Real-time Digital Twin Development for Additive Manufacturing

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12/16/2025
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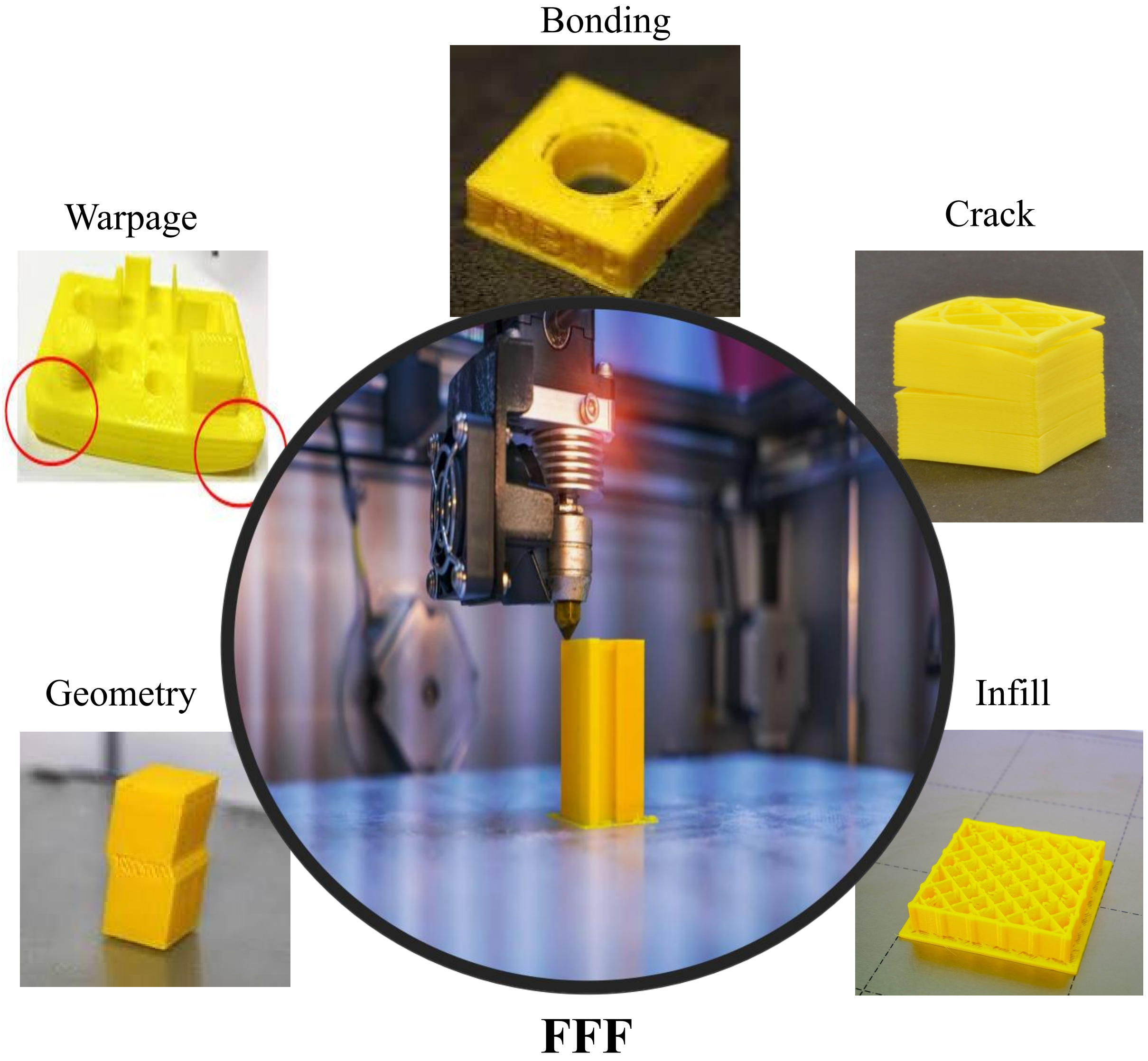
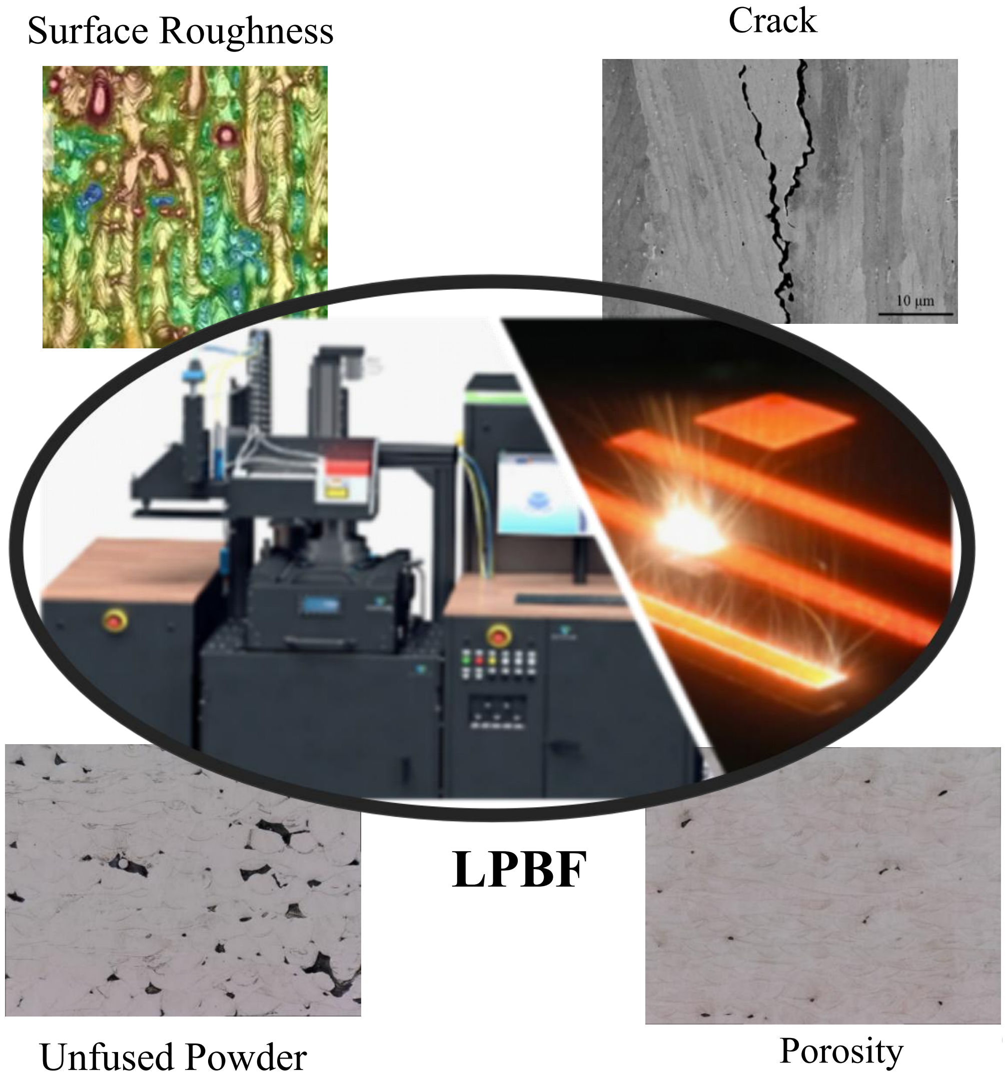
Engineering and Computing

Contents

1. Motivation & Problem Statement





1. Motivation & Problem Statement

tensile test

bending test

compression test

1. Motivation & Problem Statement

Gap in Current Additive Manufacturing Monitoring

Existing monitoring systems

- Mostly post-process inspections
- Limited real-time defect detection
- Poor integration of structural validation

