

## 1. Introduction

Micro computed tomography or micro-CT or XCT is x-ray imaging in 3D. It uses similar technology as medical CT scans (or CAT scans). **However, XCT is for small scale objects with significantly increased resolution (in the order of microns).** It is equivalent to 3D microscopy, where fine scale internal structures are imaged non-destructively. It doesn't involve any sample preparation, staining, thin slicing or gold coating. A single scan captures multiple images (in the order of 1000s) of the sample's internal 3D structure at a very high resolution. Spatial resolution (voxel) can be in the order of micrometre. **Fig. 1** shows the XCT setup at the Department of Engineering.



**Fig. 1.** XCT setup.

In a hospital CT, the patient (sample) is held fixed while the detector rotates taking images from different angular positions. In a lab XCT, **the sample rotates and the detector is held fixed**, which reduces the size and simplifies operation of the machine as rotating the bulky detector is cumbersome.

## 2. Objectives

- Acquire XCT images and construct 3D models and obtain 2D slices.
- Perform Single Edge Notch Bend (SENB) experiments with an octet truss lattice. *Post processing can be conducted on a personal computer using a standard CT visualisation software (open source) like myVGL. (Hardware requirement: min 8GB RAM)*
- Run FE calculations in Abaqus and compare results with experiments.

### 3. Working

A micro-focus x-ray source illuminates the sample and a planar x-ray detector collects magnified projection images (Fig. 2). Based on thousands of angular views acquired while the sample rotates, a computer synthesizes a stack of virtual cross section slices through the object. We can then scroll through the cross sections, interpolating sections along different planes, to inspect the internal structure. Selecting simple or complex volumes of interest, we can measure 3D morphometric parameters and create realistic visual models for virtual travel within the object. X-rays travel in straight lines like light but optical lenses cannot be used for magnification. So, magnification is increased by moving the sample closer to the X-ray.

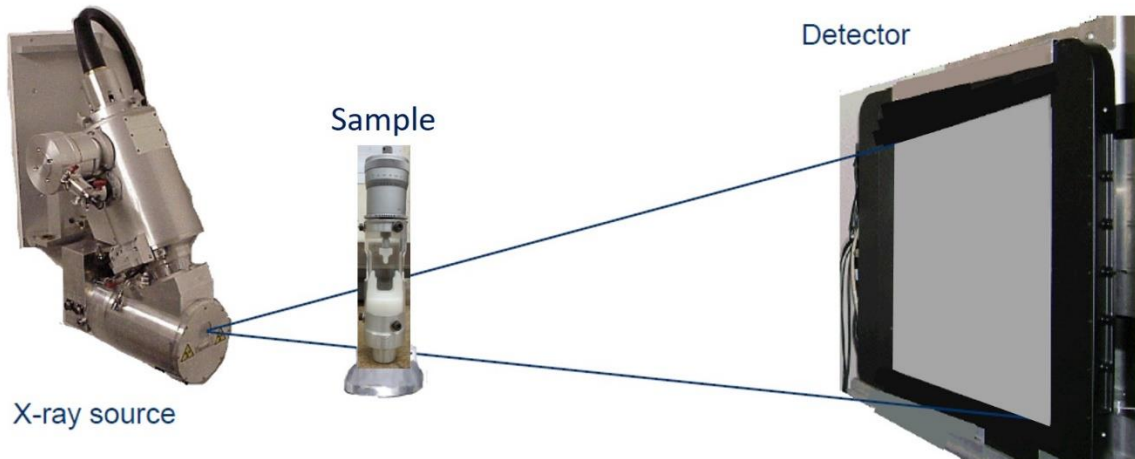


Fig. 2. Schematic for XCT imaging.

### 4. Experiments

#### a. Experiment setup

A manually operated fixture is fabricated according to ASTM standards for Single Edge Notch Bend (SENB) experiments (Fig. 3). It is designed to support specimens with a support span of 30 mm. Mounted with a dial-gauge from the top, displacements up to 5 mm can be loaded. Ideal for soft materials like polymers, unsuitable for metals. See Fig. 4.

