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## Folded-Beam Suspension

- Use of folded-beam suspension brings many benefits
  - Stress relief: folding truss is free to move in y-direction, so beams can expand and contract more readily to relieve stress
  - High y-axis to x-axis stiffness ratio

Comb-Driven Folded Beam Actuator

Folding Truss

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## Beam End Conditions

TABLE 4.1  
Types of commonly used support conditions for beams and frames

Type of support	Displacement boundary conditions	Force boundary conditions
 FREE	None	All, as specified
 PINNED	$u = 0$ $w = 0$	Moment is specified
 ROLLER (vertical)	$u = 0$	Transverse force and moment are specified
 ROLLER (horizontal)	$w = 0$	Horizontal force and bending moment are specified
 FIXED or CLAMPED	$u = 0$ $w = 0$ $dw/dx = 0$	None specified

[From Reddy, Finite Element Method]

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## Common Loading & Boundary Conditions

- Displacement equations derived for various beams with concentrated load  $F$  or distributed load  $f$
- Gary Fedder Ph.D. Thesis, EECS, UC Berkeley, 1994

cantilever	guided-end	fixed-fixed
$x = \frac{F_x L}{Ehw}$	$x = \frac{F_x L}{Ehw}$	$x = \frac{F_x L}{4Ehw}$
$y = 4 \frac{F_y L^3}{Eh w^3}$	$y = \frac{F_y L^3}{Eh w^3}$	$y = \frac{1}{16} \frac{F_y L^3}{Eh w^3}$
$z = 4 \frac{F_z L^3}{Ew h^3}$	$z = \frac{F_z L^3}{Ew h^3}$	$z = \frac{1}{16} \frac{F_z L^3}{Ew h^3}$

(a) Concentrated load.

cantilever	guided-end	fixed-fixed
$x = \frac{f_x L}{E}$	$x = \frac{f_x L}{E}$	$x = \frac{f_x L}{4E}$
$y = \frac{3}{2} \frac{f_y L^4}{Eh w^3}$	$y = \frac{1}{2} \frac{f_y L^4}{Eh w^3}$	$y = \frac{1}{32} \frac{f_y L^4}{Eh w^3}$
$z = \frac{3}{2} \frac{f_z L^4}{Ew h^3}$	$z = \frac{1}{2} \frac{f_z L^4}{Ew h^3}$	$z = \frac{1}{32} \frac{f_z L^4}{Ew h^3}$

(b) Distributed load.

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## Folded-Beam Stiffness Ratios

- In the x-direction:
 
$$k_x = \frac{24EI_z}{L^3}$$
- In the z-direction:
  - Same flexure and boundary conditions
$$k_z = \frac{24EI_x}{L^3}$$
- In the y-direction:
 

[See Senturia, §9.2]  $k_y = \frac{8EWh}{L}$
- Thus:
 
$$\frac{k_y}{k_x} = 4 \left( \frac{L}{W} \right)^2$$

Much stiffer in y-direction!

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### Folded-Beam Suspensions Permeate MEMS

The slide displays three micrographs of MEMS devices. The top-left image shows an Accelerometer [ADXL-05, Analog Devices] with a dense grid of folded-beam suspensions. The top-right image shows a Gyroscope [Draper Labs.] with a central micro-platform and surrounding folded-beam structures. The bottom image shows a Micromechanical Filter [K. Wang, Univ. of Michigan] with a complex arrangement of folded-beam suspensions.

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### Folded-Beam Suspensions Permeate MEMS

- Below: Micro-Oven Controlled Folded-Beam Resonator

The slide features a micrograph of a Micro-Oven Controlled Folded-Beam Resonator. The device consists of a central micro-platform supported by struts, surrounded by a network of folded-beam suspensions. Labels with yellow arrows point to various components: Temperature Sensing Resistor, Heating Resistor, Support Struts, Substrate Edge, and Micro-Platform.

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