for the four types (at both locations). The thickness and width at the narrow portion is within the range defined by the ISO standard [3] for all test specimens; the average value for each set is given in Table 2.3.

Table 2.3 Overview of test specimen types.

Specimen type ID	Production location	Print orientation	Thickness (mm)	Width at narrow portion (mm)	Cross-section area (mm^2)
EDA-OB-1	Prodintec facilities	YX (90°)	4.03 ± 0.02	5.13 ± 0.03	20.70 ± 0.19
EDA-OB-2	Prodintec facilities	C+45 from XY (45°)	4.04 ± 0.03	5.14 ± 0.02	20.75 ± 0.16
EDA-OB-3	Prodintec facilities	XY (0°)	3.98 ± 0.03	5.09 ± 0.02	20.23 ± 0.15
EDA-OB-4	Prodintec facilities	ZX	3.90 ± 0.03	5.00 ± 0.02	19.53 ± 0.11
EDA-OB-5	Container Zaragoza	YX (90°)	4.00 ± 0.01	5.10 ± 0.03	20.40 ± 0.13
EDA-OB-6	Container Zaragoza	C+45 from XY (45°)	4.00 ± 0.03	5.10 ± 0.01	20.50 ± 0.17
EDA-OB-7	Container Zaragoza	XY (0°)	4.00 ± 0.03	5.00 ± 0.03	19.90 ± 0.23
EDA-OB-8	Container Zaragoza	ZX	3.90 ± 0.04	5.00 ± 0.06	19.10 ± 0.41

3 Tensile testing

3.1 Test set-up

Tensile testing of different test specimen types was done. The testing was conducted according to the ISO 527-2 standard [3] on a Zwick BZ2.5/TN1S material testing machine at FFI. As already shown in the summary table for the specimens, see Table 2.3, the outer cross-sectional area of the narrow parallel-sided portion of the test specimen was very close to 4 mm × 5 mm for all specimens.

The specimens were gripped in the broader ends and aligned so that the load-direction was parallel to the narrow portion. A clip-gauge extensometer, which was used for recording the strain, was thereafter attached. The test speed was 1 mm/min. The most important mechanical properties of the material were determined by the tensile test machine software, i.e. the tensile modulus of elasticity, E_t, the maximum tensile stress, or the tensile strength, σ_m, and the tensile strain at maximum tensile stress, ε_m.

Before presenting the obtained test results, it is important to note, that the mechanical properties are calculated based on the cross-sectional area of a dense test specimen, as given in Table 2.3 and in the ISO standard. The empty voids in the cell-like structure are not taken into consideration. This will inevitably give lower (and erroneous) values for the calculated mechanical properties.

3.2 Fracture surface/internal structure

As already mentioned, all test specimens had an internal cell-like structure.

Figure 3.1 shows pictures and microscopy images of the failure surface after tensile testing, as well as the specimen cross section, of the factory/workshop specimen types. The cross-section structure (not the fracture surface) was investigated by cutting a sharp knife through the specimen test section.

In a similar way, Figure 3.2 shows pictures and microscopy images of the failure surface after tensile testing, as well as the specimen cross-section, of the container specimen types.

