CADEM0019 Artificial Intelligence Applications in Structures and Materials

Coursework – 2025

AI driven Modelling and Optimisation of a Cantilever plate.

Deadline	*Monday 08/12/2025*
Marks	*100 (100% of total course mark)*
Submission	*Blackboard*
Expected time to Complete	*20 Hrs*

Your submission should consist of the following:

- 10 Pages technical report excluding a title page, covering your answers for Q1 – Q4.
- Jupyter notebooks: including your source codes, with detailed markdown, and figures for the surrogate model and optimisation tasks.

In this coursework, you are provided with a dataset for the mechanical response of a cantilever plate under combined loading, *Figure 1*. The dataset consists of the thickness distribution across the plate as input, and the von-misses stresses distribution from each element from an FEA model as output. It is required that you utilise your knowledge of surrogate modelling and optimisation to identify the optimal thickness distribution for this plate, which reduces the plate weight, while satisfying the design constraints. Additionally, using your knowledge of digital twining, you will design a monitoring system to capture the plates performance in service.

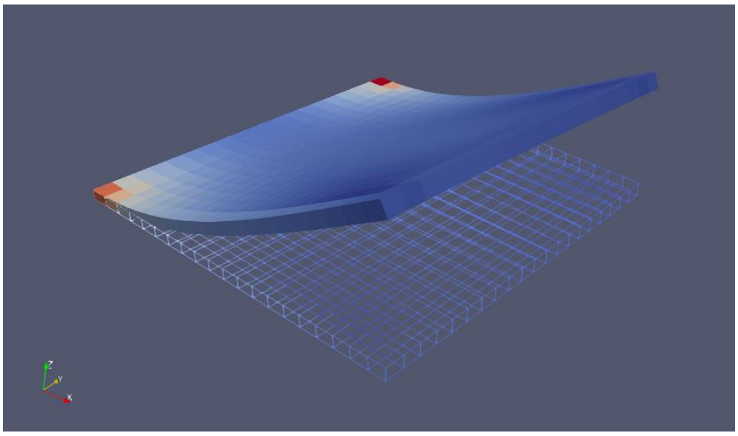

Figure 1 An example variable thickness plate under combined loading.

Table 1 Plate Properties

Young Modulus	72 GPa
Poisson Ratio	0.3
Yield	250MPa
Width	2 m
Length	2 m
Traction Load in X	0.1 N/m
Traction Load in Y	0.1 N/m

Design Criteria

Your final design should satisfy the following criteria:

- Minimize the plate weight
- No-Yield is allowed anywhere in the plate

Using Python and TensorFlow carryout the following tasks:

Q1. [15 Marks] - Exploratory Data Analysis (EDA): Create a data pipeline which reads the dataset and stores it in a format suitable for machine learning. Conduct an EDA with purpose of identifying and excluding any outliers in the dataset. Include an explanation of your EDA results in the technical report.

Q2. [30 Marks]- Surrogate Modelling: Identify a surrogate modelling strategy which can link the plate thickness distribution to the von-misses stresses. In your report:

- **A.** Explain the reasoning behind choosing this modelling approach. Were there any other models that could have worked.
- **B.** Provide model training and validation results, indicating and justify your choice of validation approach.
- **C.** Explain how you employ your knowledge of materials and structures to investigate the model robustness.

Q3 - Optimisation

Q3.1 [20 Marks] - Beam Optimisation:

A customer has approached you to design and optimise a cantilever **rectangular hollow section beam** subject to a tip load. The customer team has defined the objective and problem constraints, as outlined below.

The aim is to **minimize the mass** of the beam while ensuring that it satisfies stress, displacement, and geometric constraints.

The beam is modelled as a simple **cantilever of length** $L = 1$ meter, made of aluminium alloy with **Young's modulus** $E = 70\ GPa$, and **yield strength** $\sigma_y = 250\ MPa$. A load of $P = 1000\ N$ is applied at the free end. The team is only interested in the beam's static response, and has informed you that using Euler-Bernoulli Beam theory (https://en.wikipedia.org/wiki/Euler%E2%80%93Bernoulli_beam_theory) will be sufficient for this preliminary design study.

