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NUMERICAL STUDY OF A MULTI- LAYERED STRAIN SENSOR FOR STRUCTURAL HEALTH MONITORING OF ASPHALT PAVEMENT

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• Introduction

- ❑ Crack initiation and propagation vary the mechanical properties of the pavement and further alter its designed function [1].
- ❑ Current sensing technology for structural health monitoring(SHM):
 - Optical fibers [2]→Expensive
 - Conventional strain gauges [3]→rarely used in asphalt materials
 - Metal-foil-type gauges [4] →rarely used in asphalt materials
- ❑ challenges of installation conditions:
 - High temperatures (up to 164 °C)[5]
 - High pressure (around 290ksi) [6]

❑ Piezoelectric materials:

Mechanical deformation → Generate electrical charges

❑ piezoelectric materials for SHM and energy harvest :

A. piezoceramic material (Lead Zirconate Titanate, PZT)

B. piezoelectric plastic material (PVDF) [7-10]

❑ Advantage of piezoelectric-based sensors:

strong piezoelectric effects and wide bandwidth.

❑ Disadvantage of PZT:

1. suffers from saturation due to its high piezoelectric coefficient
2. too brittle to sustain high strain.

❑ Advantage of Piezoelectric plastic materials, such as PVDF [11-12]:

1. high sensitivity
2. good flexibility
3. good manufacturability
4. small distortion
5. low thermal conductivity
6. high chemical corrosion resistance, and heat resistance