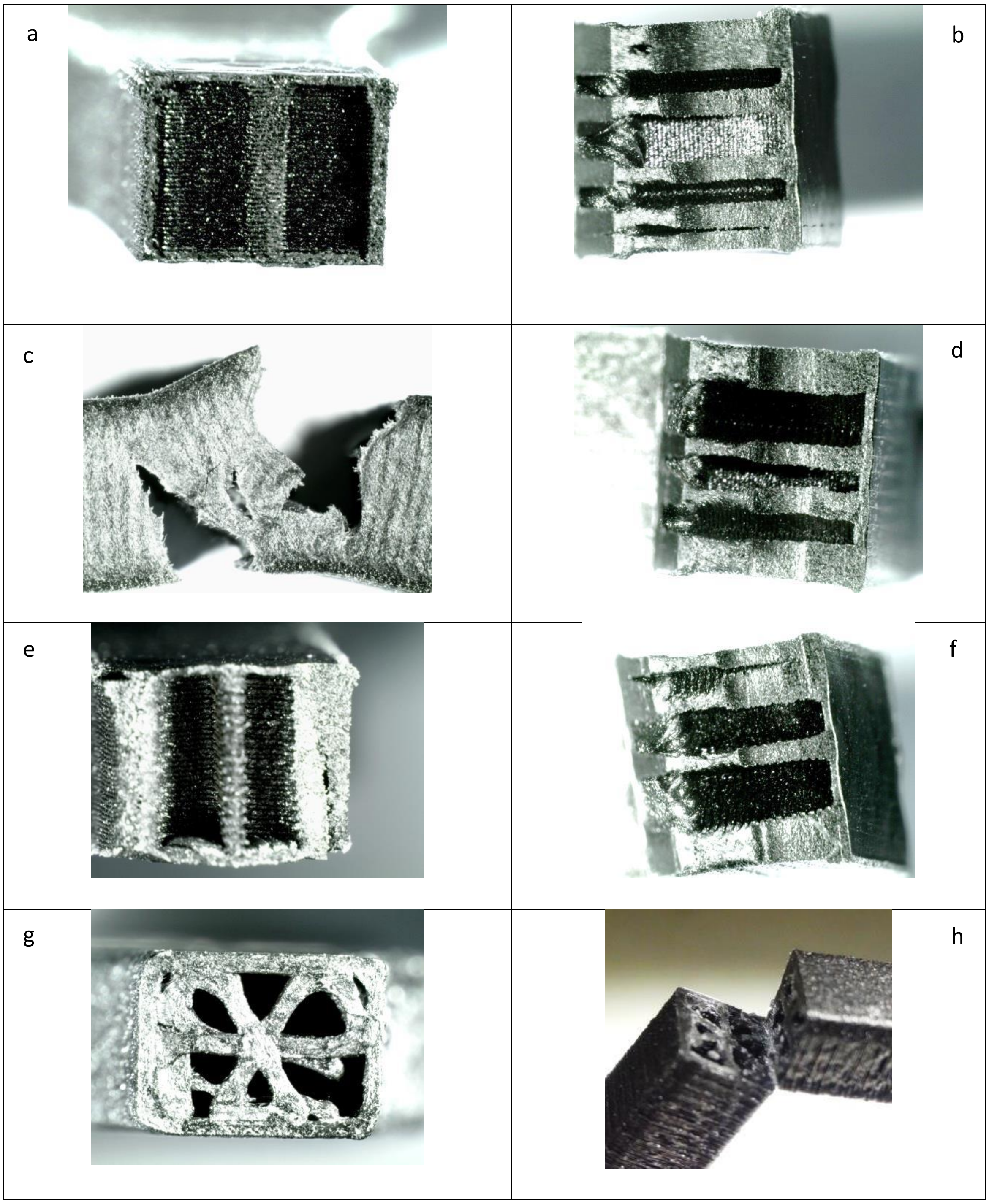


Figure 3.1 Fracture surface/internal structure of the specimen types. a) Fracture surface of test specimen EDA-OB-1-6, b) cross-section of test specimen EDA-OB-1-5 , c) side view of fracture of EDA-OB-2-2, d) cross-section of test specimen EDA-OB-2-3, e) fracture surface of EDA-OB-3-5, f) cross-section of test specimen EDA-OB-3-1, g) fracture surface of test specimen EDA-OB-4-6, h) cross-section of test specimen EDA-OB-4-4.

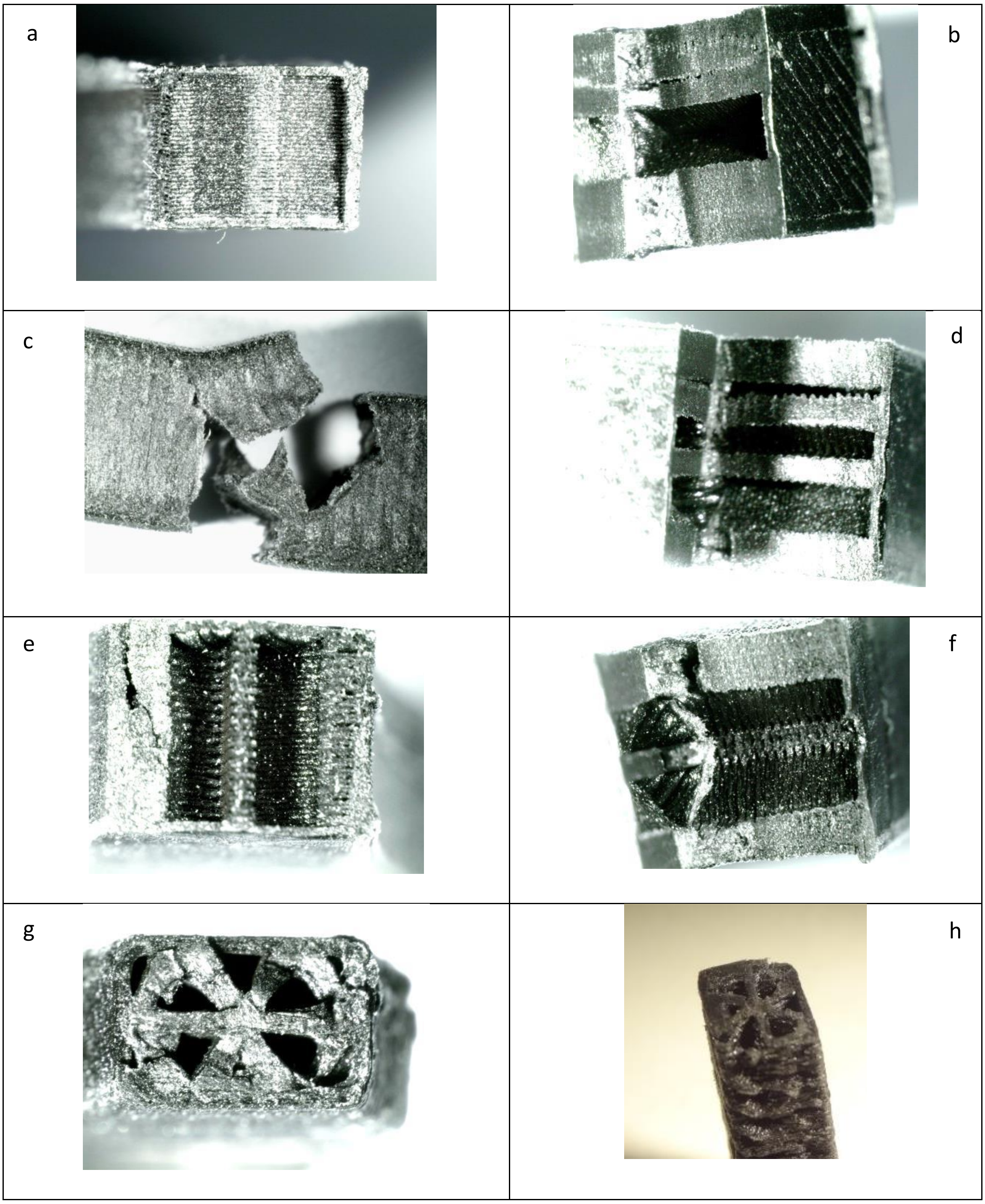


Figure 3.2 Fracture surface/internal structure of the specimen types. a) Fracture surface of test specimen EDA-OB-5-3, b) cross-section of test specimen EDA-OB-5-2 , c) side view of fracture of EDA-OB-6-3, d) cross-section of test specimen EDA-OB-6-3, e) fracture surface of EDA-OB-7-3, f) cross-section of test specimen EDA-OB-7-6, g) fracture surface of test specimen EDA-OB-8-2, h) cross-section of test specimen EDA-OB-8-2

3.3 Load-strain curves

Most of the test specimens experienced a linear stress-strain phase before the material started to yield and finally broke. Some of the test specimens broke before yield occurred in the material. Moreover, some of the specimens experienced an unrealistic large elongation, as the specimen started failing, but not broke completely.

The load-strain curves for each specimen type are provided in the following subsections.

3.3.1 Specimen type EDA-OB-1

Figure 3.3 shows the load-strain curves for test specimen type EDA-OB-1, with the YX (90°) print orientation. All specimens experienced yield before breaking.