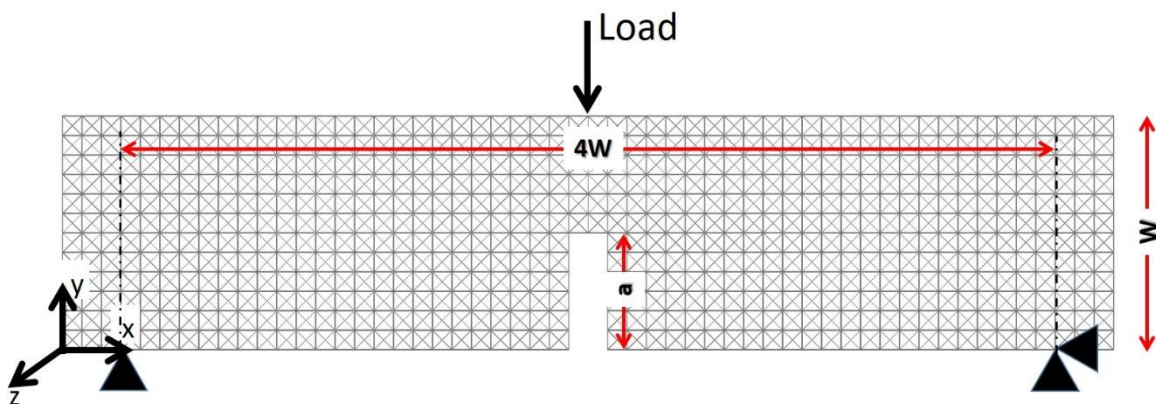


Fig. 3. ASTM standard specimen for SENB experiment.

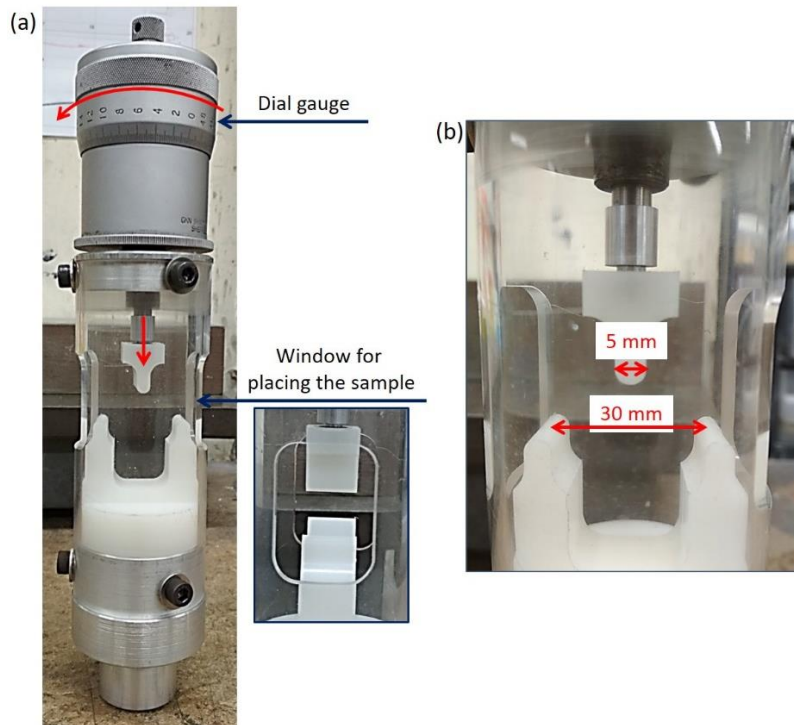


Fig. 4. Fixture for SENB experiments. The acrylic perspectives do not absorb x-rays.