WHAT'S MISSING

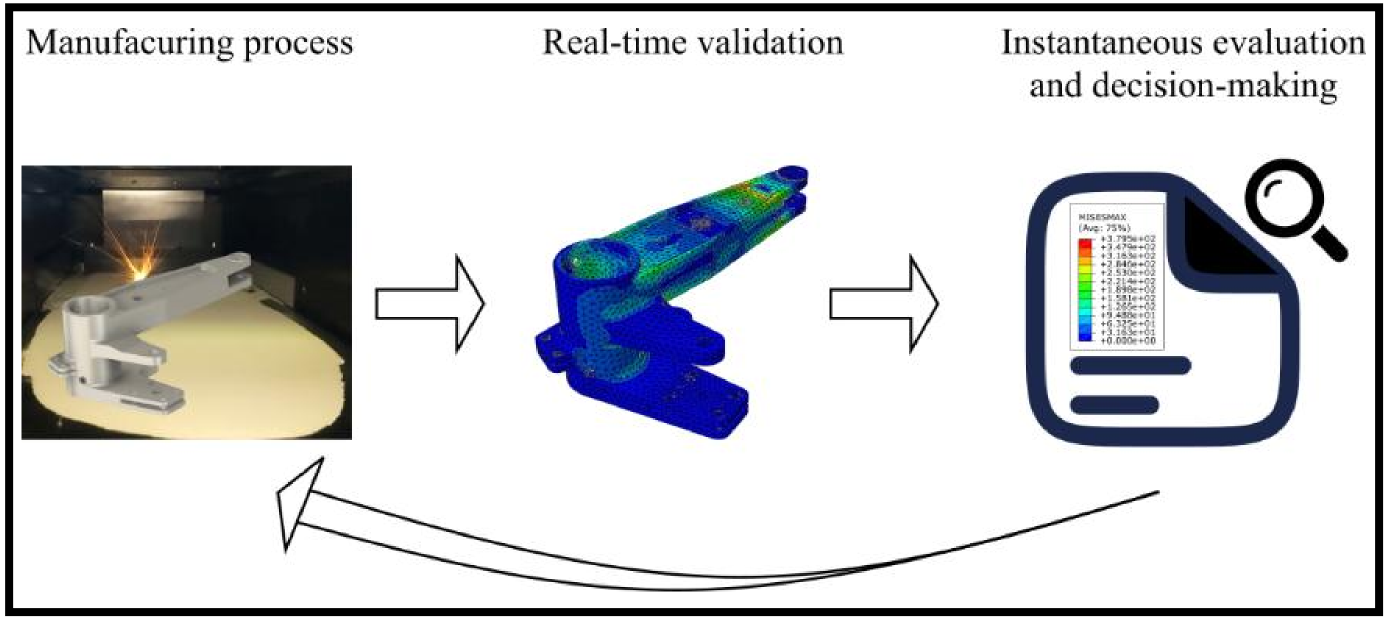
Integration of sensing, ML, and validation for real-time quality assurance

My intelligent AM monitoring & validation system

- Multi-sensor fusion
- Machine learning-driven detection
- Real-time structural validation
- Decision-making-in-the-loop

Contents

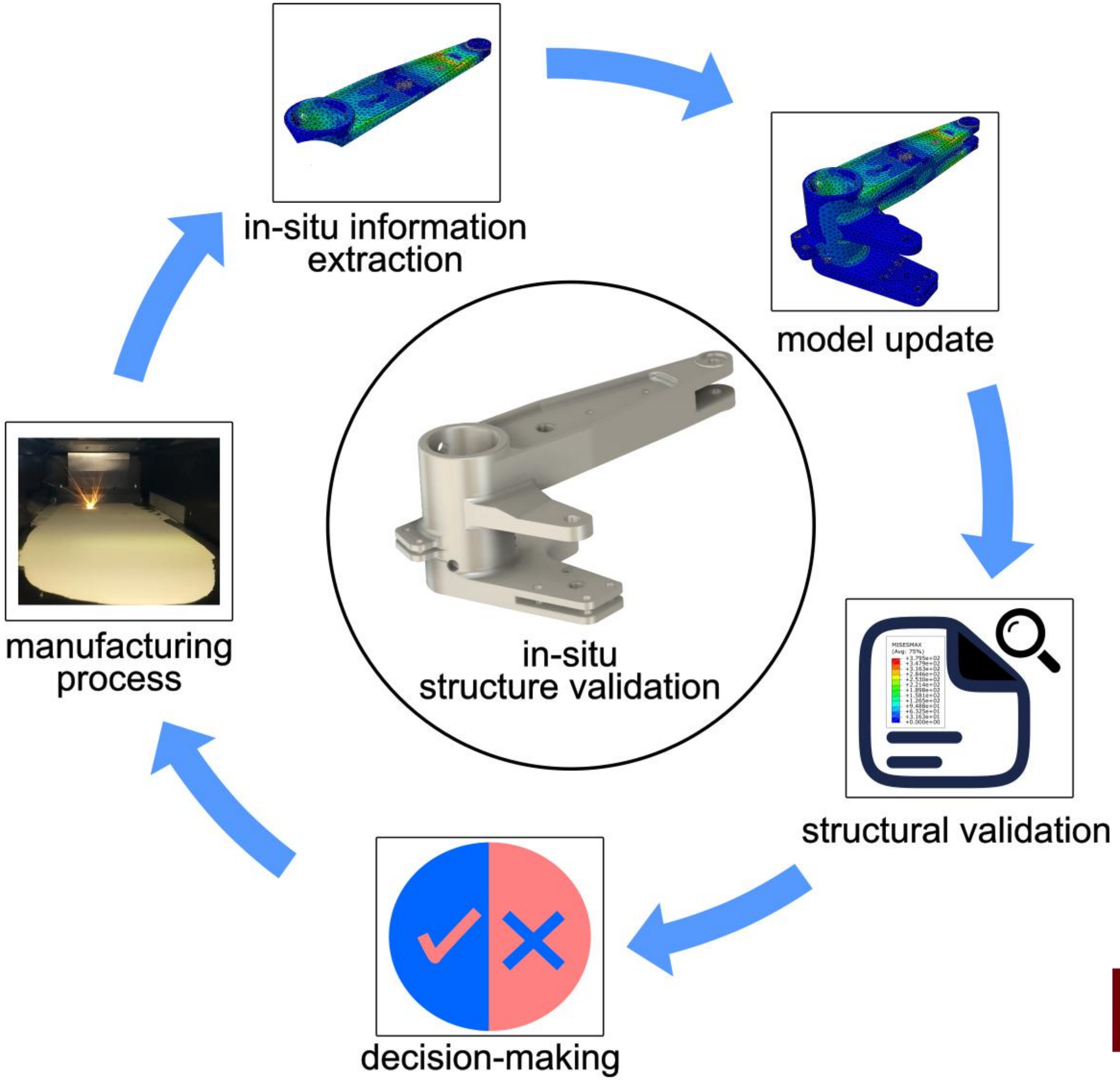
2. Research Vision & Objective



printing cycle quality guaranteeing

pull off and ready for use

2. Research Vision & Objective



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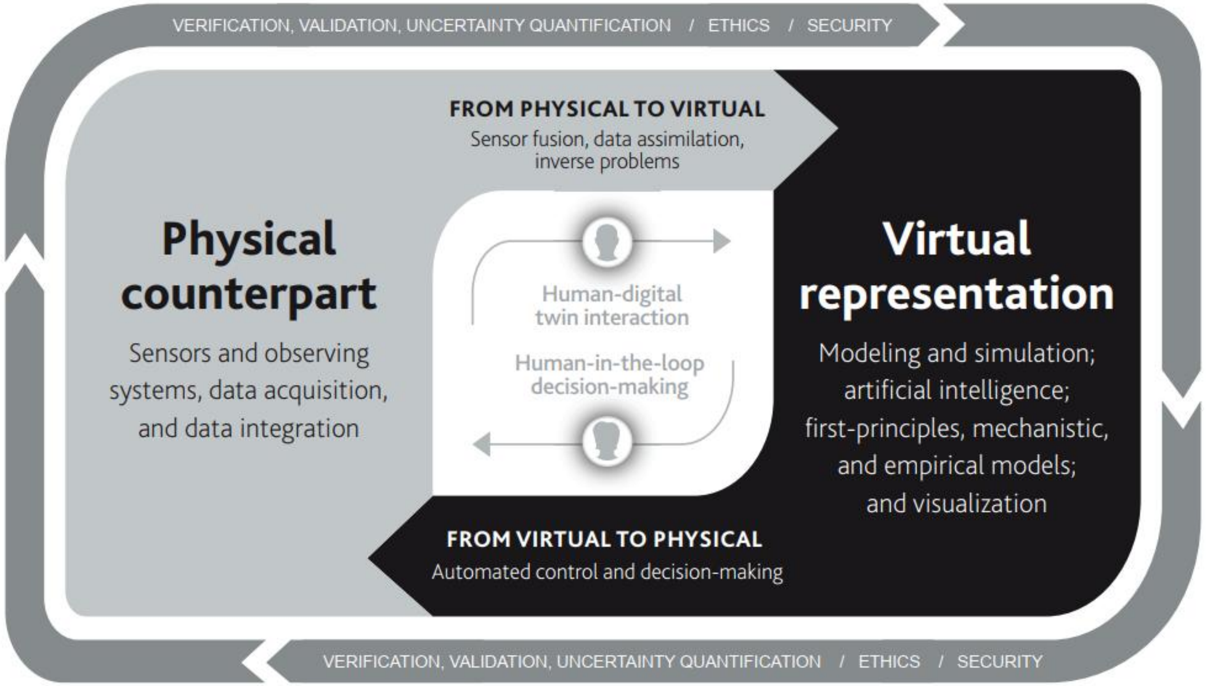
Contents