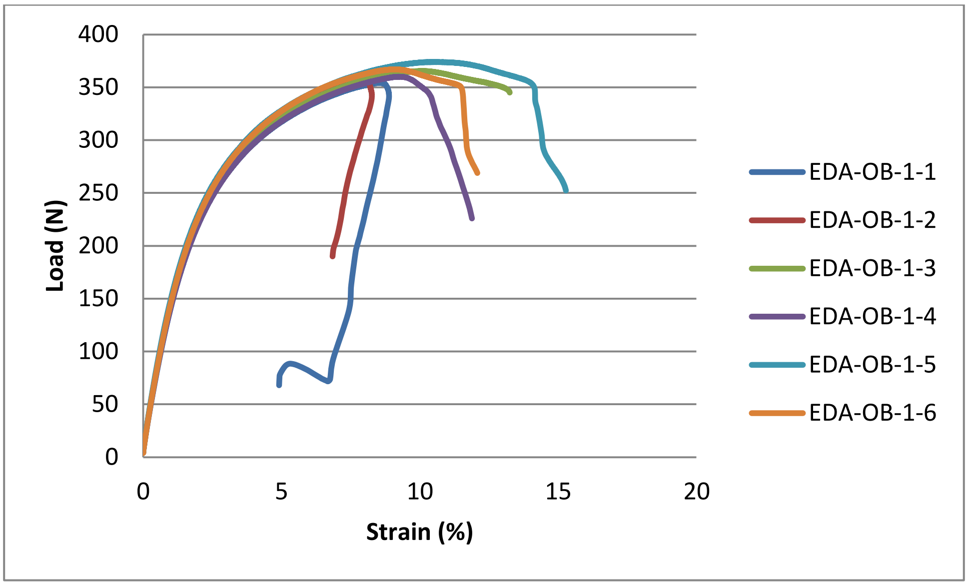


Figure 3.3 Load-strain curves for the test specimen type EDA-OB-1.

3.3.2 Specimen type EDA-OB-2

Figure 3.4 shows the load-strain curves for test specimen type EDA-OB-2, with the C+45 XY (45°) print orientation. All specimens experienced yield before breaking.

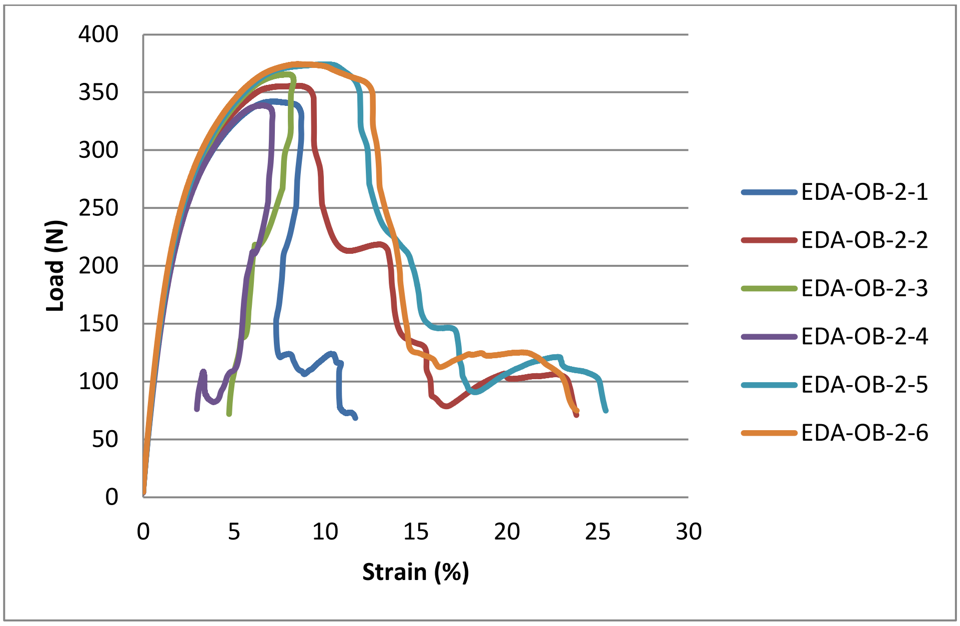


Figure 3.4 Load-strain curves for the test specimen type EDA-OB-2.

3.3.3 Specimen type EDA-OB-3

Figure 3.5 shows the load-strain curves for test specimen type EDA-OB-3, with the XY (0°) print orientation. All specimens experienced yield before breaking.

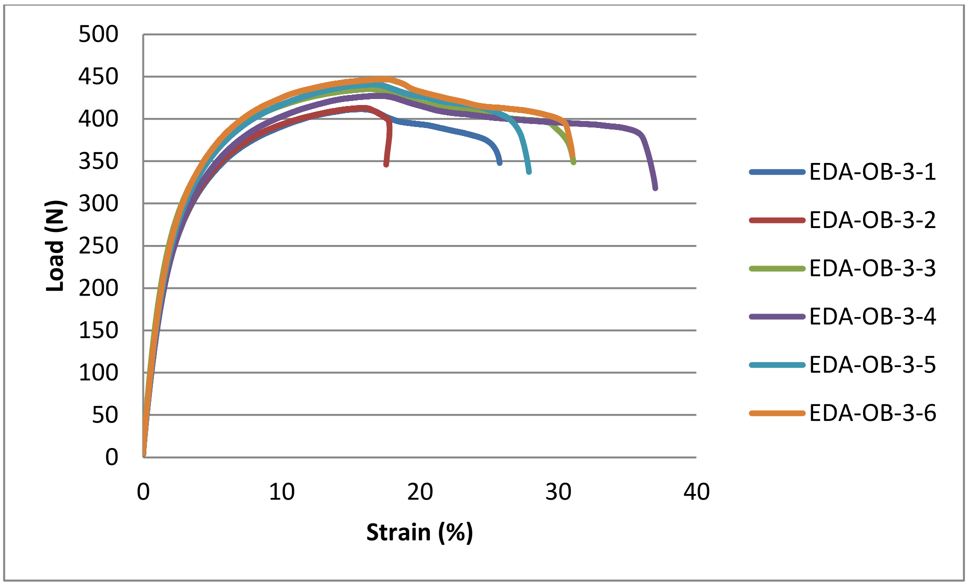


Figure 3.5 Load-strain curves for the test specimen type EDA-OB-3.

3.3.4 Specimen type EDA-OB-4

Figure 3.6 shows the load-strain curves for test specimen type EDA-OB-4, with the ZX (vertical) print orientation. Only two of the specimens (i.e. EDA-OB-4-3 and EDA-OB-4-4) experienced yield before breaking, whereas the other specimens seemed to break when entering the non-linear phase of the load-strain curve.