PVDF → Key sensing unit of our strain sensor

- # Sensor Configuration

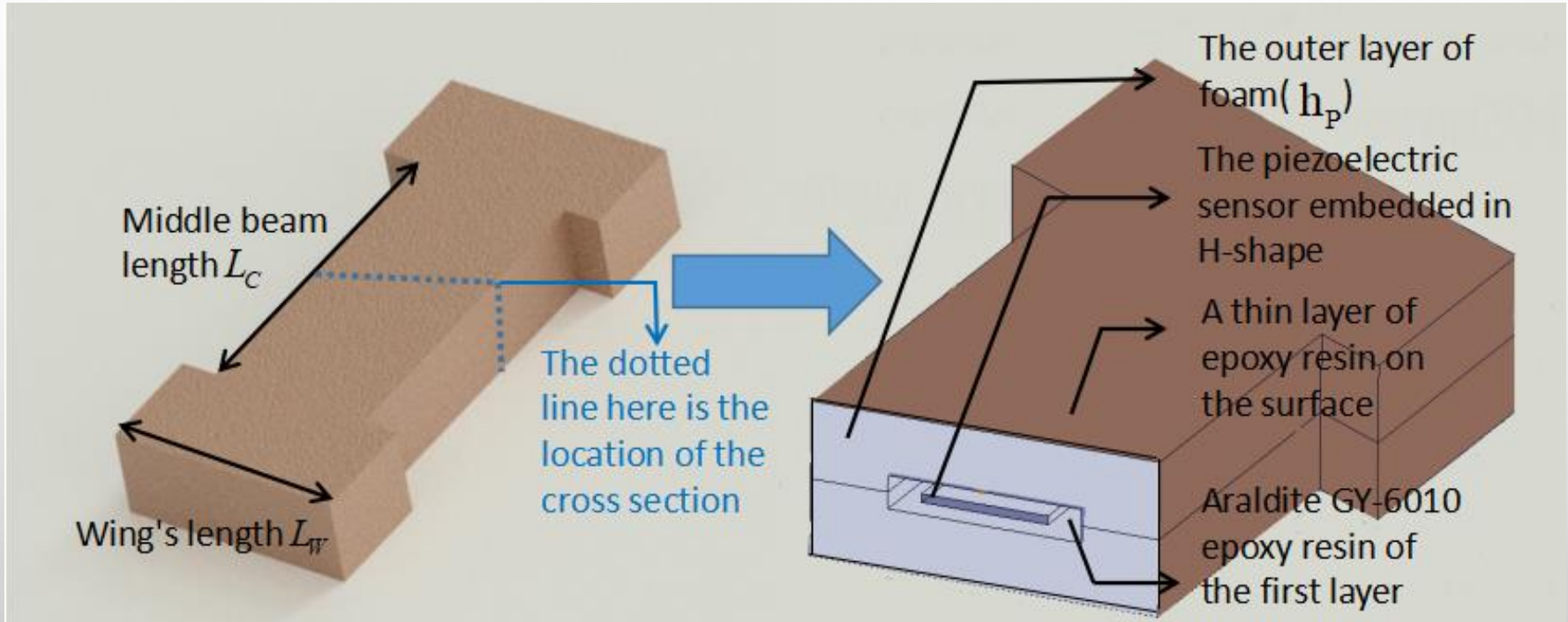
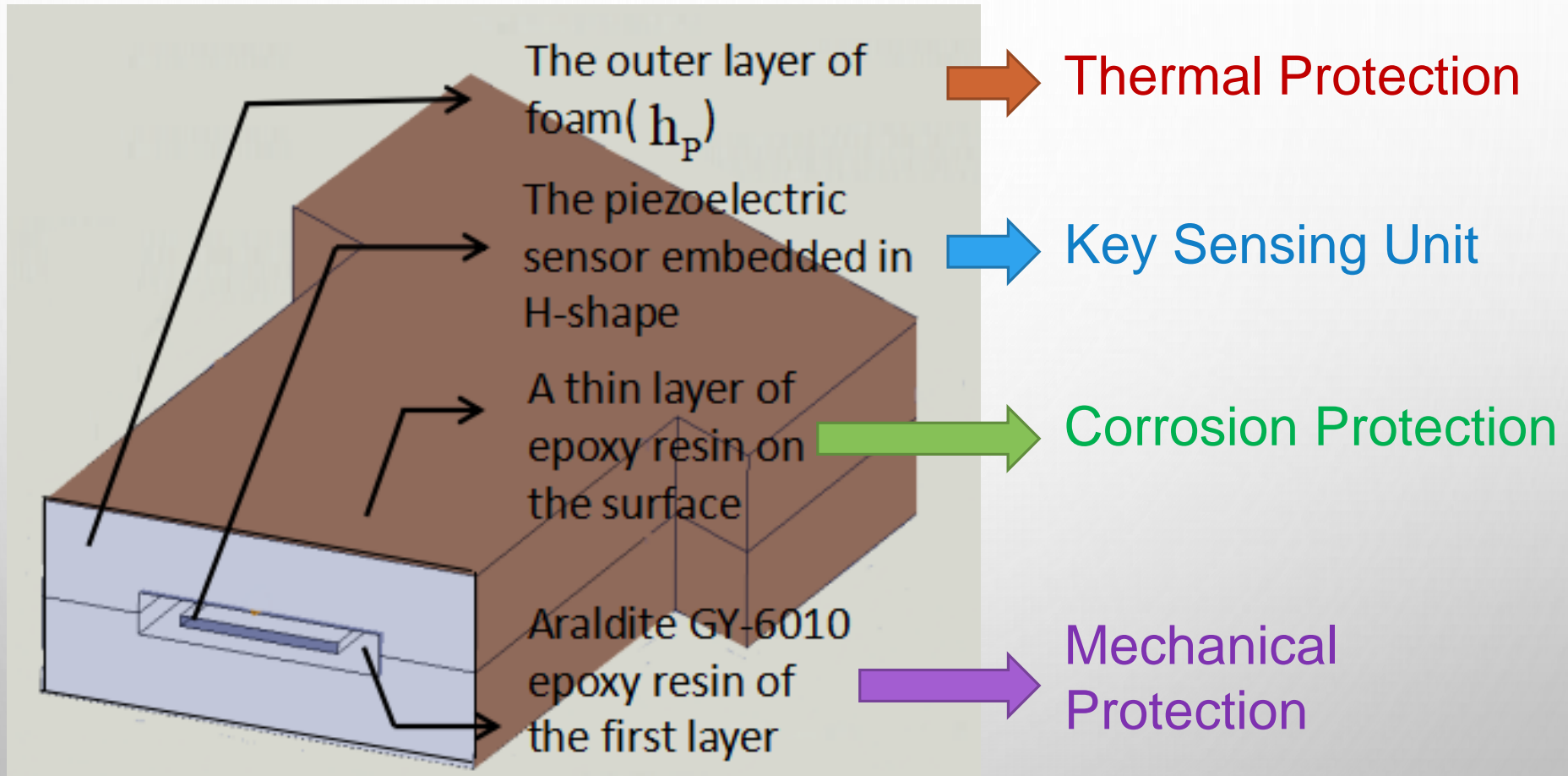


Figure 1. Configuration of the multi-layered strain sensor

• Sensor Configuration



• Thermal Analysis

	Mechanical Protection	Thermal Protection	Corrosion Protection
Material	Araldite GY-6010 epoxy	polyurethane foam	urethane casting resin
Thermal Conductivity	$0.2 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$	$0.022 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$	Negligible
Layer Thickness	10mm	5mm-12mm	1mm

∴ Thermal Conductivity: Thermal Protection << Mechanical Protection

∴ Thermal Analysis mainly focuses on thermal protection layer

Theoretical Model

$$d_z \rho C_p \frac{\partial T}{\partial t} + d_z \rho C_p u \cdot \nabla T + \nabla \cdot q = d_z Q + q_0 + d_z Q_{ted}$$

$$q = -d_z k \nabla T$$

Q --heat content, J

k--thermal conductivity, $\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$

