핵연료 비선형 특성을 반영한 해석 모델 개발 및 성능 평가

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❖ 방법

- 핵연료집합체를 대상으로 기계적 특성 시험을 수행
- DB 분석에 따른 자료 생산

❖ 핵연료 해석 모델 특성 변수

- 고유진동수, 굽힘 강성, 충격 강성 등

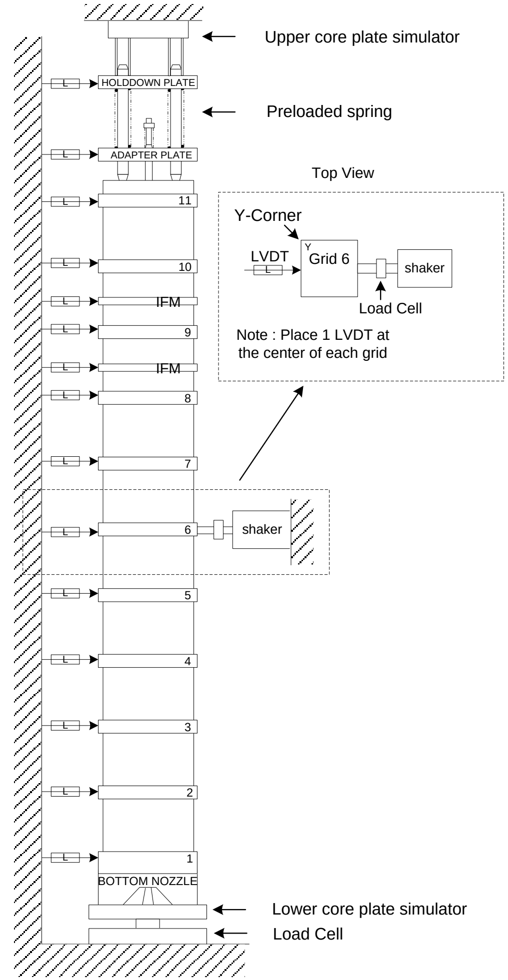
❖ 활용

- 노심 내진해석 및 응력 평가

I. Introduction

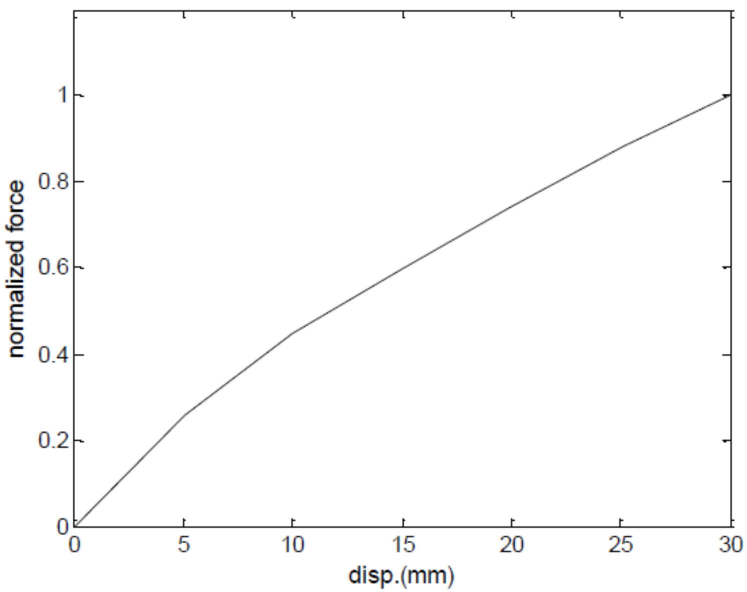
핵연료집합체 시험(mechanical test) 개요

- 노심경계 조건
  - upper & lower core plate simulator
- 하중 및 변위 제어
- 계측기
  - LVDT, load cell, strain gage 등