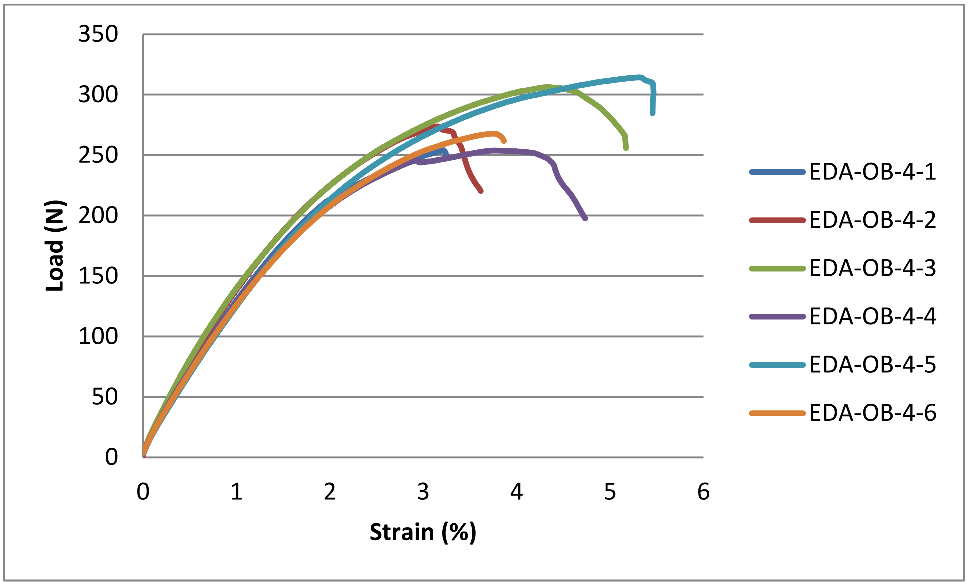


Figure 3.6 Load-strain curves for the test specimens EDA-OB-4.

3.3.5 Specimen type EDA-OB-5

Figure 3.7 shows the load-strain curves for test specimen type EDA-OB-5, with the YX (90°) print orientation. All specimens experienced yield before breaking, except for specimen EDA-OB-5-2.

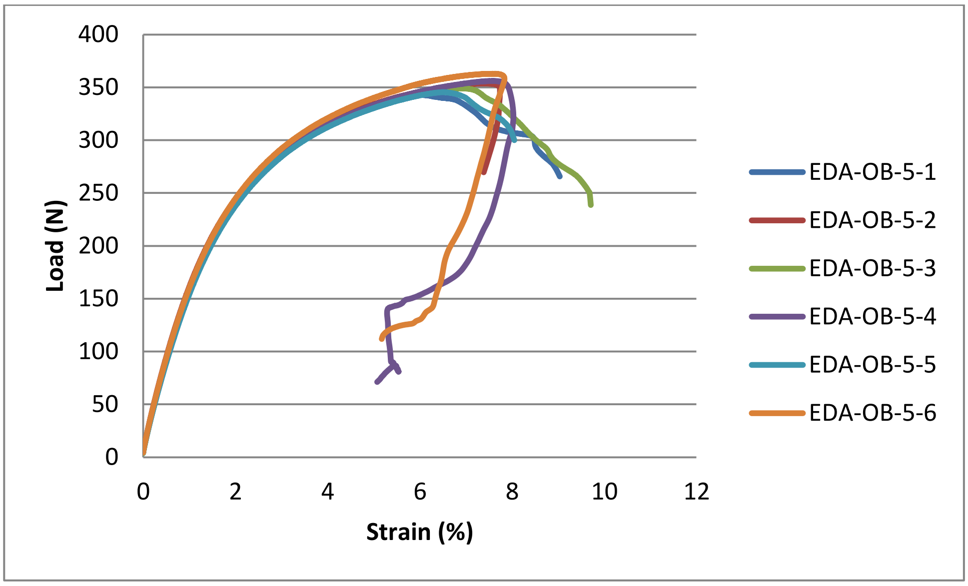


Figure 3.7 Load-strain curves for the test specimen type EDA-OB-5.

3.3.6 Specimen type EDA-OB-6

Figure 3.8 shows the load-strain curves for test specimen type EDA-OB-6, with the C+45 XY (45°) print orientation. All specimens experienced yield before breaking.

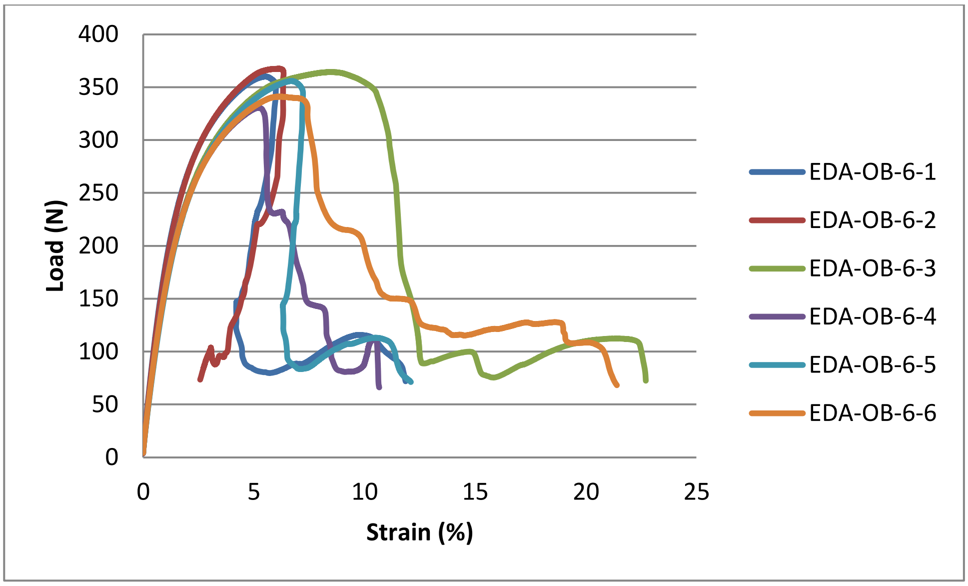


Figure 3.8 Load-strain curves for the test specimen type EDA-OB-6.