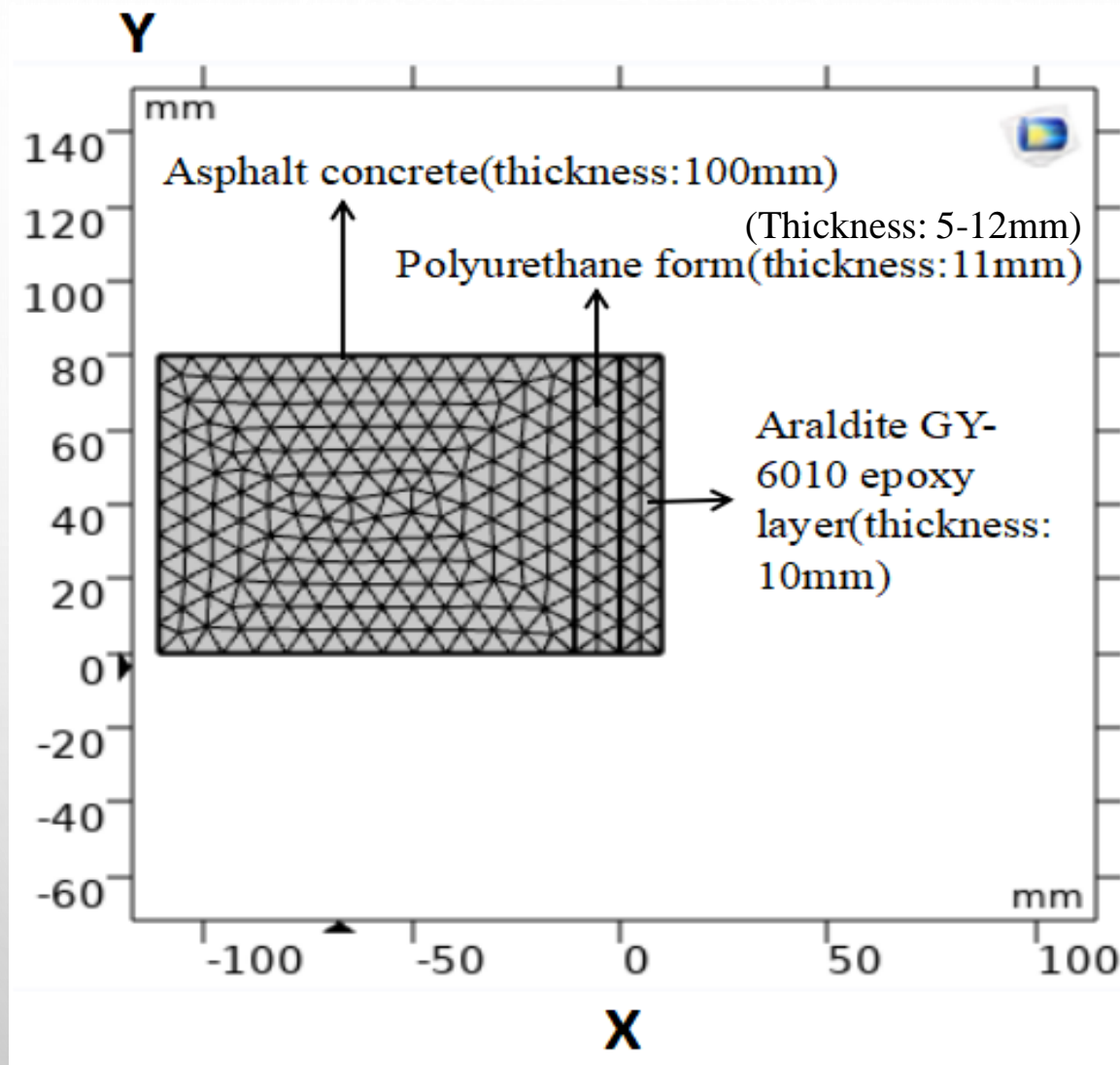
q-- local heat flux density, $\text{W} \cdot \text{m}^{-2}$