3. Digital Twin

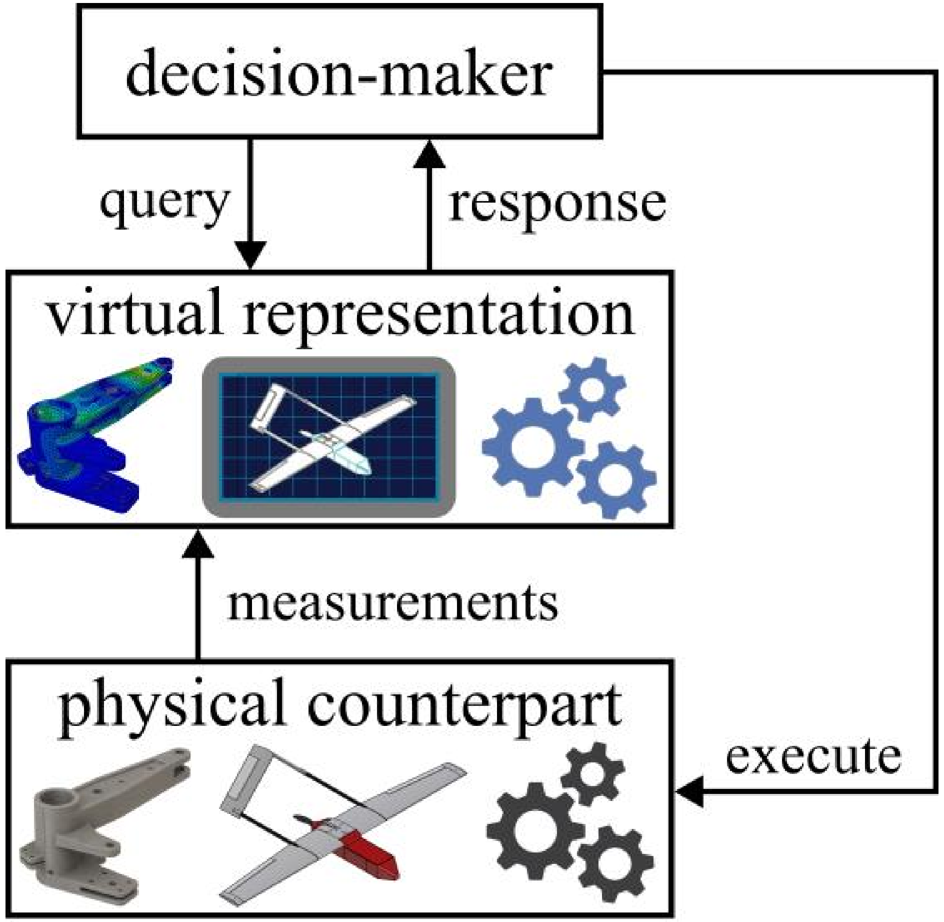
What a digital twin is: A live computer model of a real system that stays synced with sensor data. Not just CAD.

- Information flows bidirectionally between the virtual representation and physical counterpart.
- These information flows may be through automated processes, human-driven processes, or a combination of the two.



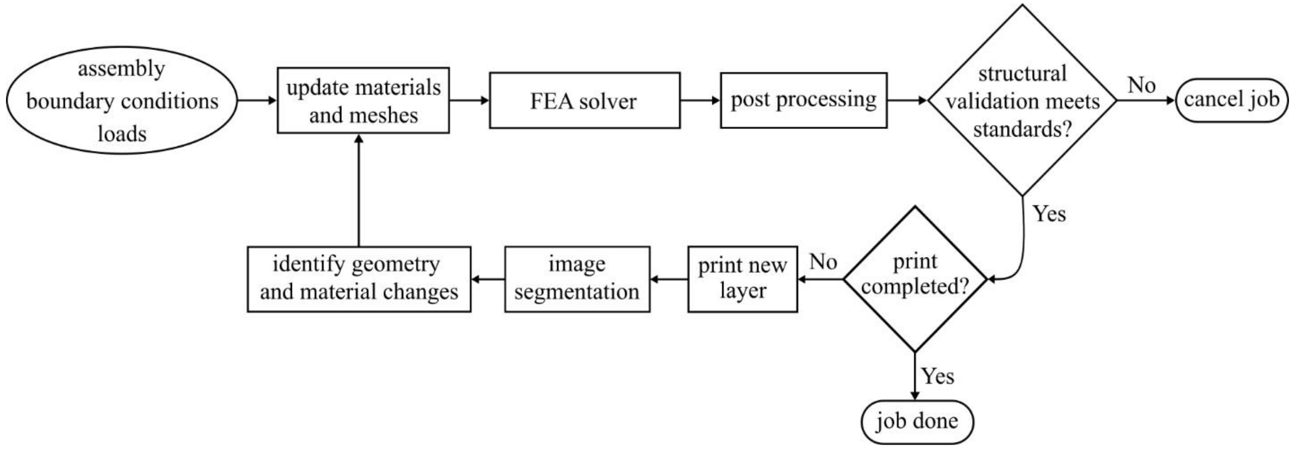
3. Digital Twin

- **Decision Maker:** Uses DT insights to issue controls
  - Actions are directed towards the physical counterpart
  - Queries are directed towards the virtual representation
- **Query/Response Loop:** The virtual representation answers targeted questions and provides predictions for informed decisions