*In the following sections, most of the figures are provided as a Supplementary Information (SI). This is because, they require annotations and observed to be more appropriate as a standalone document with larger dimensions and font sizes.*

### b. Acquisition of CT scans

The specimen is gently placed in the fixture and the dial gauge is turned for the top support to just press the specimen (Fig. 5). This is no load condition. The fixture loaded with the specimen is placed inside the XCT machine and shall remain in the chamber until the completion of all experiments.



Fig. 5. Loading the specimen (here, no load condition).

System is turned ON and the interface is shown in **Pages 3-4** (Supplementary Information, SI).

The specimen is turned 360 degrees to ensure that it remains within the frame of observation for all rotations. Region of interest (ROI) is set around the specimen. Then, brightness and contrast are adjusted focussing on the surface layer. The inner layers can remain out of focus. The following settings are applied in the 'Position and Optimise' tab:

Beam energy: 55 kVA

Beam Current: 130  $\mu$ A

Voxel size: 30x30x30  $\mu$ m. All other settings are set to default. Press 'Scan'. *Nearly 1 hour is required for acquiring 3000 images.*

## 5. Post-processing

### a. Construction of 3D model

The detailed procedure for constructing the 3D model from raw files is explained in SI (**Pages 6-15**).

All adjustments are available in the 'Tool Dock'. Two of the key features are: **Opacity curve** and **Isosurface Threshold line**. Opacity curve is moved to adjust the contrast of the 2D curve whereas the red Isosurface Threshold line is for 3D model. The opacity curve changes the contrast of the voxel grey values in the 2D views. The Isosurface Threshold changes the location of the surface rendering in the 3D view only.

Furthermore, the use of clipping box is explored (**Pages 16-22, SI**). A clipping box is taken around the crack tip. The unit cell type and orientation are identified (Octet lattice- **Page 22, SI**).

### b. Taking 2D projections/slices

In addition to 3D explored view, 2D slices are also important in XCT studies. In fact, medics consider CT slices for investigation. In the present experiments, 2D slices are taken at the midsection along the thickness and near crack tip (**Pages 23-26**). It reveals condition of the struts in the lattice for a given layer. Results can be qualitatively compared with FE calculations.

The above procedure is repeated for the loaded specimen (**Pages 27-31**) and the crack tip condition is continuously monitored in each case.

## 6. FE calculations

- **Simulations**

A Matlab script is used to generate the octet truss lattice. **Orientation of the unit cell must be same as that of the experimental specimen (Page 22, SI)**. The same Matlab file generates the input file required for calculations in Abaqus. Number of unit cells along x, y and z directions are set to  **$n_x = 27$ ,  $n_y = 6$ , and  $n_z = 3$** . Unit cell size set as,  **$L = 1.93$  mm**. Strut diameter,  **$D = 0.23$  mm**. **Material elasticity,  $matEs = 430$  MPa and Poisson ratio,  $\mu = 0.45$** .

Calculate relative density using eq. 1,

$$\bar{\rho} = 6\sqrt{2}\pi \left(\frac{a}{l}\right)^2 \quad (1)$$

where, a and l are the radius and length of a strut, respectively. Relative density is calculated as **0.189**.

Boundary conditions (for three point bending) are shown in Fig. 5. and displacements are provided in steps of 0.5 mm, similar as the experiments.