ρ -density of each material, $\text{kg} \cdot \text{m}^{-3}$

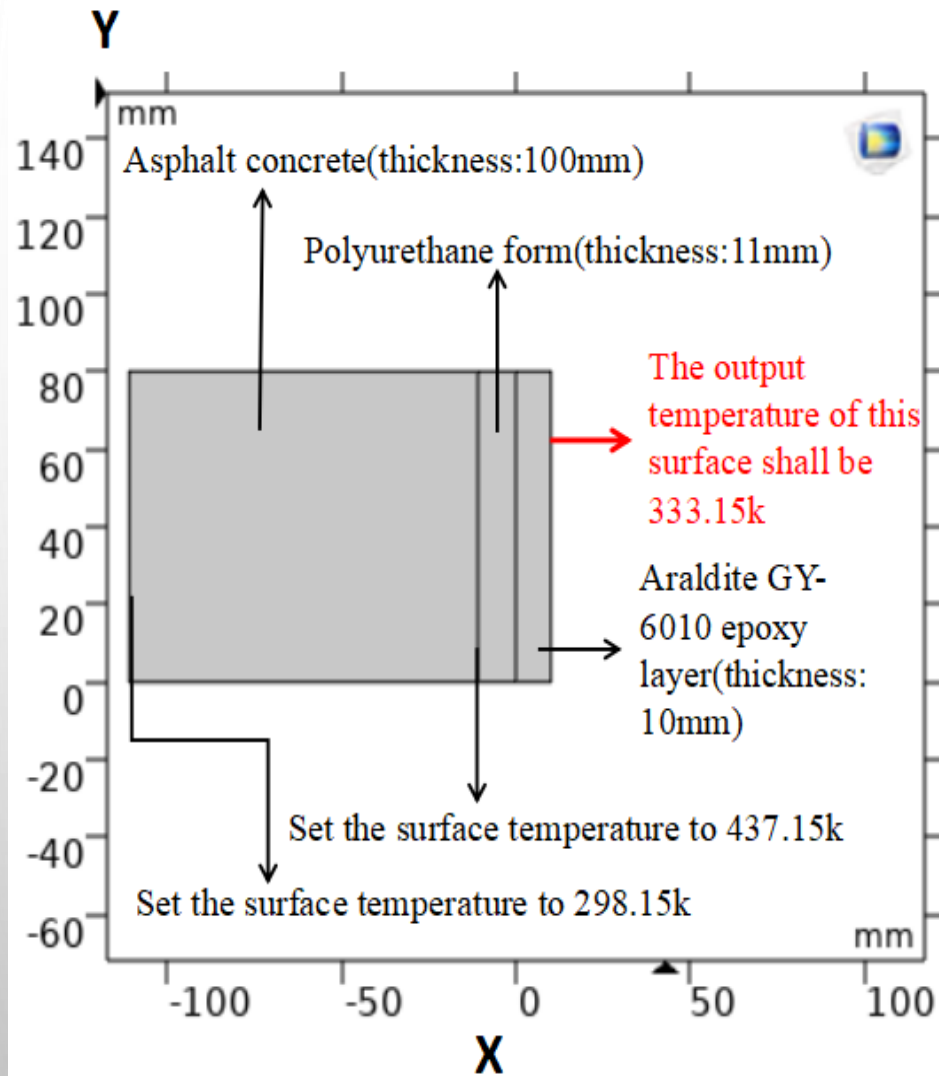
C_p --heat capacity, $\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$.

∇T is the temperature gradient, $\text{K} \cdot \text{m}^{-1}$.

t time,s



2D Finite Element Model with 422 elements;