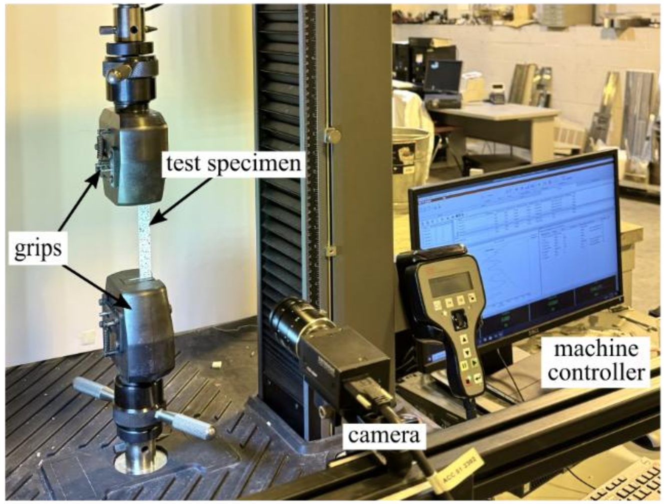


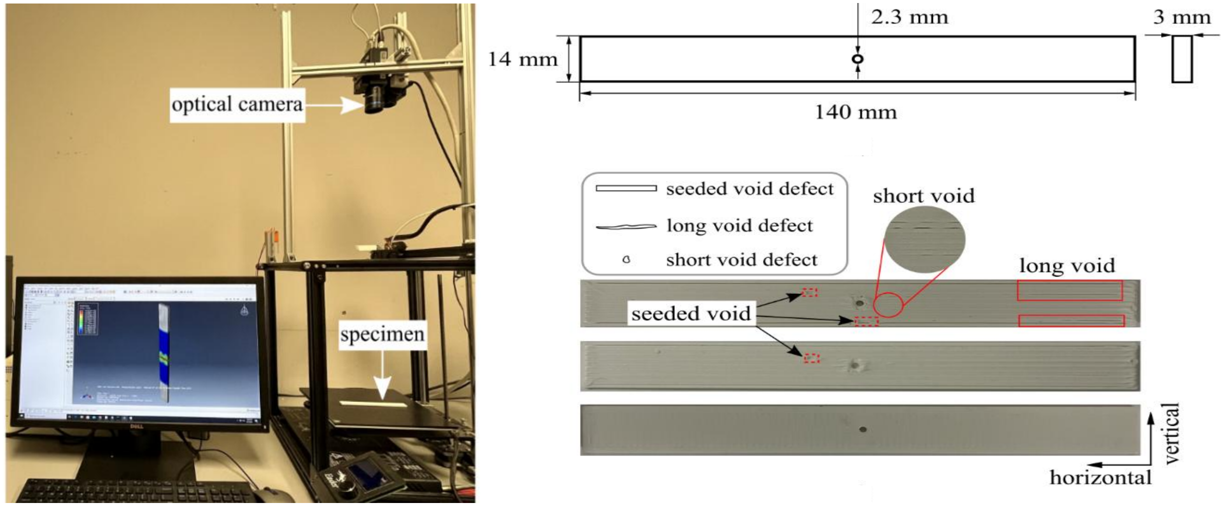
Contents

4. Model-based Simulation-in-the-loop Validation

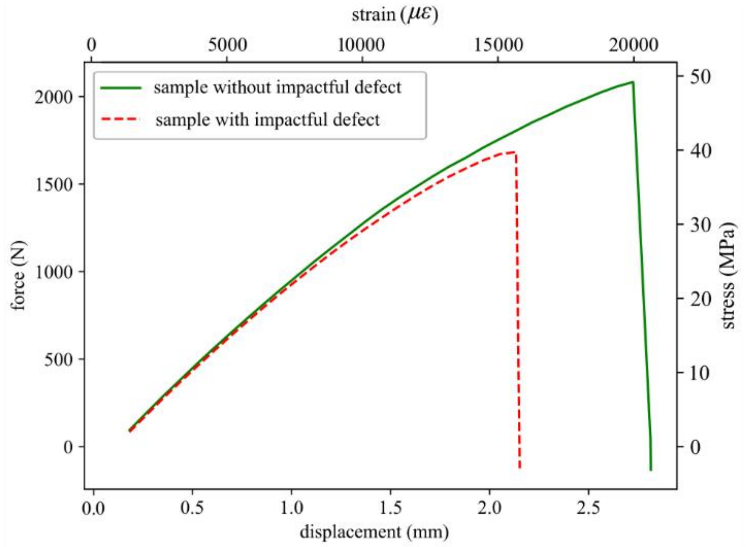


flowchart of simulation-in-the-loop validation





experiment setup and specimen with defect



experiment setup and specimen with defect

1. **Fu, Y.**, Downey, A. R., Yuan, L., Huang, H. T., & Ogunniyi, E. A. (2025). **Additive Manufacturing**, 98, 104631.

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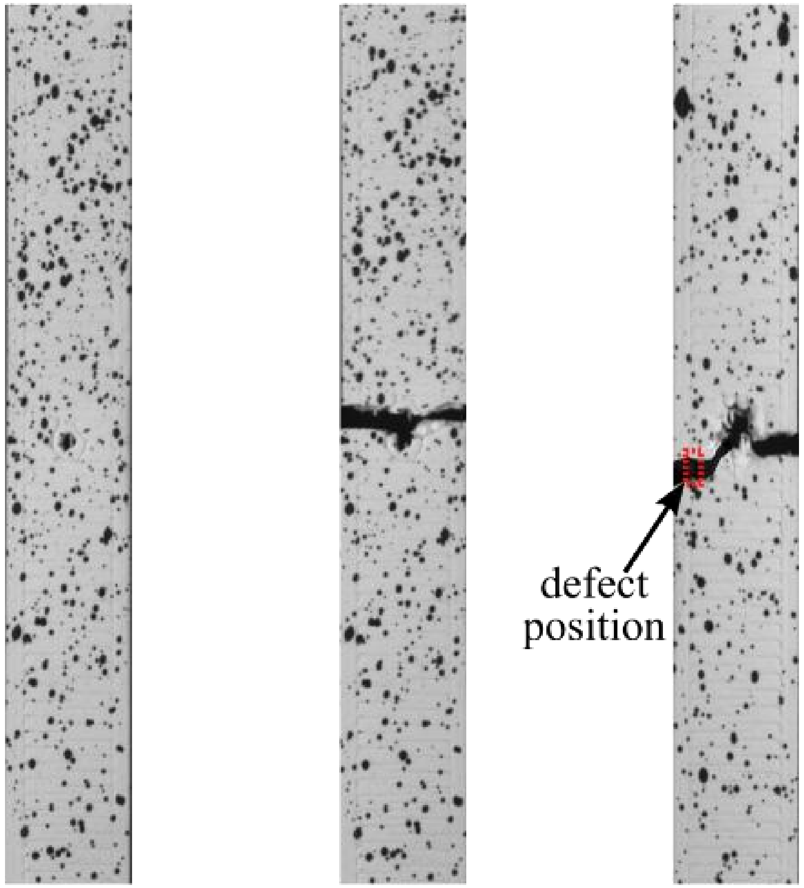
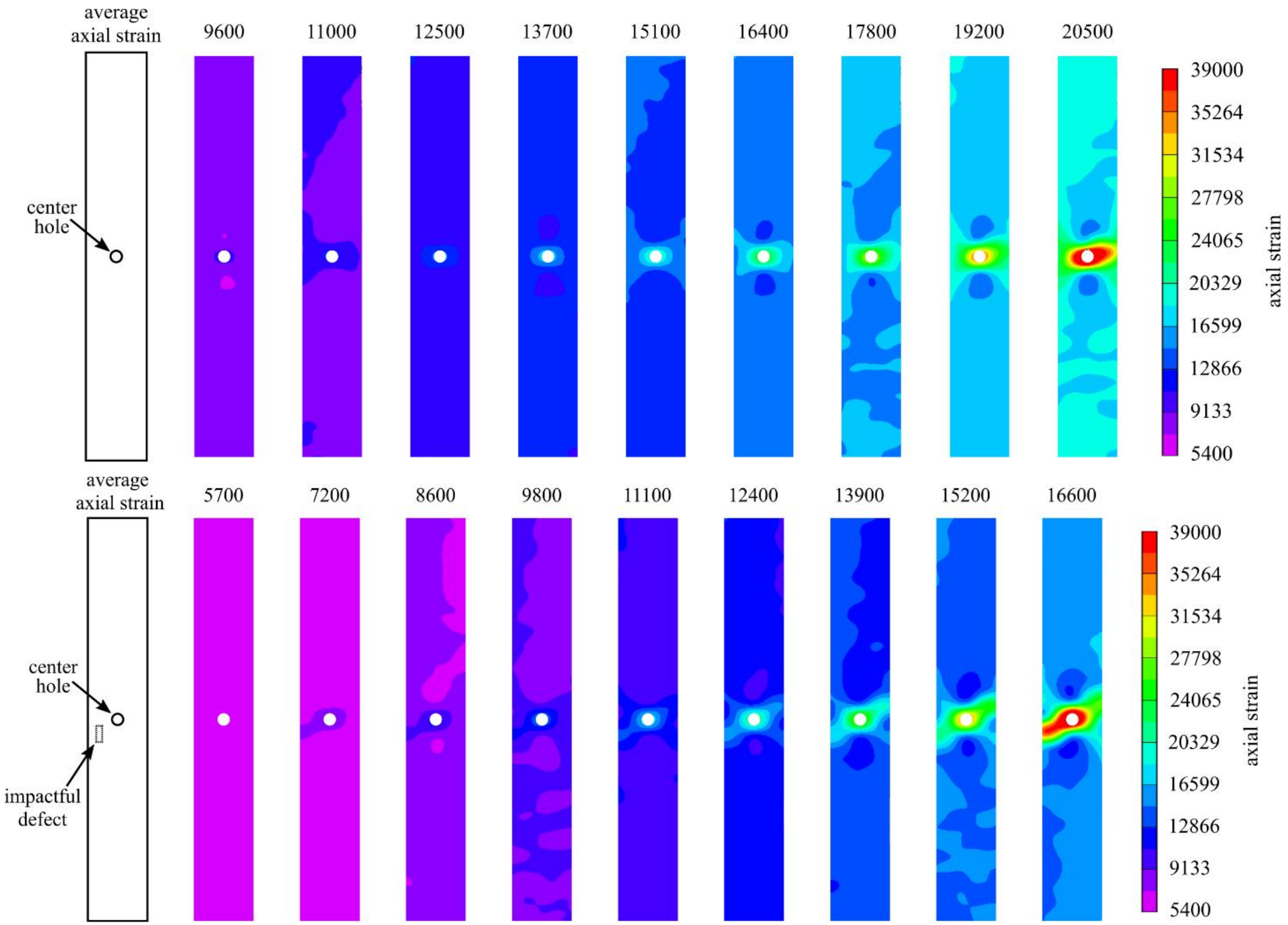


speckled specimen



DIC results for specimen without and with defect

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4. Model-based Simulation-in-the-loop Validation

Table 1
Tensile and DIC test results with stress and strain difference.