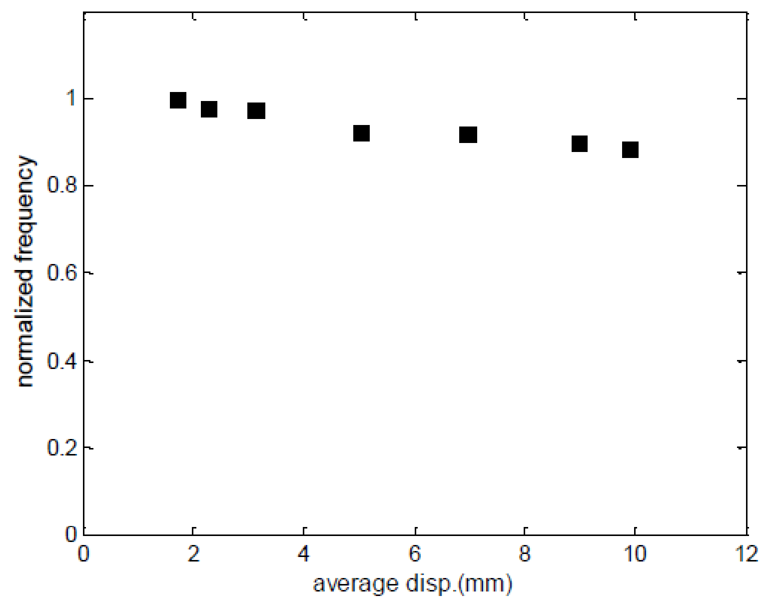


핵연료 비선형 거동 예시

Lateral bending test



Lateral vibration test



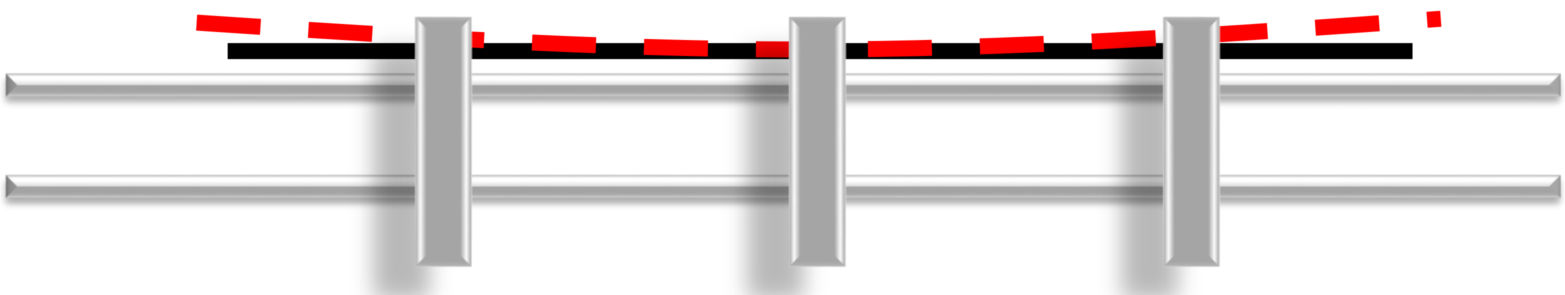
I. Introduction

비선형 유발요인

- **Material-induced nonlinearity (X)**
  - **Plastic deformation**
- **Geometry-induced nonlinearity(X)**
  - **Large strain (Green-Lagrange strain)**

$$\varepsilon_{ij} = \frac{1}{2}\left(u_{i,j} + u_{j,i} + u_{k,i}u_{k,j}\right)$$

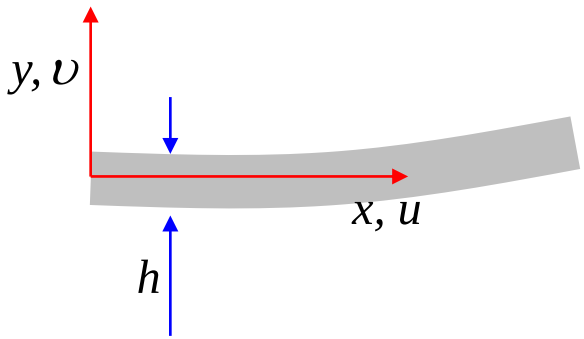
- **Friction-induced nonlinearity**
  - **Interaction btw the fuel rods & grids**



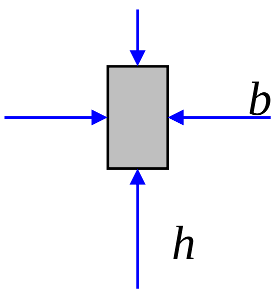
I. Introduction

- 비선형 핵연료 모델 개발 목적
  - 현실성을 반영한 핵연료 모델 개발
  - 비선형성 모사에 따른 과보수성 제거
- 방법
  - 노심내진해석 활용성 고려한 단순화
  - 비선형성을 대표할 수 있는 물리량 모사

Euler 빔(beam) 변형 및 변형률(linear system)



Cross section view



Axial deformation due to the lateral deformation

$$u = -y\frac{\partial \upsilon}{\partial x}$$

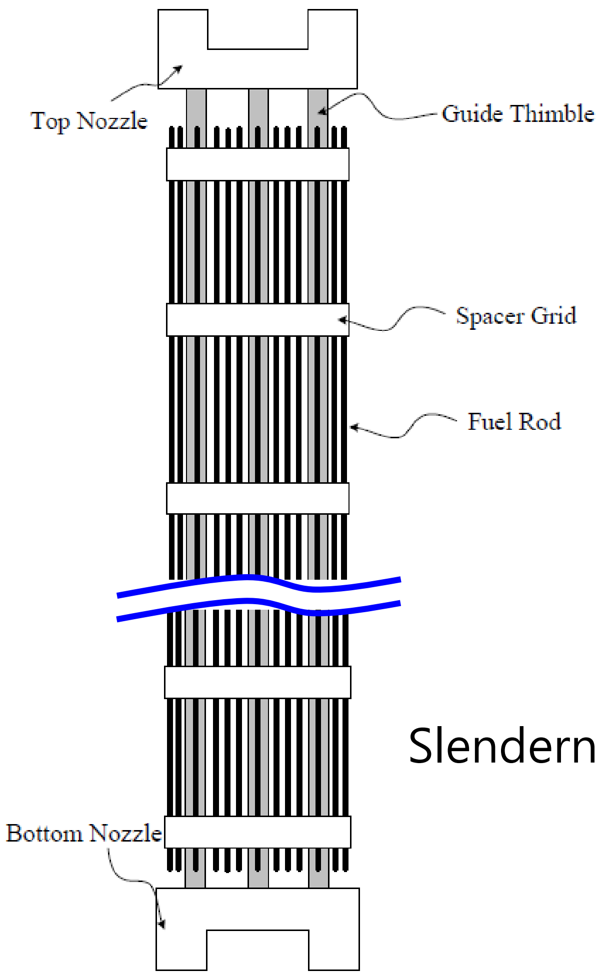
Axial strain

$$\varepsilon_{xx} = -y\frac{\partial^2 \upsilon}{\partial x^2}$$

Potential energy in the linear beam

$$\pi = \int_0^l \int_{-h/2}^{h/2} \frac{1}{2}\sigma_{xx}\varepsilon_{xx} b\,dy\,dx = 0.5I\int_0^l E\left(\frac{\partial^2 \upsilon}{\partial x^2}\right)^2 dx, \ where \ \ I = \int_{-h/2}^{h/2} by^2 dy$$