The design variables define the beam rectangular hollow cross-section:

- b: outer width [m] must be within the range [0.001,0.05]
- h: outer height [m] must be within the range [0.001,0.06]
- t: wall thickness [m] must be within the range [0.00001,0.1]

Constraints:

- The bending stress (i.e. axial stress caused by bending) at any point along the beam must be less than the yield strength
- The beam tip displacement should be less than $0.07m$
- The wall thickness must not lead to negative area $h - 2t > 0$ and $b - 2t > 0$
- Geometric constraint: $h - 2b > 0$
- Thickness ratios: $t < h/20$ and $t < b/20$

It is your job to try and satisfy the customer's needs, to the best you can, and recommend / advice the customer on the results achieved and how to potentially improve them. In your report, you should at least show:

A. Your choice for the optimisation problem formulation, and the reasoning behind it.

B. A diagram/figure of the cross-section and the definition of the design variables.

C. Your numerical implementation of the optimization, i.e. your code. You can use existing optimisation toolboxes.

D. If you chose numerical gradient calculations, then show how the gradient quality change with the change in finite difference steps and recommend a step size. If, otherwise, you use analytical gradients make sure to include their derivations and validate them against numerical gradients.

E. A couple of convergence history from different starting points, and the best design found each time.

F. A couple of plots showing the design space and constraints. The way to best show this is up to you, but since you have three variables you could consider using multiple 2D slices to explain the behaviour of the optimiser.

G. A discussion regarding the best design found, and the overall problem as it has been given to you.
H. Suggestions, to the customer, on how the improve/change the design problem, and what would the new optimal design be.

Q3.2 [**15 marks**] **– Surrogate Model Optimisation**

Identify a suitable strategy to optimise the surrogate model of the plate you generated in **Q2**, minimising mass while satisfying the stress design criteria. You are tasked with running four different optimisation studies:

A. **Constant thickness design** - Find the best plate design assuming the plate thickness must be constant, i.e. all your elements must have the same thickness.
B. **Corner-point interpolation design** - Find the best plate design assuming the plate thickness is represented by a surface/grid. Use four design variables, representing the thickness at the four corner points of the plates. Then for all other elements, perform a 2D linear interpolation of the corner point values (use existing function for interpolation).
C. **5×5 grid interpolation design** - Find the best plate design assuming the plate thickness is represented by a 5x5 surface/grid. This time, use 25 design variables, representing the thickness of the plate using a 5x5 uniformly spaced grid over the plate's geometry. Then, perform a 2D interpolation of the surface values to find the element thickness (use existing function for interpolation).
D. **Full-variable design** - Lastly, perform an optimisation using all thicknesses as design variables.

For each case, explain/detail the following in your report:

- The optimisation problem formulation chosen, and the reasoning behind it.
- The optimisation method of choice and the reasoning behind this method.
- A description of the optimisation results and the optimal design.
- Explain how you employ your knowledge of materials and structures to ensure that the optimal solution is a reasonable design for this problem.

Q4. [20 Marks]- Digital Twining: Consider the cantilever plate as part of a larger engineering structure, such as an aircraft wing. In this context, the plate is monitored via a digital twin and real-time sensor data is available, describe the following in no more than 2-pages:

A. Suggest what types of sensors (e.g. strain, displacement, vibration) you would place on the plate to monitor its behaviour as part of a wing and justify their locations.

B. Explain how AI could use the sensor data to detect early signs of damage or degradation.

C. How could this information feedback to update the surrogate model and support maintenance decisions?

D. Discuss practical considerations for deploying this AI-based system in engineering workflows

E. How would you ensure interpretability and transparency of the AI predictions, especially for safety-critical decisions?
Highlight any ethical or safety issues related to relying on AI for structural monitoring and maintenance.

Dataset description

- A set of Finite Element Analysis models were run using Latin Hyper Cube sampling for plates with varying thicknesses. The input and output from each simulation is provided in the attached dataset.
- **Input:** 2000 CSV files each storing a 20X20 Matrix containing the plate thickness (in meters) at each location in X and Y directions. See Figure 2
- **Output:** 2000 CSV files each storing a 20X20 Matrix containing the Von-Misses stress (in MPa) at each location. See Figure 3
- The dataset is avaliable for download in the same folder as this coursework document.

Y/X	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050
2	0.048	0.048	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.050	0.050	0.050	0.050	0.050	0.050	0.050
3	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049
4	0.047	0.047	0.047	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.049	0.049	0.049	0.049	0.049
5	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048
6	0.046	0.046	0.046	0.046	0.046	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.048	0.048	0.048	0.048
7	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047
8	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.047	0.047
9	0.044	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.046	0.046	0.046	0.046	0.046	0.046	0.046
10	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045
11	0.043	0.043	0.043	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.045	0.045	0.045	0.045	0.045
12	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044
13	0.042	0.042	0.042	0.042	0.042	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.044	0.044	0.044
14	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043
15	0.041	0.041	0.041	0.041	0.041	0.041	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.043	0.043
16	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.042	0.042	0.042	0.042	0.042	0.042	0.042
17	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.042
18	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.041	0.041	0.041	0.041	0.041	0.041	0.041
19	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.041
20	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.040	0.040	0.040	0.040	0.040	0.040	0.040