3.3.7 Specimen type EDA-OB-7

Figure 3.9 shows the load-strain curves for test specimen type EDA-OB-7, with the XY (0°) print orientation. All specimens experienced yield before breaking.

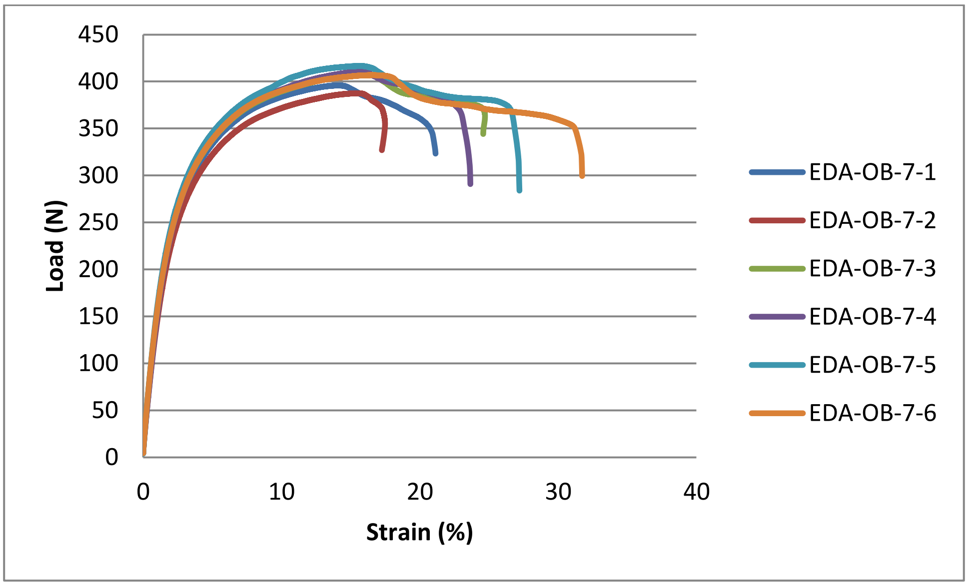


Figure 3.9 Load-strain curves for the test specimen type EDA-OB-7.

3.3.8 Specimen type EDA-OB-8

Figure 3.10 shows the load-strain curves for test specimen type EDA-OB-8, with the ZX (vertical) print orientation. Only three of the specimens (i.e. EDA-OB-8-2, EDA-OB-8-3 and EDA-OB-8-4) experienced yield before breaking, whereas the other specimens seemed to break at an earlier stage.

In general, all specimens of this series had a poor quality and resulted in much lower parameter values compared to the other types. The test results may thus not be representative for the properties of the printed material.

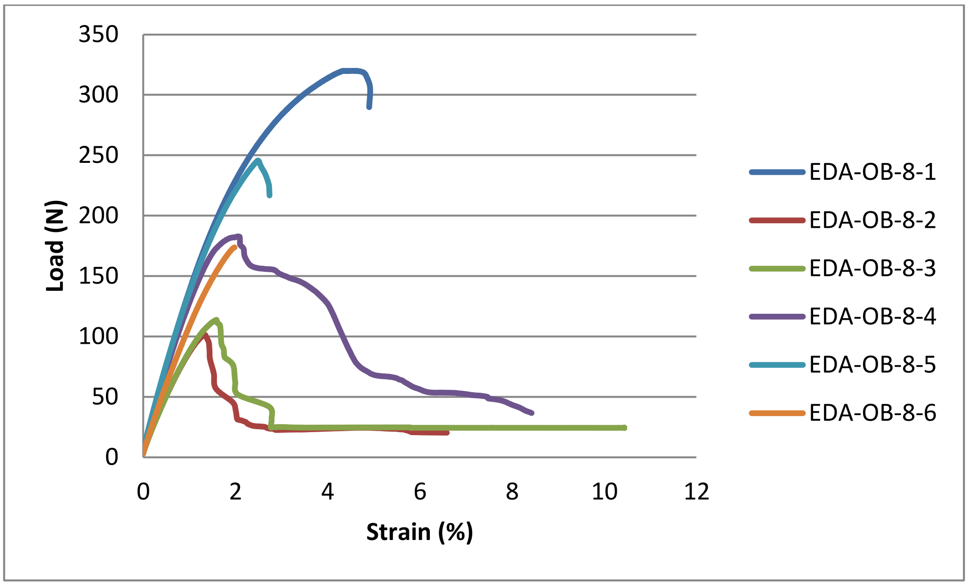


Figure 3.10 Load-strain curves for the test specimen type EDA-OB-8.

3.4 Mechanical properties

Table 3.1 shows a summary of the obtained mechanical properties for the eight types of test specimens. The tensile modulus, E_t, was determined from the linear part of the stress-strain curve in the strain range from 0.05% to 0.25%. Average values of six replicate specimens are reported; for some of the types a reduced number of specimens are used, as indicated in the table. The ambient temperature during the testing was 20 ± 1°C. The mechanical properties obtained for all specimens are included in Appendix A.

As also emphasized in Section 3.1, it is important to note that the mechanical properties are calculated based on the cross-sectional area of a dense test specimen, as given in Table 2.3 and in the ISO standard, and not the real cross-sectional area. Due to the internal cell-like structure, the real cross-sectional area is smaller than the cross-sectional area employed in the calculation. First of all, this will give a calculated normal stress value that is lower compared to using the real cross-sectional area. Moreover, the tensile modulus will also be lower. Hence, the calculated results are expected to be lower than what has been reported by others. The real cross-sectional area of each specimen type has not been measured correctly.

Table 3.1 Results from tensile testing of the eight specimen sets, according to ISO 527-2 [3]. Note that the cross-sectional area for a dense specimen, as given in Table 2.3, is applied in the calculations, and not the real cross-sectional area (due to the cell-like structure).

Test specimen type ID	**Tensile modulus (MPa)**	**Tensile strength (MPa)**	**Tensile strain at tensile strength (%)**
EDA-OB-1	769 ± 19	17.5 ± 0.4	9.3 ± 0.9
EDA-OB-2	822 ± 25	17.3 ± 0.7	8.1 ± 1.2
EDA-OB-3	861 ± 59	21.2 ± 0.7	16.5 ± 0.7
EDA-OB-4	726 ± 63	14.3 ± 1.3	3.9 ± 0.8
EDA-OB-5	860 ± 21	17.2 ± 0.4	7.0 ± 0.7
EDA-OB-6	905 ± 62	17.2 ± 0.6	6.4 ± 1.2
EDA-OB-7	829 ± 44	20.3 ± 0.5	15.6 ± 0.9
EDA-OB-8	636 ± 114	11 ± 4 (*)	2.5 ± 1.2 (*)
Superior 3D Solutions [6]	1400	25	-

(*) Average value and standard deviation based on 5 specimens.