Specimen	Test type	Number of samples	Averaged strain (με)	Strain standard deviation	Strain difference (με)	Averaged stress (MPa)	Stress standard deviation	Stress difference (MPa)
Without impactful defect	Tensile test	10	19 600	80.10	–	49.59	0.24	–
Without impactful defect	DIC test	10	20 500	86.32	900	50.61	0.28	1.02
With impactful defect	Tensile test	10	15 528	91.45	–	40.10	0.37	–
With impactful defect	DIC test	10	16 600	102.96	1072	41.43	0.43	1.33

Table 2
Material property from tensile stress–strain for FEA.

Property	Density (g/mm^3)	Young's modulus (MPa)	Poisson's ratio	Strain at UTS (με)	Ultimate Tensile Strength (UTS) (MPa)
Value	1.36	3000	0.36	19 600	49.59

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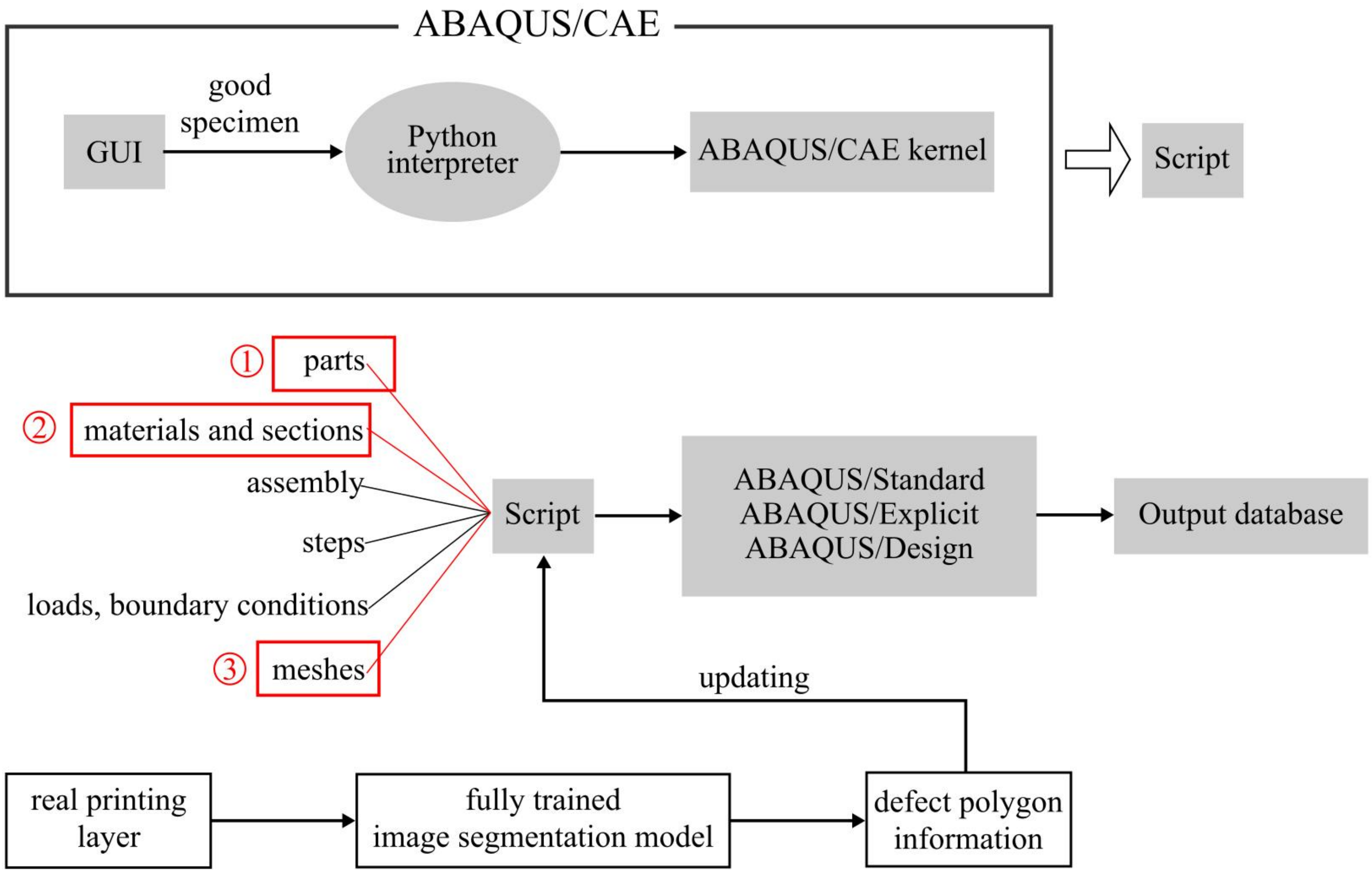

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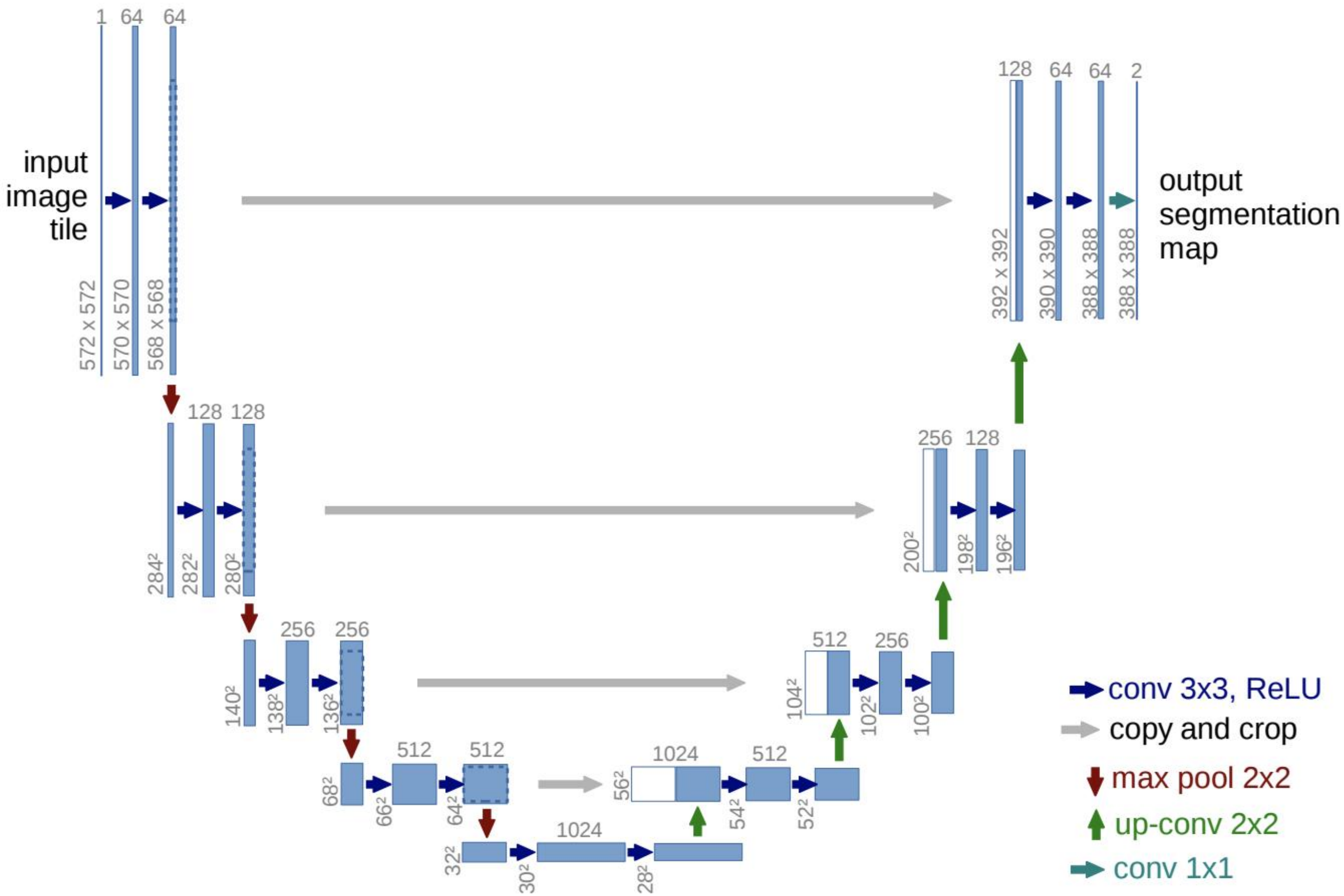