∴ Max operation temp of PVDF equals to **333.15K**

∴ output temp $T_{out} \leq 333.15K$

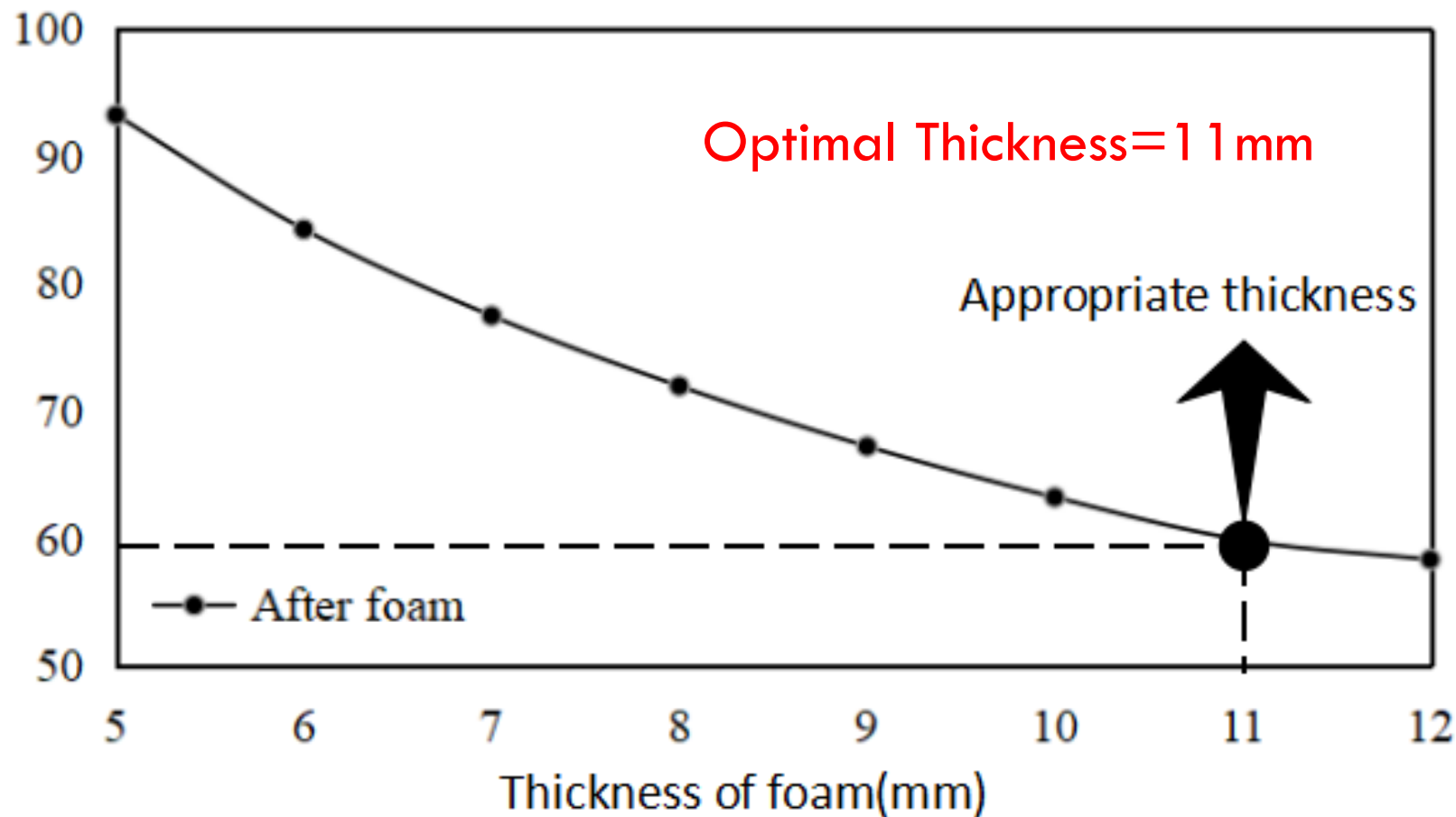
∴ Aim:

Find optimal thickness of Polyurethane foam for

$T_{out} = 333.15K$

Schematic of 2D model with boundary conditions.

Temperature(°C)



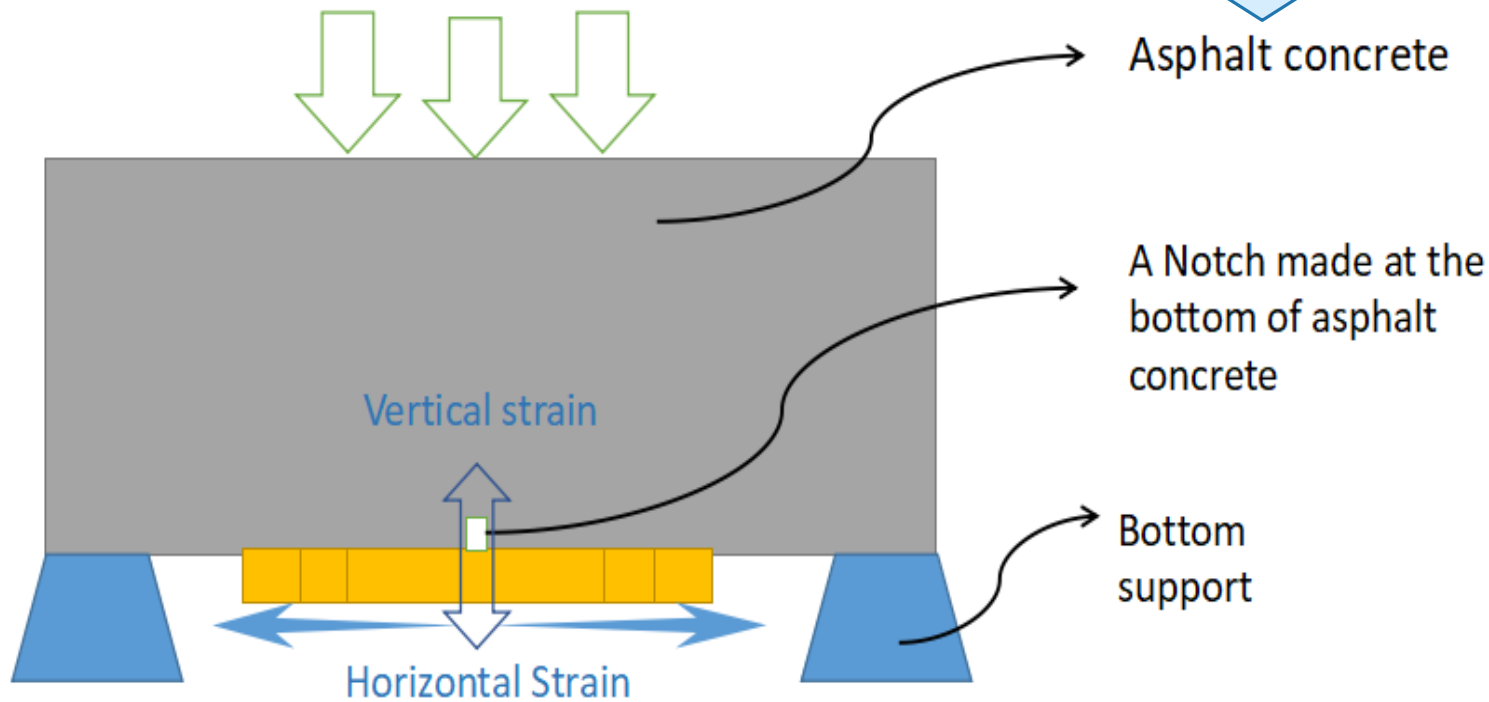
The relation between the foam thickness and output temperature