3.5 Discussion

Comparing with the data reported by Superior 3D Solutions [6] using ASTM D638, the obtained results in this study are lower for all specimen types and the parameter values included in the study. First of all, the reduced values are due to the fact that the cross-sectional area for a fully dense specimen is applied in the calculations, and not the real cross-sectional area in each case. Different geometry defined for the ASTM D638 and the ISO-527-2 standards may also influence the results, as well as the printer settings and other conditions during the printing.

Since the specimen sets are not dense but have some kind of internal cell-like structure, which seems to vary for the different specimen types, it is difficult to compare the obtained results from the tensile testing. Ideally, one should have all specimens made of dense material. Still, it is relevant to compare the printing at the two different locations, to see the effect of factory/workshop versus in-field printing conditions. The same printer input file should produce the same specimen geometry, including the internal structure. The only variation is the environmental conditions during printing.

For the tensile modulus, the value is found to vary for the different print orientations, see Table 3.1 and Figure 3.11. For the YX (90°) print orientation and C+45 to XY (45°) print orientation, the in-field produced test specimens have higher tensile modulus of elasticity compared to the specimens produced in the workshop. For the XY (0°) print orientation and the ZX print orientation, an opposite result is obtained. The lower value for the in-field ZX print orientation specimens may be due to poor production quality of that particular type. There is hence no clear reduction of tensile modulus of elasticity due to the in-field conditions for any of the orientations.

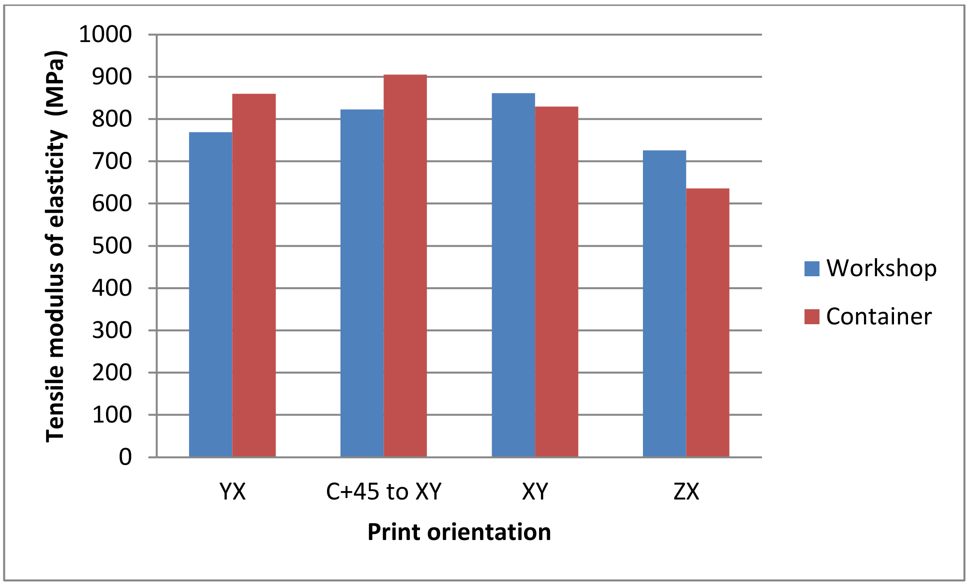


Figure 3.11 Elastic stiffness (average value) for the eight types.

For the tensile strength, no significant differences are observed for the in-field and workshop test specimens, see Table 3.1 and Figure 3.12. Again, the XY (0°) print orientation results in a higher tensile strength value than the other orientations. Moreover, the ZX print orientation results in the lowest value, with the in-field specimen type EDA-OB-8 again giving lower values than the workshop specimen type EDA-OB-4.

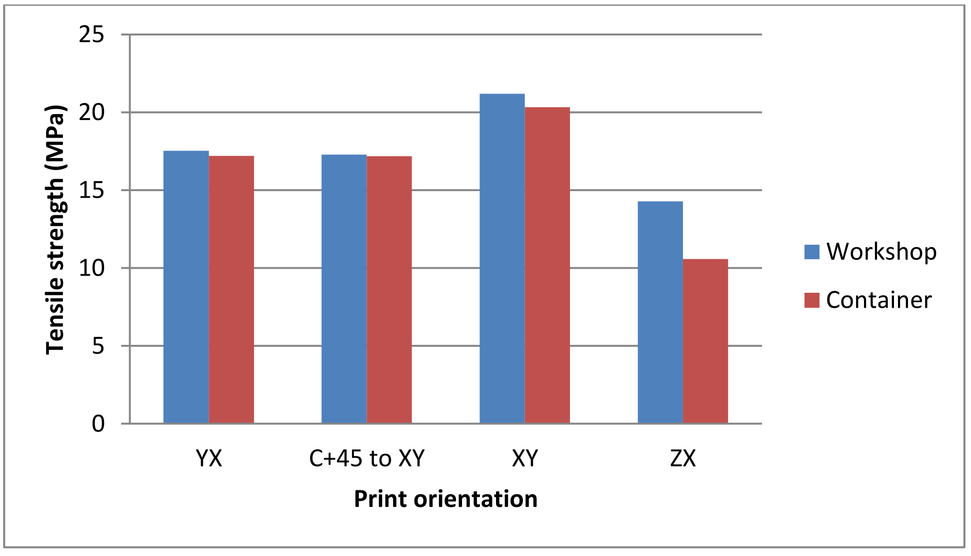


Figure 3.12 Tensile strength for the eight specimen types.

For the tensile strain at tensile strength, see Table 3.1 and Figure 3.13, the same is observed as for the tensile strength.