Fuel assembly simplification



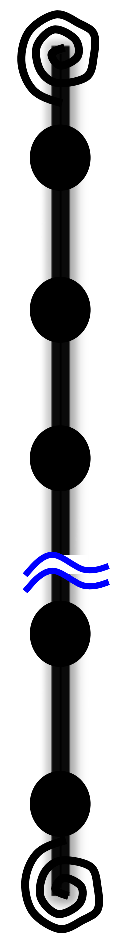
동적거동에 중요한 물리적 특성 부여

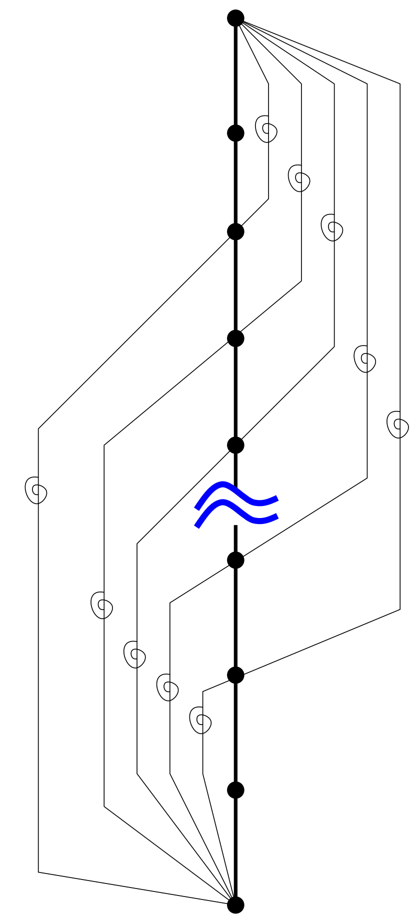
Slenderness ratio: ~70

II. Kinematics & Eq. of motion

Current FA model for core analysis

- OPR/APR fuel(HIPER16, PLUS7)
  - Linear system
  - Massless beam
  - Lumped point mass
  - Torsional springs
- WEC fuel(HIPER17, ACE7)
  - Linear system
  - Lumped spring-mass
  - Or Euler beam with torsion springs





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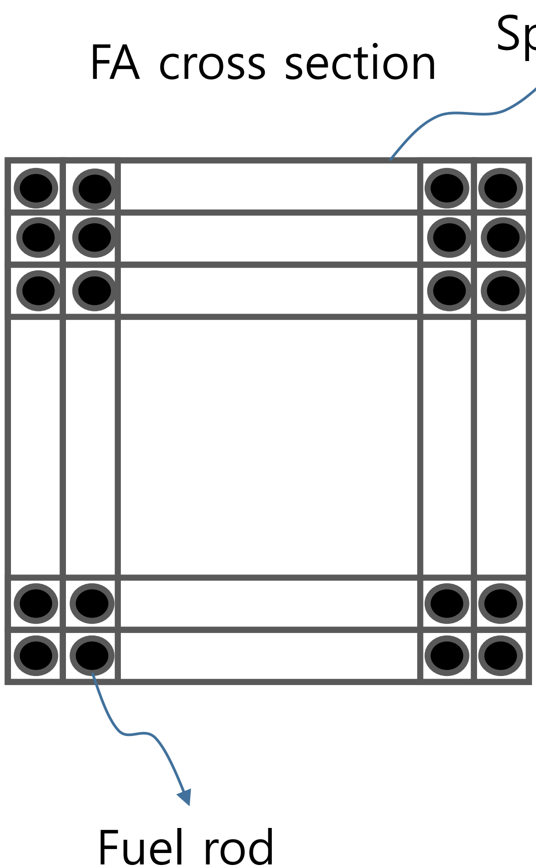
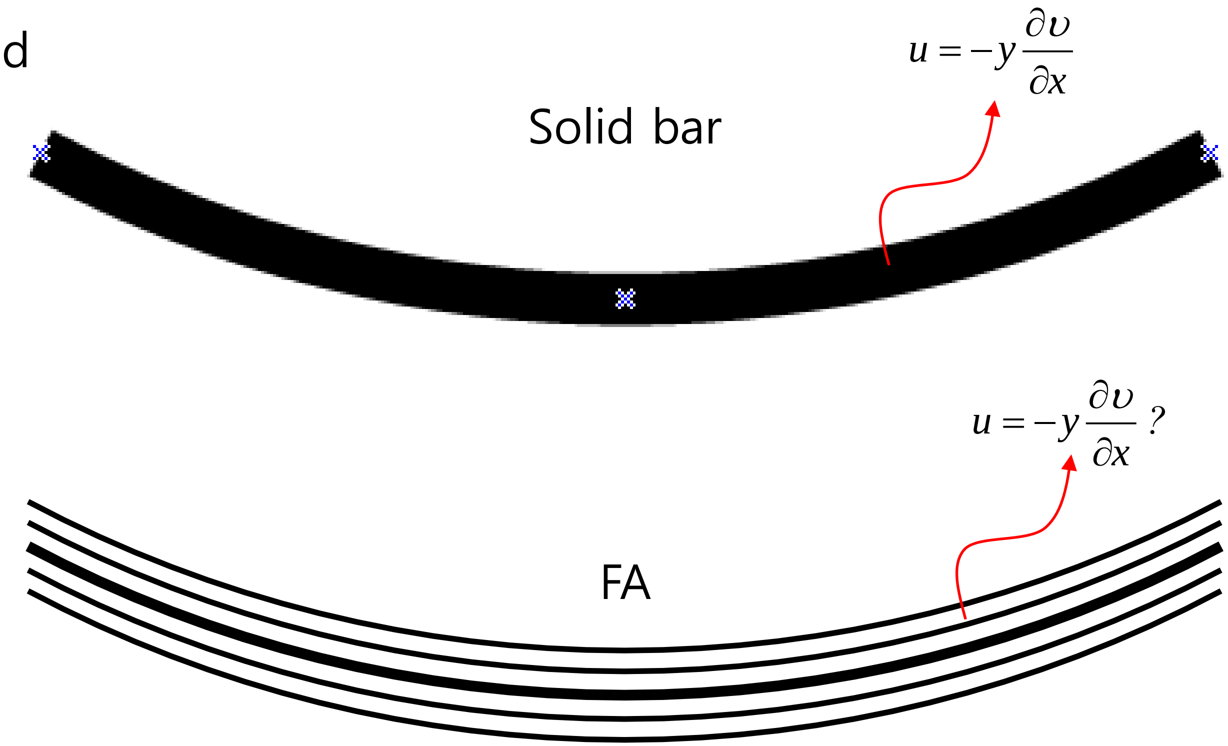
핵연료 기하구조 특성 및 거동