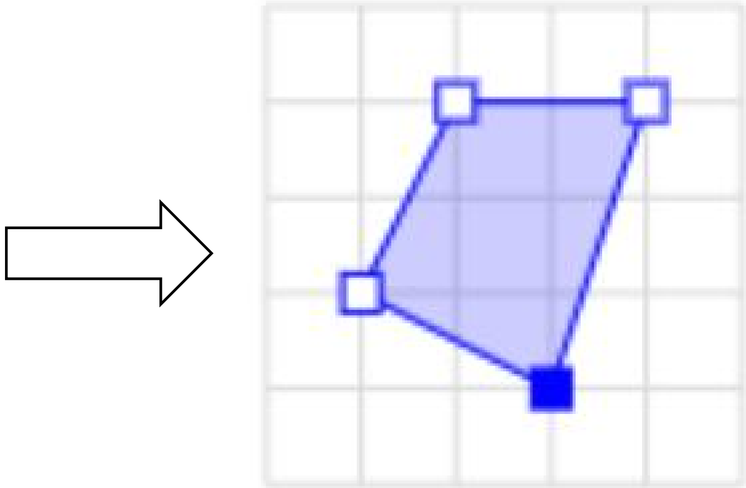

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4. Model-based Simulation-in-the-loop Validation

```
from part import *
from material import *
from assembly import *
from load import *
from mesh import *
from optimization import *
from job import *
from sketch import *
mdb.models['Model-1'].ConstrainedSketch(name='__profile__', sheetSize=200.0)
mdb.models['Model-1'].sketches['__profile__'].Line(point1=(0.0, 0.0), point2=(
    0.0, 30.0))
mdb.models['Model-1'].sketches['__profile__'].Line(point1=(0.0, 30.0), point2=(
    15.0, 30.0))
mdb.models['Model-1'].sketches['__profile__'].Line(point1=(15.0, 30.0), point2=
    (15.0, -25.0))
mdb.models['Model-1'].Part(dimensionality=THREE_D, name='Dogboen_test', type=
    DEFORMABLE_BODY)
mdb.models['Model-1'].parts['Dogboen_test'].BaseSolidExtrude(depth=5.0, sketch=
    mdb.models['Model-1'].sketches['__profile__'])
mdb.models['Model-1'].Material(name='PLAMaterial')
mdb.models['Model-1'].materials['PLAMaterial'].Density(table=((7.8e-09, ), ))
mdb.models['Model-1'].materials['PLAMaterial'].Elastic(table=((210000.0, 0.3), ))
mdb.models['Model-1'].materials['PLAMaterial'].Plastic(table=((770.0, 0.0), (
    800.0, 0.01), (830.0, 0.02), (850.0, 0.1), (900.0, 0.15), (930.0, 0.35), (
    960.0, 1.0), (1050.0, 3.0)))
mdb.models['Model-1'].rootAssembly.Set(cells=
    mdb.models['Model-1'].rootAssembly.instances['Dogboen_test-1'].cells.getSequenceFromMask(
    ('[#8 ]', ), ), name='Set-1')
mdb.models['Model-1'].EncastreBC(createStepName='Step-1', localCsys=None, name=
    'BC-1', region=mdb.models['Model-1'].rootAssembly.sets['Set-1'])
mdb.models['Model-1'].parts['Dogboen_test'].generateMesh()
mdb.models['Model-1'].rootAssembly.regenerate()
mdb.Job(activateLoadBalancing=False, atTime=None, contactPrint=OFF)
mdb.jobs['TensileTest'].submit(consistencyChecking=OFF, datacheckJob=True)
```

Module import

Creat sketch object

Draw model sketch

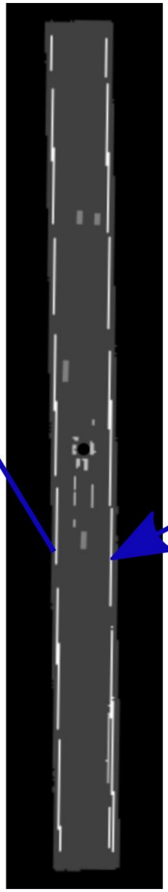
Creat model

Extrude sketch

Property setting

Boundary condition setting

Job submitting




```
"annotations": [
    {
        "id": 125686,
        "category_id": 2,
        "iscrowd": 0,
        "segmentation":  [164.81, 417.51, 164.81, 444.46]
        "image_id": 242287,
        "area": 42061.80340000001,
        "bbox": [19.23, 383.18, 314.5, 244.46]
    },
```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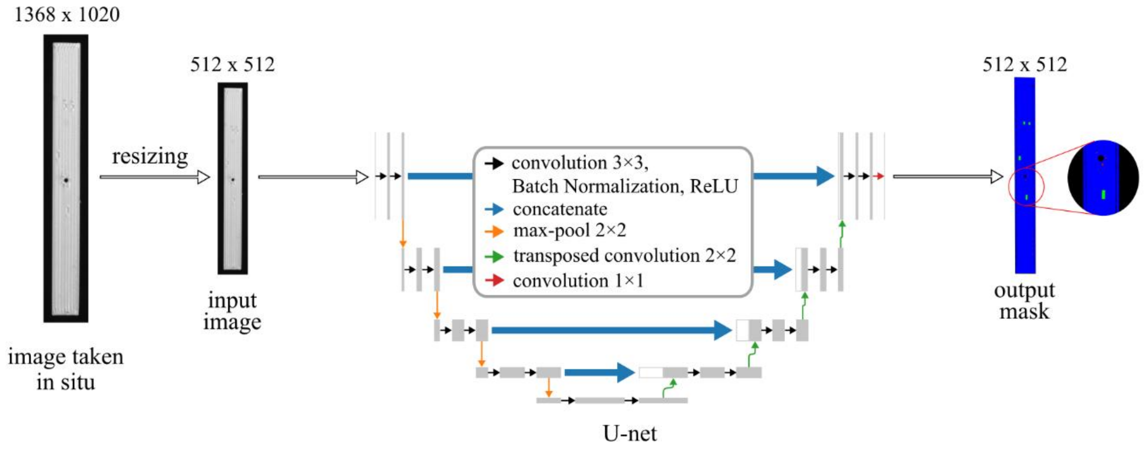
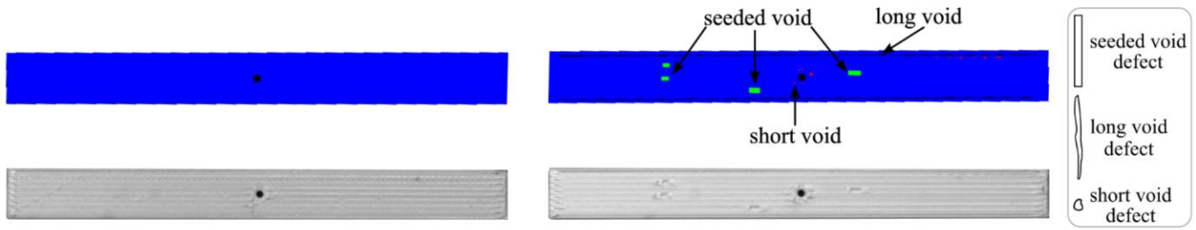
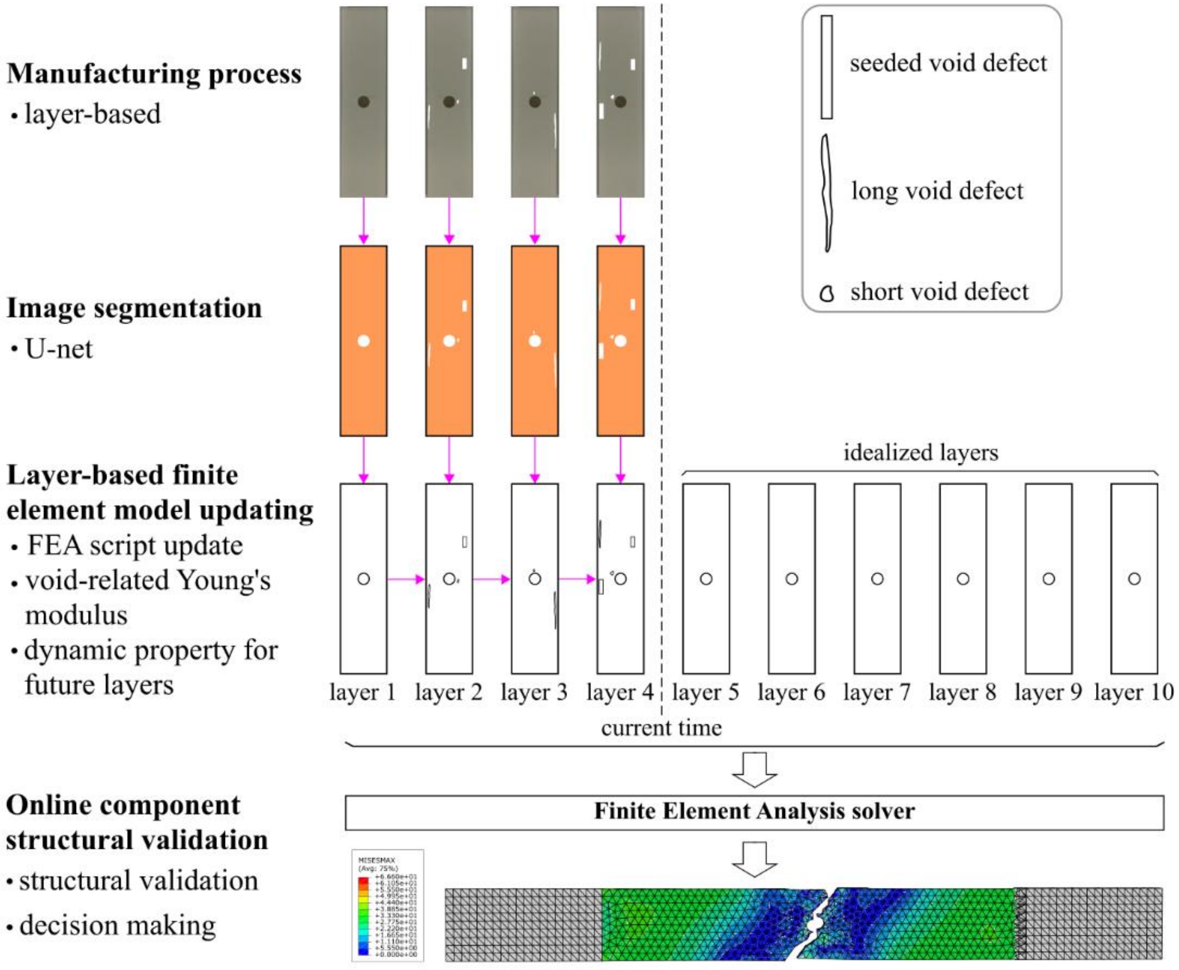