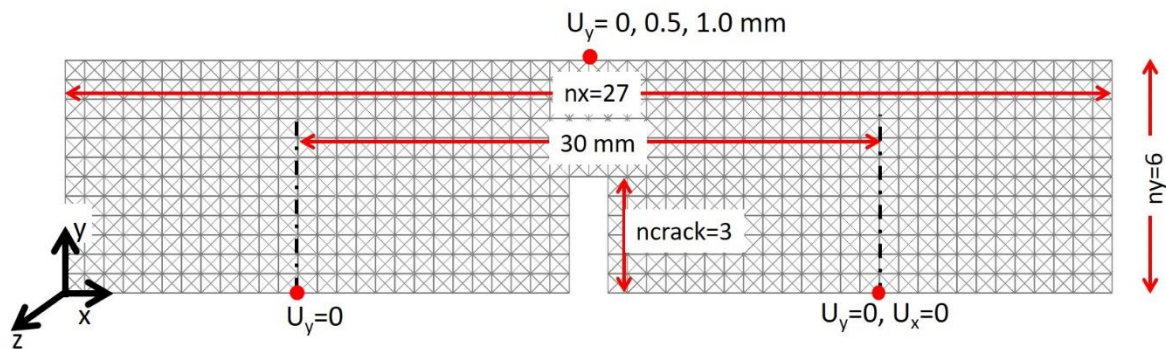


Fig. 6. Boundary conditions used in the simulation.

- **Results**

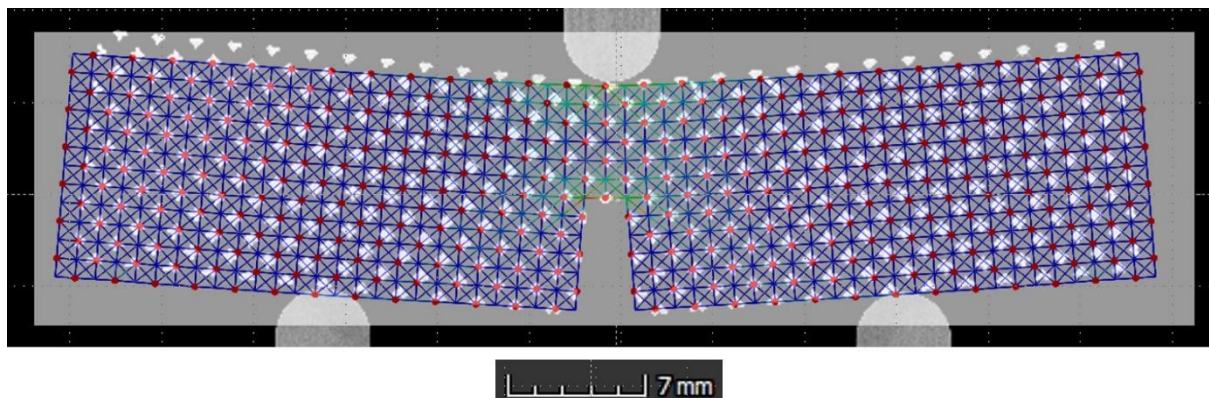
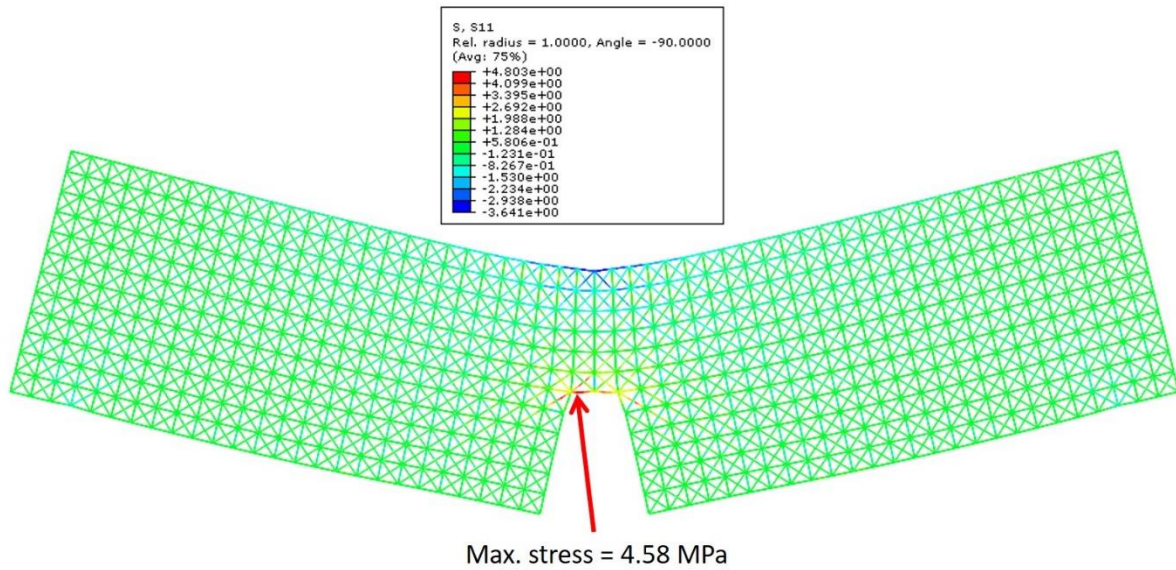