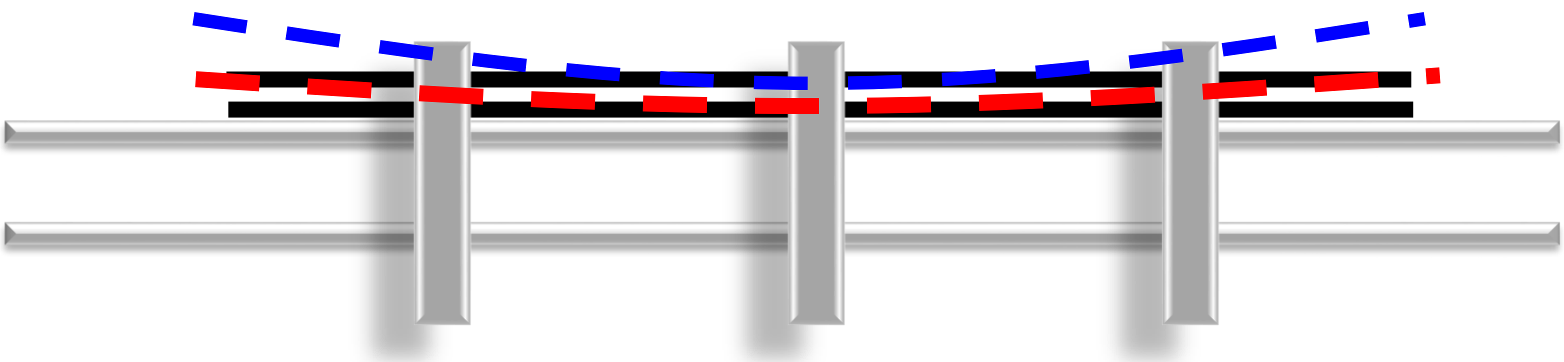




II. Kinematics & Eq. of motion

Global & local deformations

❖ Assumption to represent a local deformation



$$\upsilon_i = \kappa_i(\upsilon)\upsilon$$

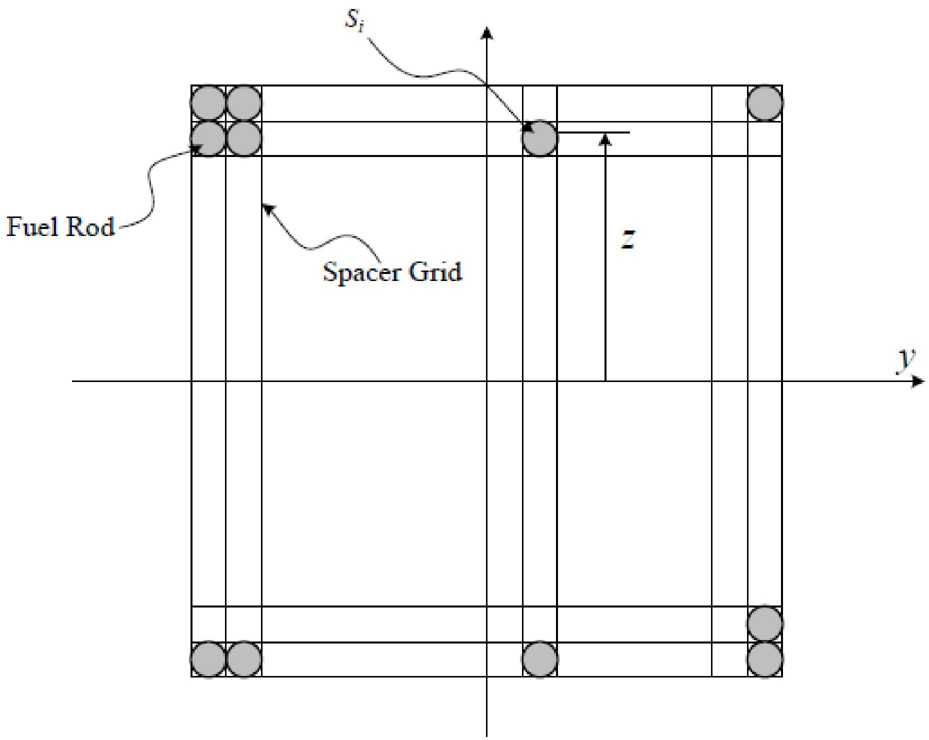
global deformation at the neutral line

parameter to link deformations (even function)

Individual deformation at each rod

II. Kinematics & Eq. of motion

Total strain energy including all the rods



$$\pi = \int_0^l \left(\sum_{i=1}^{N} \int_{S_i} \frac{1}{2} E \varepsilon_{xx}^2 dA_i \right) dx$$

$$= \frac{1}{2} E \int_0^l \left(\sum_{i=1}^{N} \int_{S_i} z_i^2 \left(\frac{\partial^2 \upsilon_i}{\partial x^2} \right)^2 dA_i \right) dx$$