U-net for defect segmentation



defect segmentation result



process of real-time simulation-in-the-loop validation

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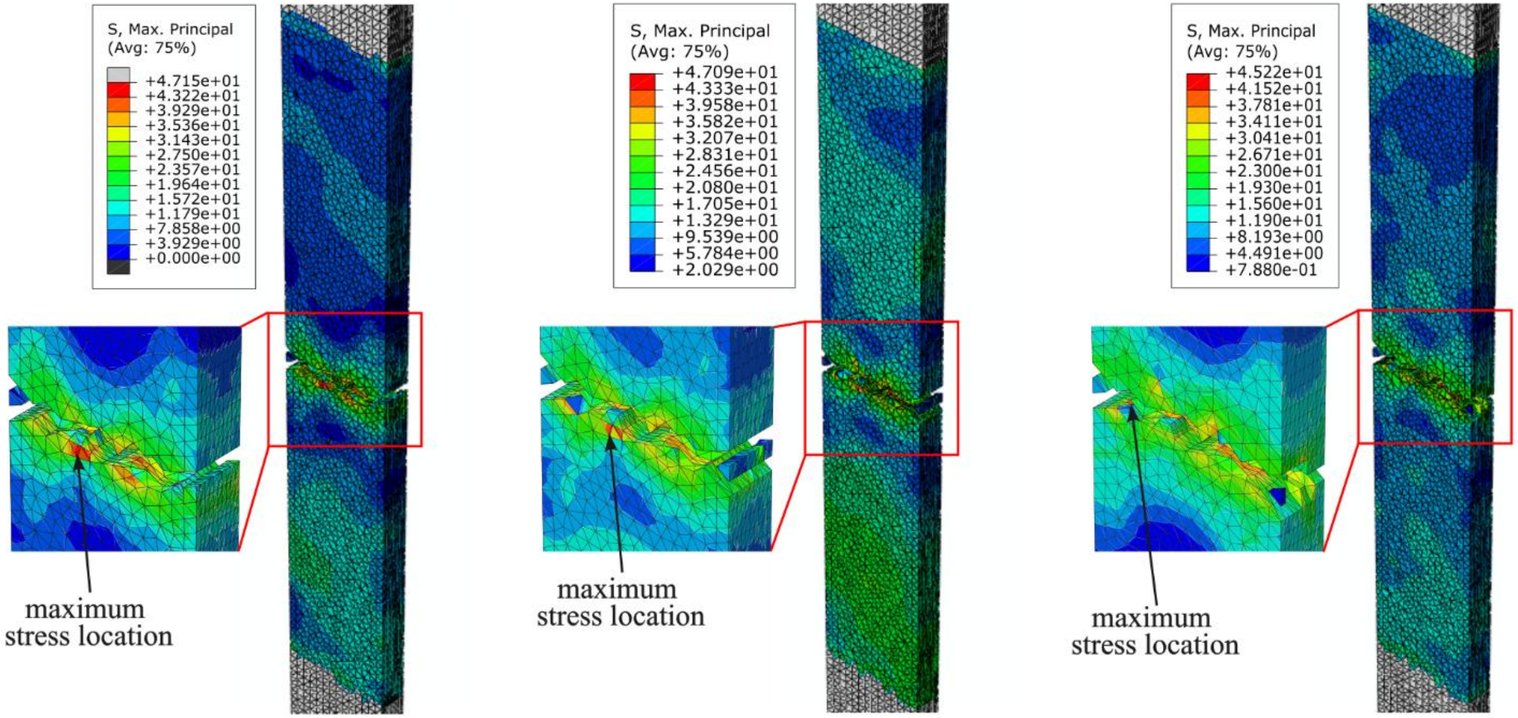
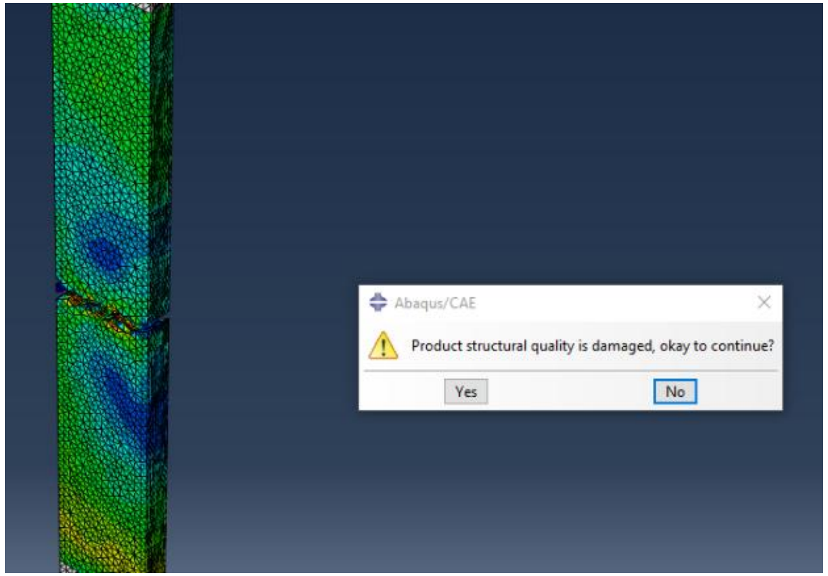


FEA simulation results



cancelation alert

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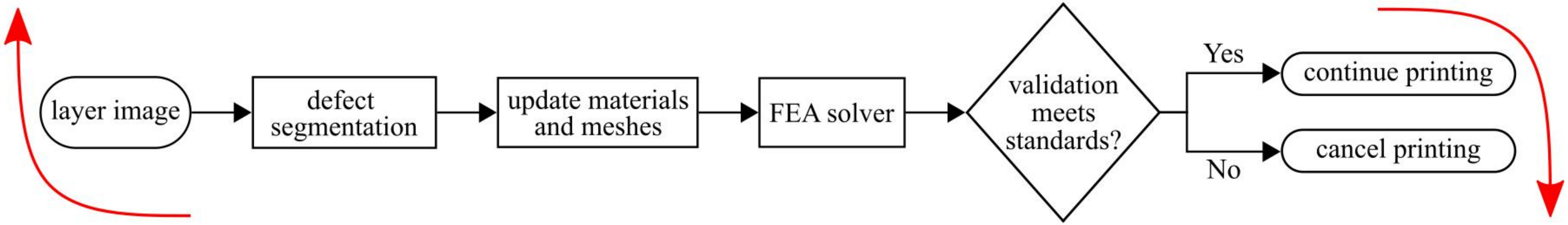

Table 3
System configurations for the real-time computational time calculation.