- **Solid mechanics model**

Three-point Bending Test

contact area:
200mm x 130mm
Load: 4900N

Elastic modulus: 1200 MPa
Density: 2.6g·cm⁻³
Poisson's ratio: 0.35
Length:300mm
Width:130mm
Height:100mm



Determine the optimal ratio of the wing length to the center beam length for the H-shape sensor structure

Goal: highest sensitivity with the lowest material cost

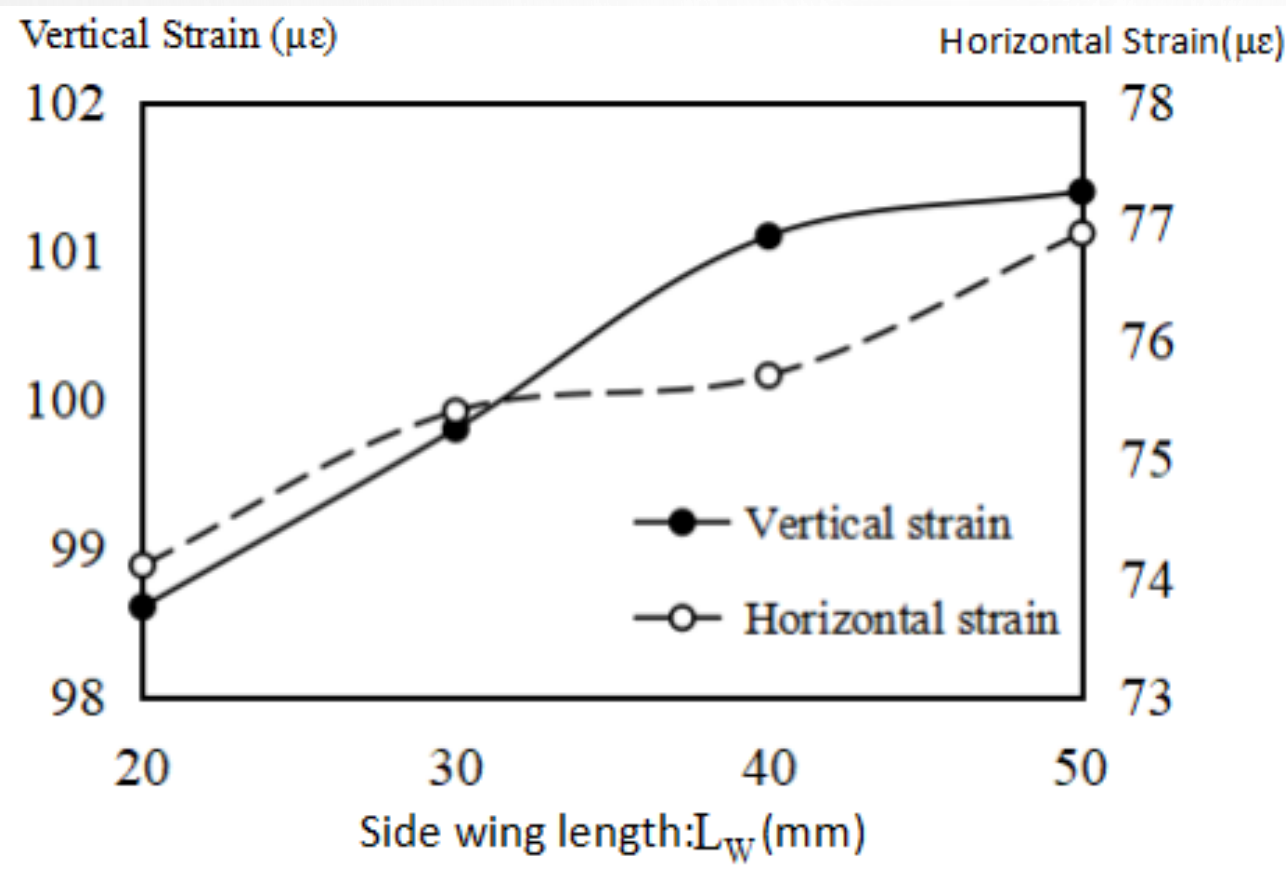
Method:

Step 1: Find optimal L_W for highest vertical/horizontal strain

Fix: length of the center beam, $L_C=160$ mm

Independent Variable: wing length, $L_W=20\text{mm}, 30\text{mm}, 40\text{mm}, 50\text{mm}$

Dependent Variable: Horizontal strain, Vertical Strain



When $L_W=50$ mm

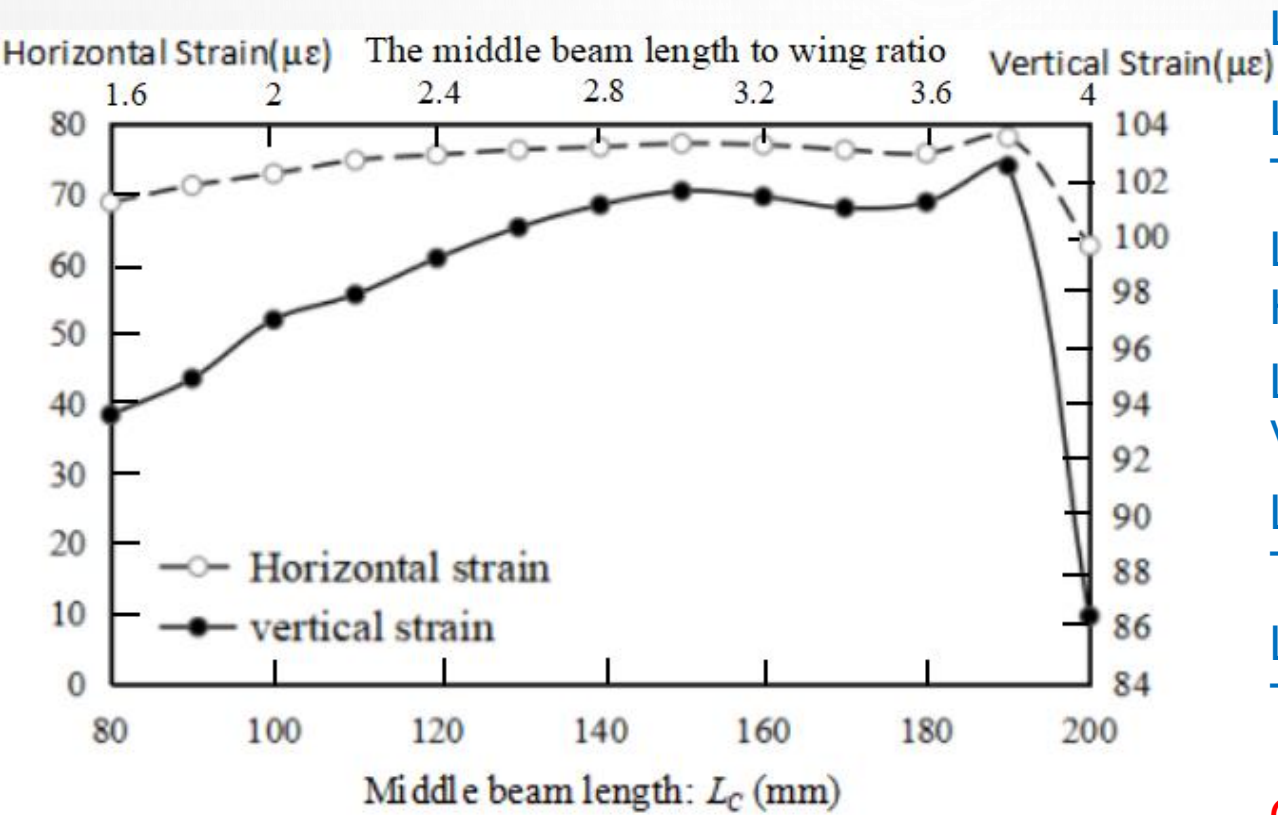
- vertical strain curve begins to flatten and it stabilizes at around $101\mu\epsilon$
- horizontal strain first shows a gentle trend and then shows a sharp upward trend

Step 2: Find optimal ratio of the wing length to the center beam length for highest vertical/horizontal strain

Fix: $L_w=50\text{mm}$

Independent Variable: $L_c=0\text{-}200\text{ mm}$ (20mm increment)