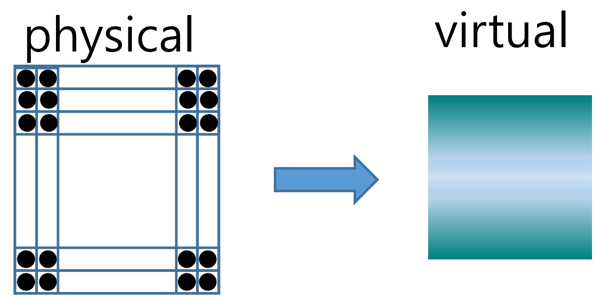
Nonlinearity involved 2nd area moment

$\upsilon_i = \kappa_i \upsilon \qquad \left(\frac{\partial \upsilon}{\partial x}\right)^2 << 1$

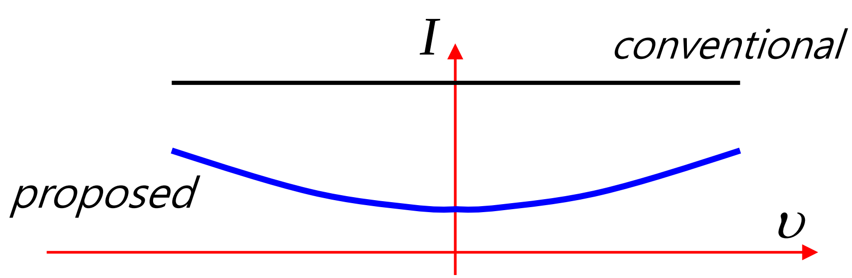
$$\pi = \frac{1}{2}E\int_0^l \left(\sum_{i=1}^N \int_{S_i} z_i^2 \left(\frac{\partial^2 \upsilon_i}{\partial x^2}\right)^2 dA_i\right)dx \approx \frac{1}{2}E\int_0^l\left(\left(\frac{\partial^2\upsilon}{\partial x^2}\right)^2 \boxed{\sum_{i=1}^N\int_{S_i} z_i^2\left(\kappa_i+\upsilon\frac{\partial\kappa_i}{\partial\upsilon}\right)^2 dA_i}\right)dx = \frac{1}{2}E\int_0^l\left(\frac{\partial^2\upsilon}{\partial x^2}\right)^2 I(\upsilon)dx$$

$z_i = \alpha z$

$$\boxed{\alpha^2\int_S z^2 dA \sum_{i=1}^N\left(\kappa_i+\upsilon\frac{\partial\kappa_i}{\partial\upsilon}\right)^2 = I_c\sum_{i=1}^N\left(\alpha\kappa_i+\upsilon\alpha\frac{\partial\kappa_i}{\partial\upsilon}\right)^2}$$



$$I(\upsilon) = I_c\sum_{i=1}^N\left(\alpha\kappa_i+\upsilon\alpha\frac{\partial\kappa_i}{\partial\upsilon}\right)^2 > 0$$



II. Kinematics & Eq. of motion

Variational formulation & nonlinear Eq. of motion

$$\pi_p = \frac{1}{2} E \int_0^l I(\upsilon) \left(\frac{\partial^2 \upsilon}{\partial x^2} \right)^2 dx - \int_0^l p(x,t) \upsilon dx, \qquad \pi_k = \frac{1}{2} \int_0^l m_s \left(\frac{\partial \upsilon}{\partial t} \right)^2 dx$$

$$\delta(\pi_k - \pi_p) = 0$$

$$\boxed{\rho A \frac{\partial^2 \upsilon}{\partial t^2} + \underbrace{\frac{1}{2} E \frac{\partial I(\upsilon)}{\partial \upsilon} \left(\frac{\partial^2 \upsilon}{\partial x^2} \right)^2 + E \frac{\partial^2 I(\upsilon)}{\partial x^2} \frac{\partial^2 \upsilon}{\partial x^2}}_{\text{Additional nonlinear terms}} + \underbrace{EI(\upsilon) \frac{\partial^4 \upsilon}{\partial x^4}}_{\text{Nonlinear stiffness}} = p(x,t)}$$

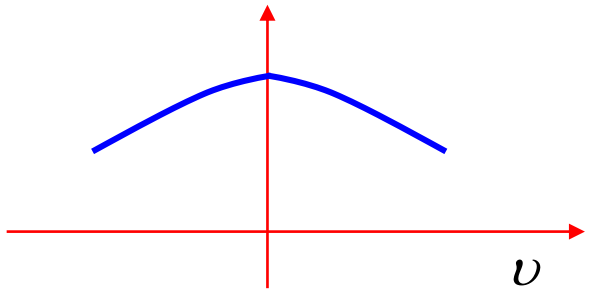
Nonlinear 2nd area moment

Requirements

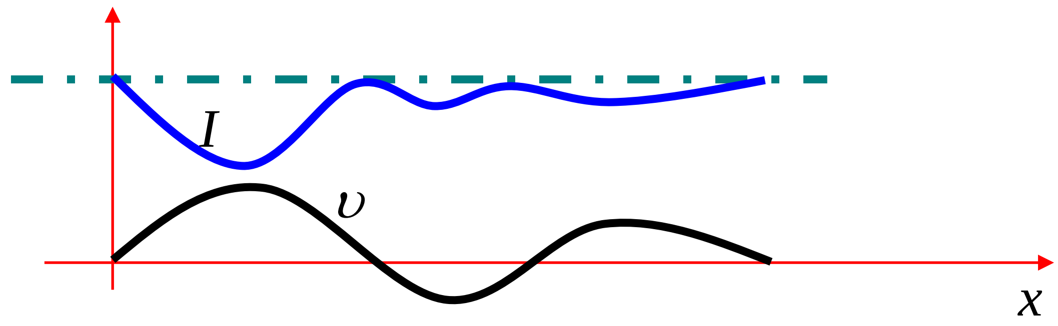
- Maximum when the deformation is zero.
- Positive over all deformation
- Symmetric and differentiable at the zero displacement