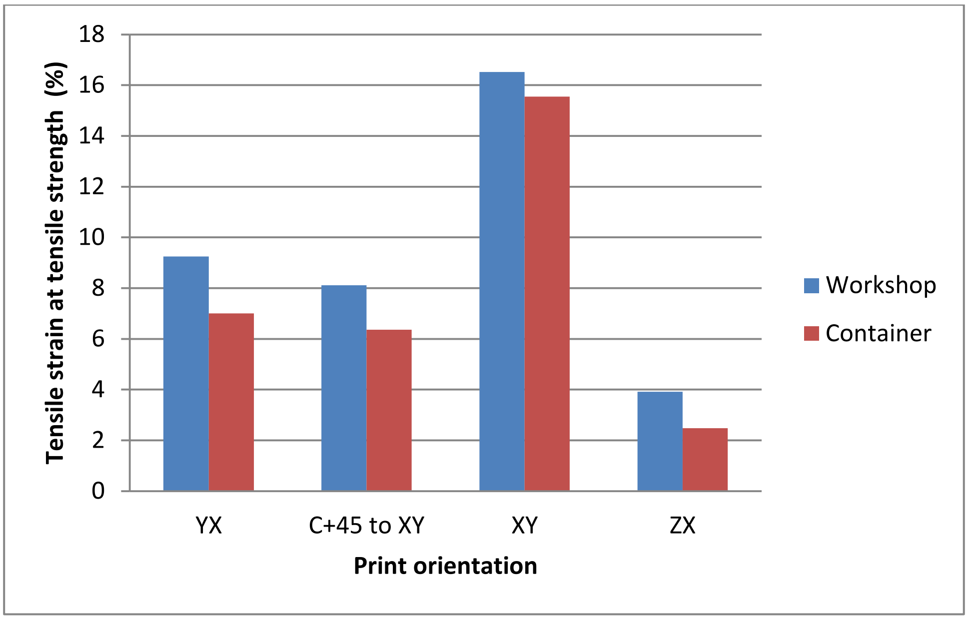


Figure 3.13 Tensile strain at tensile strength for the eight specimen types.

4 Summary and conclusions

In-field production using additive manufacturing has been demonstrated in the EDA OB study "Additive Manufacturing Feasibility Study & Technology Demonstration" (EDA contract no. 16.ESI.OP.144). As part of the demonstration of the in-field production, standardized test specimens have been printed both in field and in workshop/factory conditions. Tensile testing of the produced test specimens has been performed to characterize the mechanical properties of the materials, and to study if the mechanical properties change dramatically when printing in field compared to more controlled workshop conditions.

As an overall conclusion, based on the test results from this study, no significant reduction or change in mechanical properties are experienced for the objects printed in field compared to those printed in more controlled workshop/factory conditions.

It should be noted that the specimen geometry is not fully dense; the specimens have a cell-like internal structure. As the real cross-sectional area of the fracture surface is challenging to measure, the cross-sectional area of a dense specimen is applied in the calculations. As a result of this, the obtained parameter values included in the study for the specimen types are much lower than what is reported by the material manufacturer and other studies. Still, a comparison of printing under different conditions and locations, i.e. factory versus in-field, is relevant.

Acknowledgement

The authors would like to thank the colleagues at Fundación Prodintec for printing the test specimens and for providing input and comments to the report, and also Patricia López Vicente and her colleagues at EDA for supporting and coordinating the EDA study and in-field demonstration of additive manufacturing. Moreover, the authors would like to thank Kristin Wille von der Lippe (Fieldmade) for her contribution to the study.

A Tensile testing: Test data

Table A.1 Test data for specimen type EDA-OB-1.

Specimen ID	Regression modulus E_t (MPa)	Tensile strength σ_m (MPa)	Tensile strain at tensile strength ε_m (%)
EDA-OB-1-1	749	17,2	8,6
EDA-OB-1-2	760	17,1	8,0
EDA-OB-1-3	776	17,6	10,1
EDA-OB-1-4	749	17,3	9,2
EDA-OB-1-5	793	17,9	10,5
EDA-OB-1-6	788	18,0	9,1
AVERAGE	**769**	**17,5**	**9,3**
STDEV	**19**	**0,4**	**0,9**

Table A.2 Test data for specimen type EDA-OB-2.

Specimen ID	Regression modulus E_t (MPa)	Tensile strength σ_m (MPa)	Tensile strain at tensile strength ε_m (%)
EDA-OB-2-1	820	16,6	7,3
EDA-OB-2-2	838	17,2	8,5
EDA-OB-2-3	800	17,4	7,9
EDA-OB-2-4	795	16,5	6,5
EDA-OB-2-5	820	18,0	10,0
EDA-OB-2-6	861	18,0	8,5
AVERAGE	**822**	**17,3**	**8,1**
STDEV	**25**	**0,7**	**1,2**

Table A.3 Test data for specimen type EDA-OB-3.

Specimen ID	Regression modulus E_t (MPa)	Tensile strength σ_m (MPa)	Tensile strain at tensile strength ε_m (%)
EDA-OB-3-1	830	20,5	15,7
EDA-OB-3-2	816	20,5	16,0
EDA-OB-3-3	964	21,3	16,3
EDA-OB-3-4	807	20,9	16,9
EDA-OB-3-5	858	21,7	16,7
EDA-OB-3-6	891	22,2	17,5
AVERAGE	**861**	**21,2**	**16,5**
STDEV	**59**	**0,7**	**0,7**

Table A.4 Test data for specimen type EDA-OB-4.

Specimen ID	Regression modulus E_t (MPa)	Tensile strength σ_m (MPa)	Tensile strain at tensile strength ε_m (%)
EDA-OB-4-1	708	13,0	3,2
EDA-OB-4-2	826	14,1	3,2
EDA-OB-4-3	778	15,6	4,3
EDA-OB-4-4	705	13,0	3,8
EDA-OB-4-5	657	16,1	5,3
EDA-OB-4-6	683	13,8	3,7
AVERAGE	**726**	**14,3**	**3,9**
STDEV	**63**	**1,3**	**0,8**

Table A.5 Test data for specimen type EDA-OB-5.

Specimen ID	Regression modulus E_t (MPa)	Tensile strength σ_m (MPa)	Tensile strain at tensile strength ε_m (%)
EDA-OB-5-1	846	16,9	6,0
EDA-OB-5-2	890	17,3	7,4
EDA-OB-5-3	846	16,9	6,9
EDA-OB-5-4	860	17,4	7,6
EDA-OB-5-5	836	16,9	6,5
EDA-OB-5-6	879	17,8	7,6
AVERAGE	**860**	**17,2**	**7,0**
STDEV	**21**	**0,4**	**0,7**

Table A.6 Test data for all specimen type EDA-OB-6.