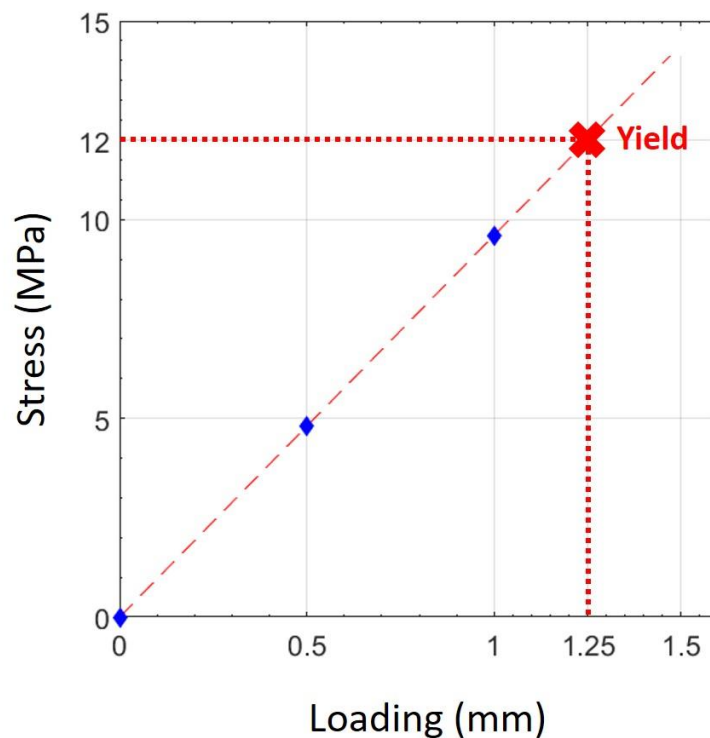
Fig. 7. Simulation results superimposed on CT slice (at the mid-plane, loading = 1 mm).

A slice is taken at the midplane showing only the planar nodes. Result from simulation is superimposed (Fig. 7). Although the simulation and experimental results do not exactly match, it can be a good qualitative comparison. The deviation can be due to use of beam elements in the simulation which neglects the finite dimension of nodes. Stress at the nodes can be included using a solid mesh instead of beam elements.



**Fig. 8.** Axial stresses (S11) in individual struts for an applied loading of 0.5 mm.

Stresses developed in the individual strut members cannot be evaluated from CT experiments. However, knowing the elastic properties of the truss material, stresses can be calculated. **Fig. 8** shows the stresses for 0.5 mm loading. The maximum stress is at the crack tip and its magnitude is calculated for different loadings. See **Fig. 9**. The material yield strength is given as ~12 MPa. It can be seen from the plot that the applied maximum load (1 mm displacement) develops a maximum stress of ~10 MPa. The crack tip failure shown in **Page 31, SI** is due to loading above 1.25 mm.



**Fig. 9.** Variation of maximum stress with loading (in displacement, mm).

## 7. Conclusion

3D models are developed from XCT scans taken at the initial no-load and different loading conditions. Isosurface threshold and opacity are the major adjustments to obtain crisp images. The truss is identified as an octet truss lattice of unit cell size  $\sim 1.93$  mm. Given the material properties, FE calculations predict similar deflection results as experiments. The material yields at  $\sim 12$  MPa and the specimen is loaded below the failure point. The failure loading ( $\sim 1.25$  mm) is predicted from FE calculations.