Physical contribution

특정 위치에서



특정 시간에서



II. Kinematics & Eq. of motion

Estimation of the parameter(κ)

Analytic solution example

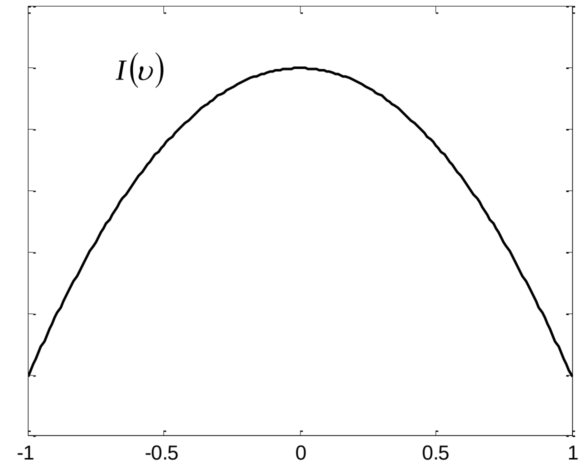
$$\text{if}\quad I(\upsilon) = I_c\, e^{-b\upsilon^2} \qquad \& \ \kappa_i = \kappa$$

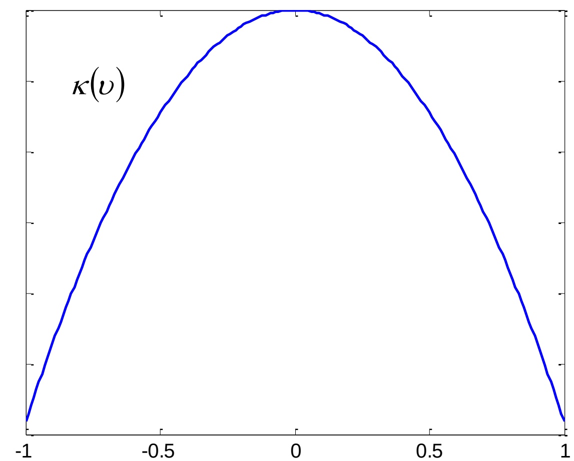
$$I(\upsilon) = I_c \sum_{i=1}^{N} \left(\alpha\kappa_i + \upsilon\alpha \frac{\partial \kappa_i}{\partial \upsilon} \right)^2$$

$$\alpha\kappa + \upsilon\alpha \frac{\partial \kappa}{\partial \upsilon} = e^{-b\upsilon^2/2} / \sqrt{N}$$

Taylor series expansion

$$\kappa = \frac{1}{\alpha\sqrt{N}} \sum_{r=0}^{\infty} \frac{1}{(2r+1) r!} \left(-\frac{b\upsilon^2}{2} \right)$$





Linearization & the solution

❖ Galerkin formulation excluding damping

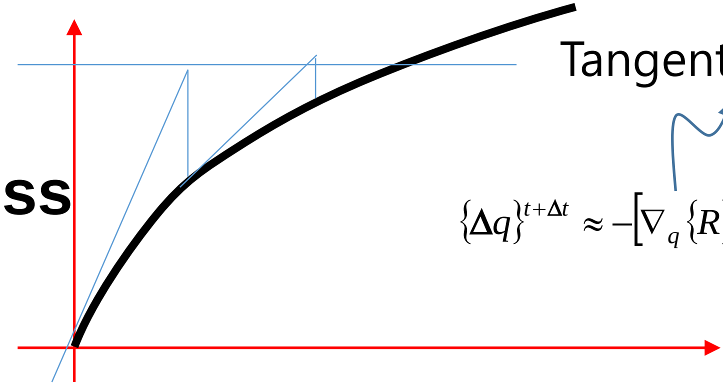
$$\upsilon(x,t) \approx \sum_{i=1}^{N} \psi_i(x) q_i(t), \quad \psi_i \in H_0^2$$

$$\int m_s \psi_i \sum_{j=1}^{N} \psi_j dx \ddot{q}_j + \int \left[\frac{1}{2} E \frac{\partial I}{\partial \upsilon} \psi_i \left(\sum_{j=1}^{N} \frac{\partial^2 \psi_j}{\partial x^2} q_j \right)^2 + EI(u) \frac{\partial^2 \psi_i}{\partial x^2} \sum_{j=1}^{N} \frac{\partial^2 \psi_j}{\partial x^2} q_j \right] dz = \int \psi_i p dz, \qquad i = 1 \cdots N$$