Figure 2. Example input file showing the thickness distribution of the cantilever plate

X/Y	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	149.4	55.5	60.1	63.6	61.6	57.5	53.1	49.2	46.1	44.0	42.7	42.4	43.1	44.8	47.3	50.7	54.1	56.5	60.9	135.2
2	118.3	74.2	69.0	64.8	60.2	55.6	51.6	48.2	45.6	43.9	43.1	43.2	44.4	46.5	49.8	54.3	60.2	67.7	78.4	108.8
3	84.7	63.3	60.9	57.8	54.5	51.4	48.6	46.3	44.4	43.2	42.7	42.8	43.7	45.4	48.0	51.4	55.9	61.4	67.3	80.3
4	65.8	55.4	54.1	52.0	49.9	47.8	46.0	44.4	43.2	42.4	42.0	42.2	42.9	44.2	46.1	48.8	52.2	56.2	60.4	66.5
5	54.7	50.6	49.3	47.7	46.1	44.8	43.7	42.7	42.0	41.5	41.3	41.4	41.9	42.8	44.3	46.2	48.8	52.0	55.6	58.7
6	48.2	47.0	45.7	44.3	43.1	42.3	41.7	41.3	40.9	40.7	40.6	40.7	40.9	41.5	42.5	43.9	45.9	48.5	51.7	54.3
7	44.2	44.1	42.7	41.5	40.7	40.3	40.1	40.0	40.0	40.0	39.9	39.9	40.0	40.2	40.7	41.7	43.2	45.4	48.3	51.9
8	42.0	41.5	40.1	39.0	38.6	38.5	38.7	38.9	39.2	39.3	39.3	39.2	39.1	39.0	39.1	39.7	40.7	42.5	45.2	50.6
9	40.6	39.1	37.7	36.9	36.7	37.0	37.5	38.0	38.5	38.8	38.8	38.7	38.3	37.9	37.7	37.7	38.4	39.8	42.2	49.9
10	39.8	36.8	35.4	34.8	35.0	35.6	36.5	37.3	38.0	38.4	38.5	38.2	37.7	37.0	36.3	35.9	36.1	37.2	39.3	49.5
11	39.3	34.7	33.2	33.0	33.5	34.5	35.6	36.8	37.6	38.1	38.2	37.8	37.1	36.1	35.0	34.2	34.0	34.6	36.6	49.1
12	38.9	32.6	31.2	31.2	32.1	33.5	35.0	36.3	37.4	38.0	38.0	37.6	36.7	35.4	34.0	32.6	31.9	32.1	33.9	48.7
13	38.5	30.6	29.2	29.6	30.9	32.7	34.5	36.1	37.2	37.9	38.0	37.5	36.4	34.9	33.1	31.3	30.0	29.7	31.3	48.2
14	37.9	28.8	27.4	28.2	29.9	32.0	34.1	35.9	37.1	37.8	37.9	37.4	36.3	34.6	32.4	30.1	28.2	27.4	28.8	47.4
15	37.3	27.0	25.8	27.0	29.2	31.7	33.9	35.7	37.0	37.7	37.8	37.3	36.2	34.4	32.1	29.4	26.8	25.3	26.3	46.4
16	36.4	25.4	24.5	26.3	28.9	31.5	33.7	35.4	36.6	37.3	37.4	37.0	36.0	34.3	32.0	29.1	26.0	23.6	24.0	44.9
17	35.3	23.9	23.7	26.3	29.1	31.5	33.4	34.9	35.9	36.5	36.6	36.4	35.6	34.3	32.3	29.6	26.1	22.6	21.9	42.9
18	33.7	22.9	24.2	27.2	29.6	31.5	32.9	33.9	34.6	35.0	35.2	35.1	34.7	33.9	32.6	30.6	27.6	23.6	20.5	40.0
19	31.0	23.9	26.5	28.9	30.3	31.3	31.8	32.3	32.6	32.8	33.0	33.1	33.2	33.1	32.8	32.0	30.4	27.4	22.7	35.2
20	32.3	28.7	30.5	31.3	31.8	32.1	32.4	32.7	33.0	33.4	33.8	34.4	35.0	35.6	36.1	36.4	36.3	35.4	32.7	37.5

Figure 3 Example output file showing the Von-Misses Stress distribution over the cantilever plate