Hardware	System 1	System 2	System 3
Processor	Intel core i7-3770	AMD Ryzen Threadripper 3970X	Intel Xeon Gold 6250
Number of processor	1	1	2
Total core count	4 cores, 8 threads	32 cores, 64 threads	16 cores, 32 threads
Base clock speed	3.4 GHz	3.7 GHz	3.9 GHz
RAM	8 GB	128 GB	96 GB
Operating system	Windows 10, 64 Bit	Windows 10, 64 Bit	Windows 10, 64 Bit

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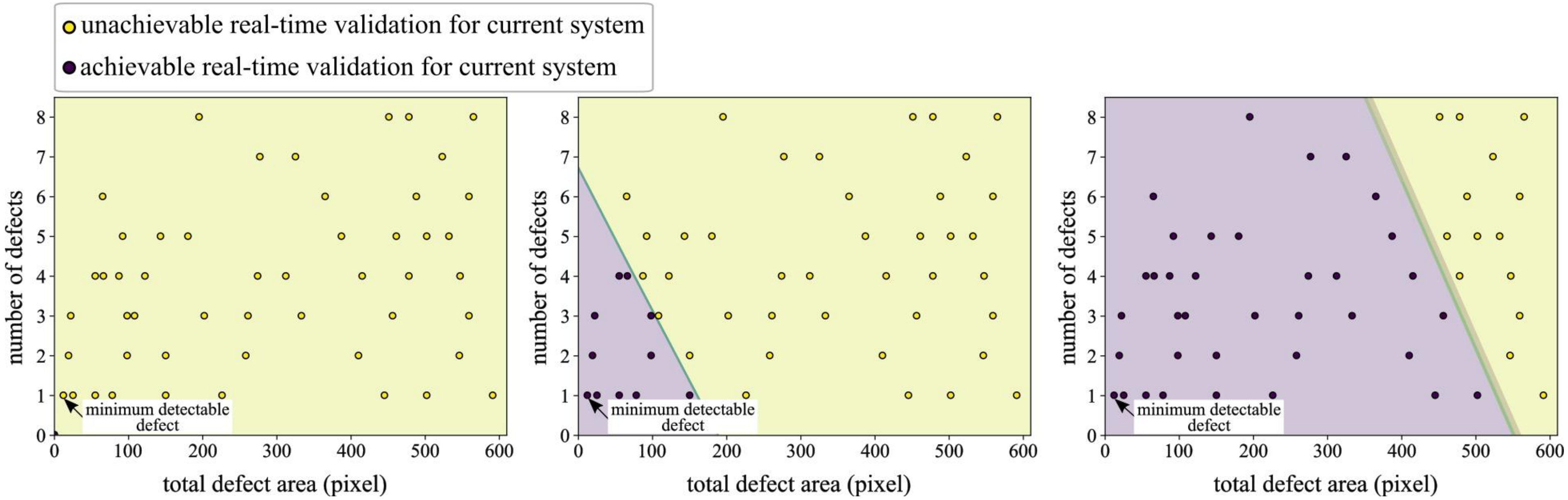

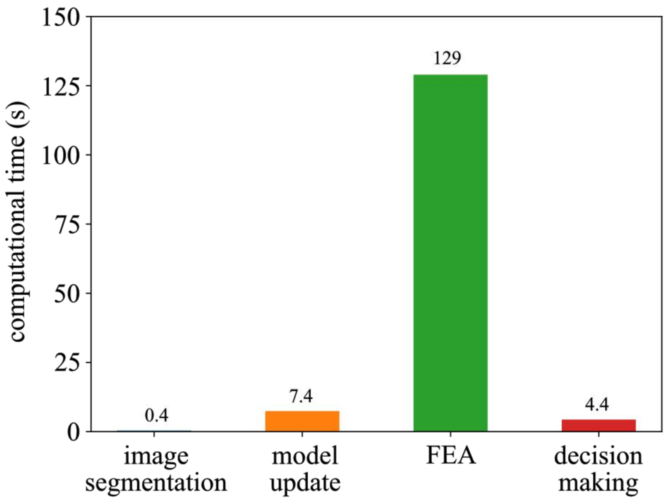

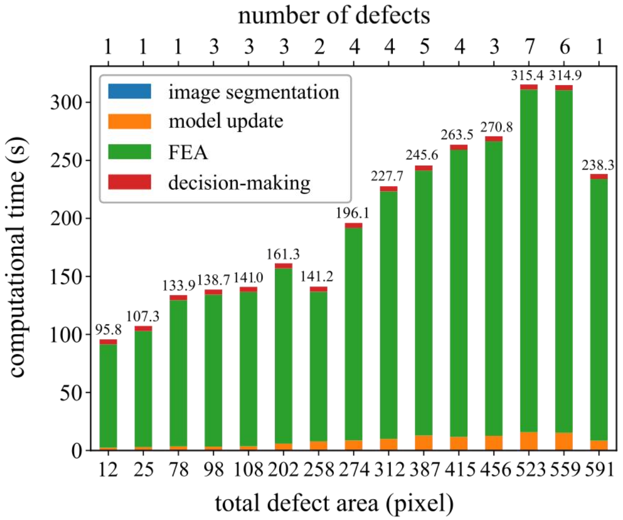

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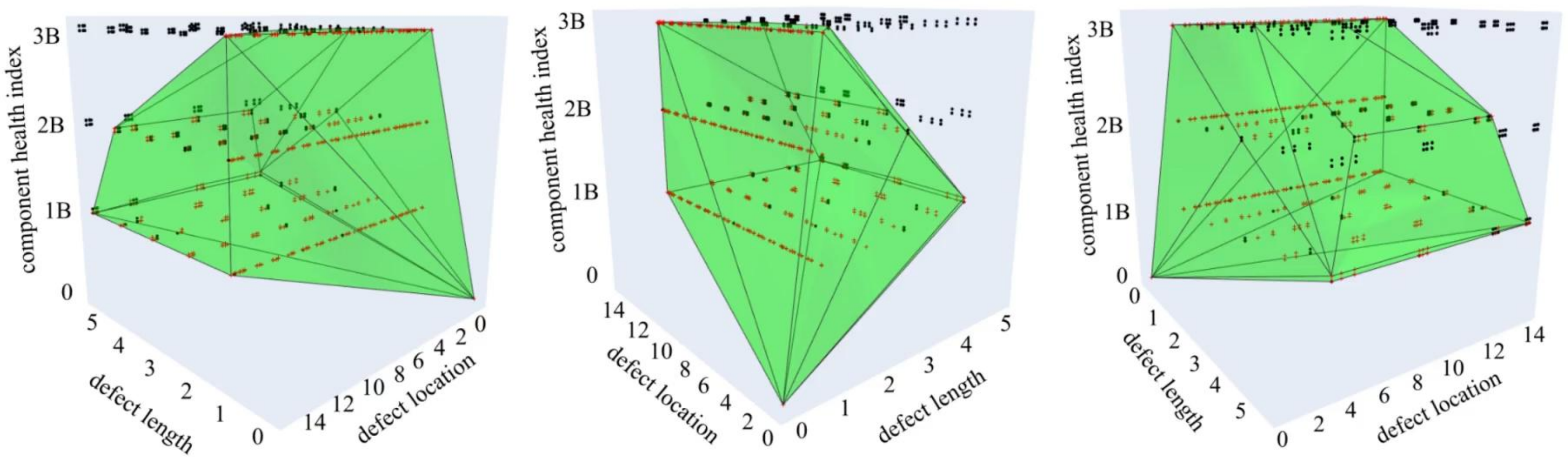
Contents

5. Data-driven Real-time Structural Validation

Real-time Product Structural Quality Validation for Material Extrusion Additive Manufacturing



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Discussion

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