$$[M]\{\ddot{q}\} + \{f(q)\} = \{\eta\}$$

❖ Iterative solution

- **Calculation of tangent stiffness**
- **Incremental solution**



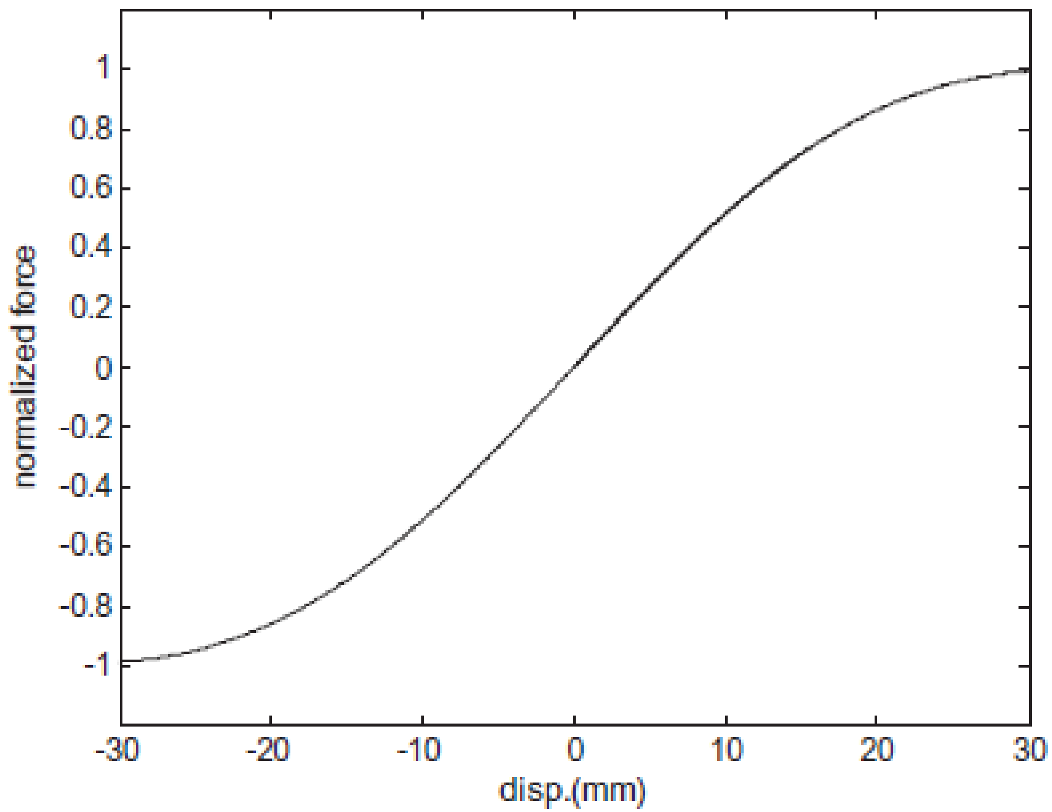
Tangent stiffness

$$\{\Delta q\}^{t+\Delta t} \approx -\left[\nabla_q \{R\}\right]^{-T} \{R\}^{t+\Delta t}$$