Dependent Variable: Horizontal strain, Vertical Strain



$L_c \uparrow$
 $L_c=0\text{-}160\text{mm}$,
Two Strains increase
 $L_c=160\text{-}200\text{mm}$,
Horizontal Strain flat
 $L_c=160\text{-}180\text{mm}$,
Vertical Strain drop
 $L_c=190\text{mm}$,
Two Strains both have peak
 $L_c=200\text{mm}$,
Two Strains decrease sharply

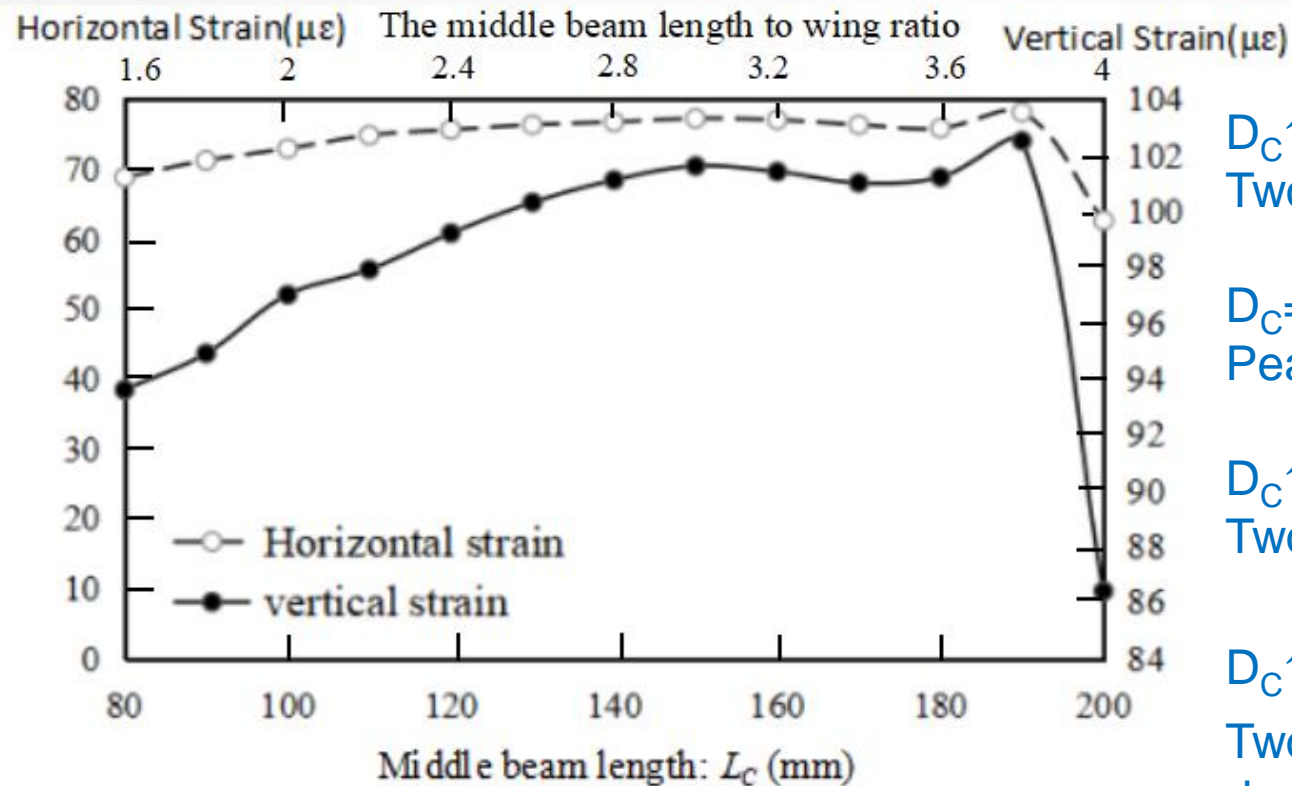
Optical length: 160mm
Optimal Ratio: $L_c/L_w=3.2$

Method: Determine sensor's capability of capturing the pavement crack

Fix: Height of asphalt pavement $D=100\text{mm}$

Independent Variable: Crack depth $D_c=0\text{--}100\text{ mm}$ (10mm increment)

Dependent Variable: Horizontal strain, Vertical Strain



$D_c \uparrow$ From 0 mm to 50mm
Two strains increase

$D_c = 50\text{mm}$
Peak of Two strain curves

$D_c \uparrow$ From 50 mm to 90mm
Two strain curves drop slightly

$D_c \uparrow$ From 90 mm to 100mm
Two strain curves drop dramatically

• Conclusion

- Optimal Ratio of the wing length to the center beam length for the H-shape sensor structure:3.2
- Optimal wing length: 50mm
- Optimal the center beam length: 160mm
- Sensor is capable to detect the horizontal/vertical strains changes with the crack initiation and propagation.

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Thank you for your attention