Specimen ID	Regression modulus E_t (MPa)	Tensile strength σ_m (MPa)	Tensile strain at tensile strength ε_m (%)
EDA-OB-6-1	986	17,3	5,5
EDA-OB-6-2	980	17,8	6,1
EDA-OB-6-3	873	17,8	8,5
EDA-OB-6-4	885	16,3	5,2
EDA-OB-6-5	842	17,4	6,7
EDA-OB-6-6	865	16,5	6,2
AVERAGE	**905**	**17,2**	**6,4**
STDEV	**62**	**0,6**	**1,2**

Table A.7 Test data for specimen type EDA-OB-7.

Specimen ID	**Regression modulus E_t (MPa)**	**Tensile strength σ_m (MPa)**	**Tensile strain at tensile strength ε_m (%)**
EDA-OB-7-1	820	20,0	14,0
EDA-OB-7-2	797	19,6	15,4
EDA-OB-7-3	847	20,3	16,2
EDA-OB-7-4	765	20,4	15,6
EDA-OB-7-5	870	20,8	15,6
EDA-OB-7-6	878	20,8	16,5
AVERAGE	**830**	**20,3**	**15,6**
STDEV	**44**	**0,5**	**0,9**

Table A.8 Test data for specimen type EDA-OB-8.

Specimen ID	**Regression modulus E_t (MPa)**	**Tensile strength σ_m (MPa)**	**Tensile strain at tensile strength ε_m (%)**
EDA-OB-8-1	725	16,1	4,5
EDA-OB-8-2	500	5,3	1,3
EDA-OB-8-3	504		
EDA-OB-8-4	732	9,7	2,1
EDA-OB-8-5	743	12,6	2,5
EDA-OB-8-6	610	9,2	2,0
AVERAGE	**636**	**11**	**2,5**
STDEV	**114**	**4,0**	**1,2**

References

[1] EDA, «Additive Manufactuing in Defence: State of the art and strategic report,» European Defence Agency; Contract EDA 16.ESI.OP.144 - Additive Manufacturing Feasibility Study & Technology Demonstration , 2017.

[2] EDA, «Additive Manufacturing in Defence: AM Facility deployment report,» European Defence Agency; Contract EDA 16.ESI.OP.144 - Additive Manufacturing Feasibilitry Study & Technology Demonstration, 2017.

[3] ISO, «ISO 527-2: Plastics - Determination of tensile properties - Part 2: Test conditions for moulding and extrusion plastics,» ISO, 2012.

[4] ASTM, «F2971 – 13, Standard Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing,» ASTM, 2013.

[5] Markforged, «www.markforged.com,» [Internett].

[6] Superior 3D Solutions, [Internett]. Available: www.superior3dsolutions.com.

About FFI

The Norwegian Defence Research Establishment (FFI) was founded 11th of April 1946. It is organised as an administrative agency subordinate to the Ministry of Defence.

FFI's MISSION

FFI is the prime institution responsible for defence related research in Norway. Its principal mission is to carry out research and development to meet the requirements of the Armed Forces. FFI has the role of chief adviser to the political and military leadership. In particular, the institute shall focus on aspects of the development in science and technology that can influence our security policy or defence planning.

FFI's VISION

FFI turns knowledge and ideas into an efficient defence.

FFI's CHARACTERISTICS

Creative, daring, broad-minded and responsible.

Om FFI

Forsvarets forskningsinstitutt ble etablert 11. april 1946. Instituttet er organisert som et forvaltningsorgan med særskilte fullmakter underlagt Forsvarsdepartementet.

FFIs FORMÅL

Forsvarets forskningsinstitutt er Forsvarets sentrale forskningsinstitusjon og har som formål å drive forskning og utvikling for Forsvarets behov. Videre er FFI rådgiver overfor Forsvarets strategiske ledelse. Spesielt skal instituttet følge opp trekk ved vitenskapelig og militærteknisk utvikling som kan påvirke forutsetningene for sikkerhetspolitikken eller forsvarsplanleggingen.

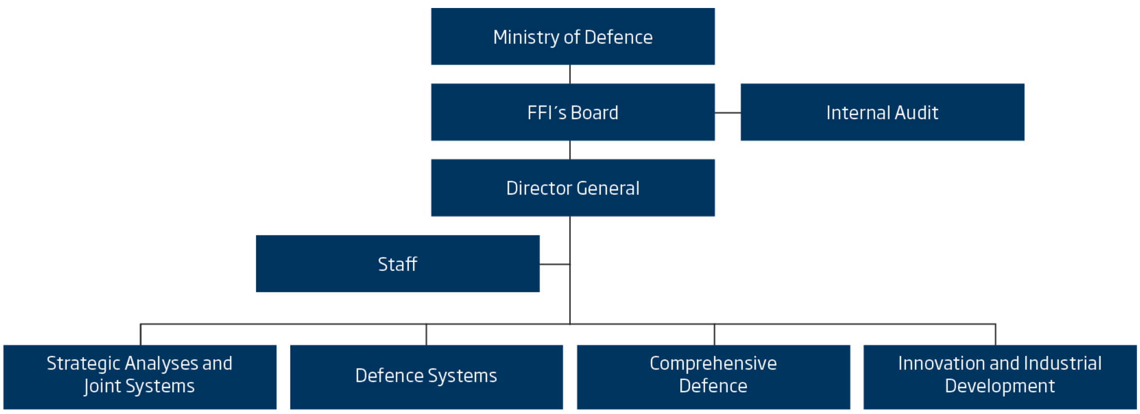
FFIs VISJON

FFI gjør kunnskap og ideer til et effektivt forsvar.

FFIs VERDIER

Skapende, drivende, vidsynt og ansvarlig.

FFI's organisation



Forsvarets forskningsinstitutt
Postboks 25
2027 Kjeller

Besøksadresse:
Instituttveien 20
2007 Kjeller

Telefon: 63 80 70 00
Telefaks: 63 80 71 15
Epost: ffi@ffi.no

Norwegian Defence Research Establishment (FFI)
P.O. Box 25
NO-2027 Kjeller

Office address:
Instituttveien 20
N-2007 Kjeller

Telephone: +47 63 80 70 00
Telefax: +47 63 80 71 15
Email: ffi@ffi.no

FFI Forsvarets forskningsinstitutt
Norwegian Defence Research Establishment