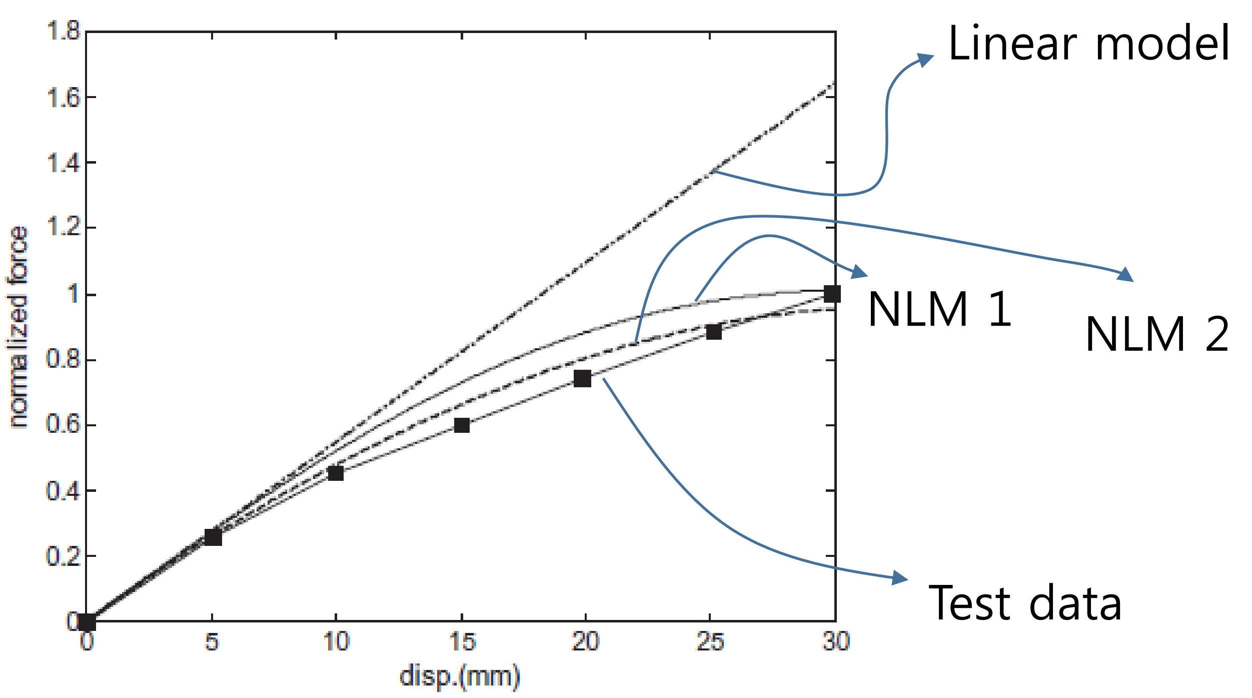
III. Solution & verification

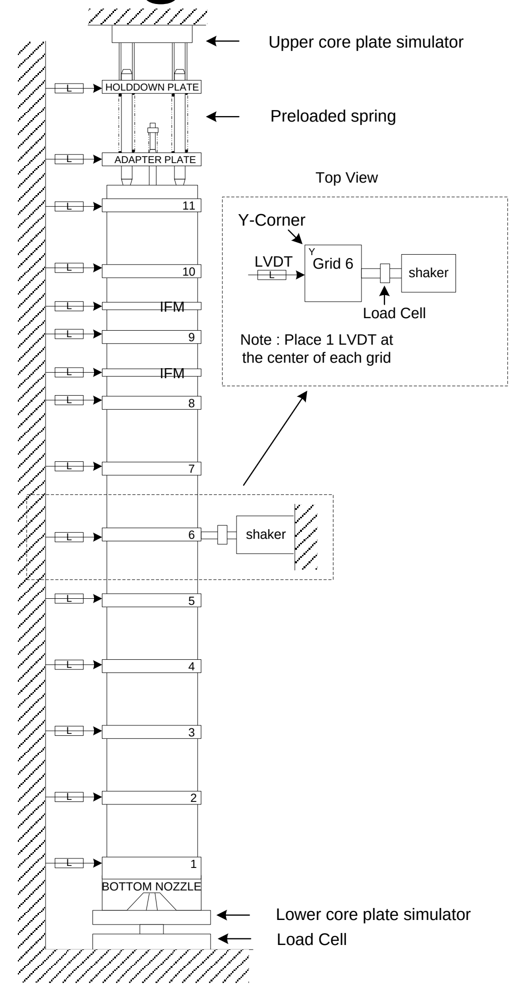
Feasibility test

❖ Lateral bending simulation



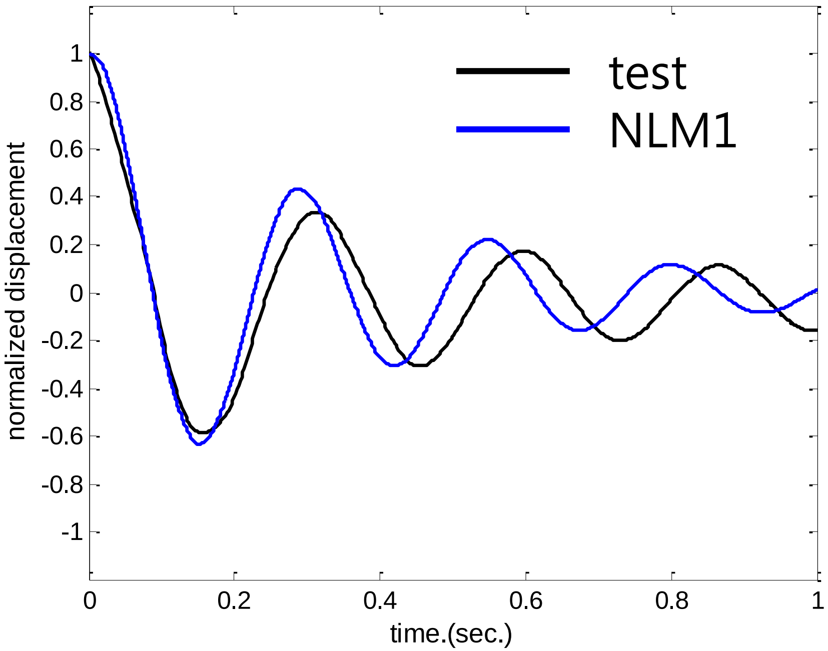
Verification problem 1: Lateral Bending

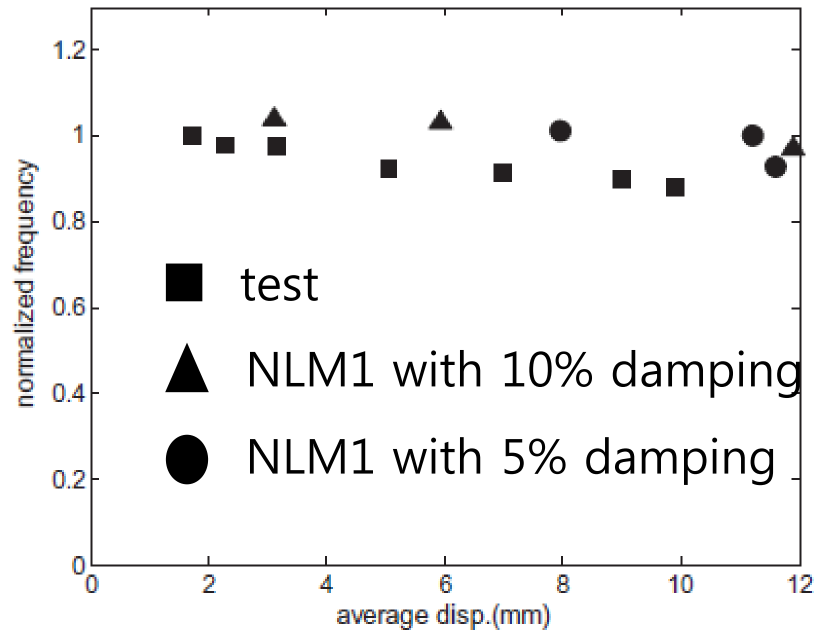




Verification problem 2: Lateral Vibration

❖ Natural freq. changes depending on the amplitude





Comparisons

Items	L.M.	N.L.M.
Second area moment	I_c	$\lambda(\upsilon)I_c$
Axial deformation	$-z\dfrac{\partial\upsilon}{\partial x}$	$-z\dfrac{\partial\kappa\upsilon}{\partial x}$
strain energy	$0.5E\int_0^l I_c\upsilon_{,xx}{}^2dx$	$0.5E\int_0^l I(\upsilon)\upsilon_{,xx}{}^2dx$
Mech. behavior	Linear elastic	Nonlinear elastic

IV. Concluding remarks

FA nonlinear model development

- 변위에 따른 핵연료 비선형성 모사
  - 피복관/지지격자 마찰에 따른 등가 물리량 도입
    - ✓Variable 2nd area moment introduction
  - 운동방정식 유도 및 Galerkin 근사해 도출
- 결과검증
  - 비선형성 모사능력 평가
  - 정적 굽힘 및 진동시험결과 비교

IV. Concluding remarks

향후 계획

- 비선형 물리량 도입 타당성 추가 검증 및 최적 모델 규명
- 비선형성 모사를 위한 추가 요인 검토
- Plastic rule 적용
- 노심내진해석 코드(DYTRAC) 반영 계획 검토

Thank you

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