towards engineered structures made of bamboo culms: **3 questions answered**

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outline

intro & motivation

design for variability

explain flexural behavior

predict embedment behavior

full-scale bamboo footbridge

conclusions

intro & motivation

my research

- non-smooth and nonlinear structural dynamics
- seismic pounding
- rocking dynamics
- vehicle-bridge interaction

Nonlinear Dyn
https://doi.org/10.1007/s11071-022-07578-1

Check for updates

ORIGINAL PAPER

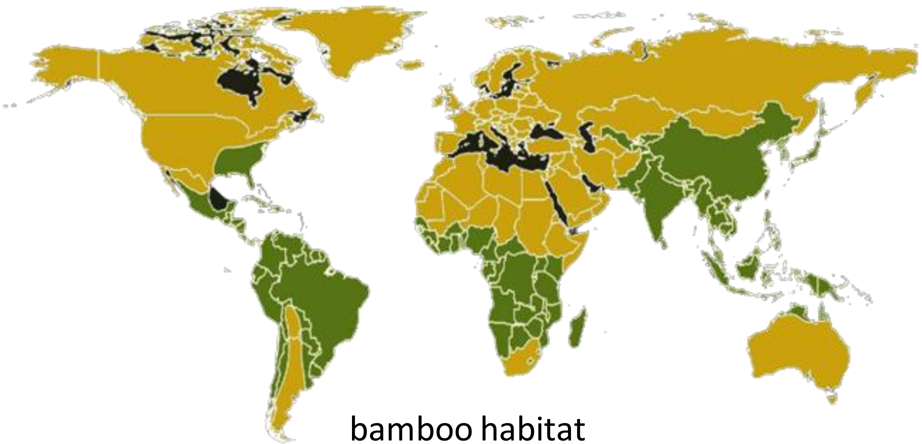
Chattering: an overlooked peculiarity of rocking motion

Anastasios I. Giouvanidis · **Elias G. Dimitrakopoulos** · **Paulo B. Lourenço**

a_{cr} depends solely on the coefficient of restitution η, reads:

$$a_{cr} = \frac{a_{g,cr}}{g\alpha} = -0.3941\eta^3 + 0.5763\eta^2 - 0.45\eta + 1.271 \tag{77}$$

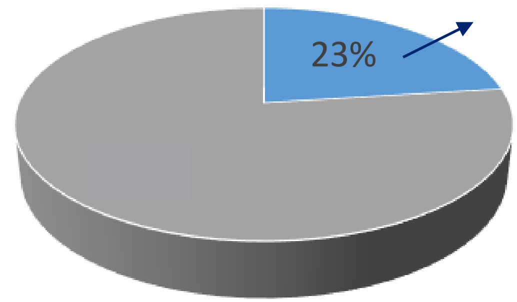
intro & motivation



bamboo habitat

developing/developed world

global economic activity
CO_2 emissions



why bamboo?

- high carbon sequestration capacity
- high strength-to-weight ratio
- low-cost
- abundant where mostly needed

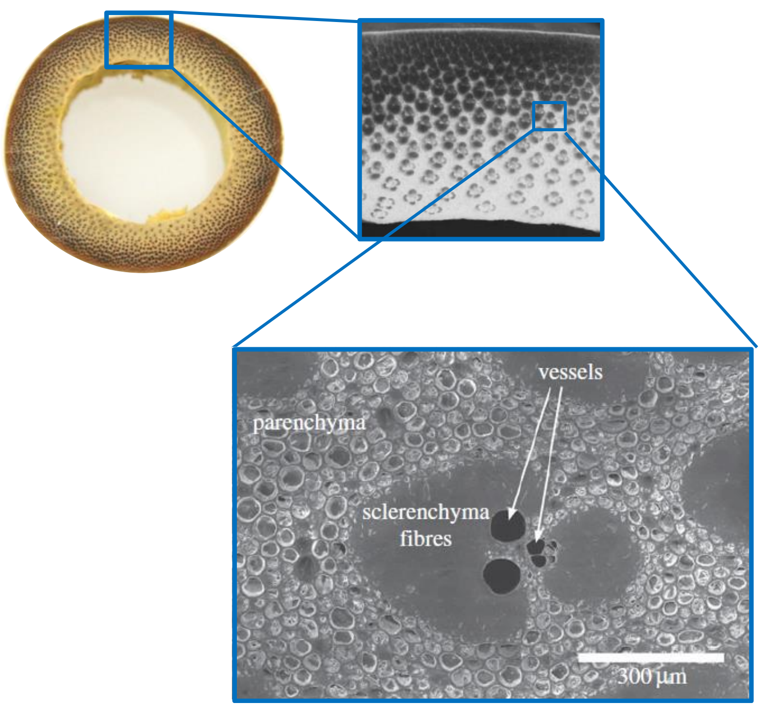
[1]Huang et al, RSER 2018, *Carbon emission of global construction sector*

intro & motivation

challenges

engineering design → lack

- standardization and design codes
- member connections
- durability
- fire resistance



bamboo forms/types

- **timber mimicking**
  laminated, cross laminated etc
  processed and industrialized

- **culm morphology**
  (akin to uni-directional, fiber-reinforced polymers) low tensile strength perpendicular to the fibers

lashing

fish-mouth

Dixon & Gibson, JRSI 2014, *The structure and mechanics of Moso bamboo material*

intro & motivation

bamboo structures

IBUKU Green Village, Bali

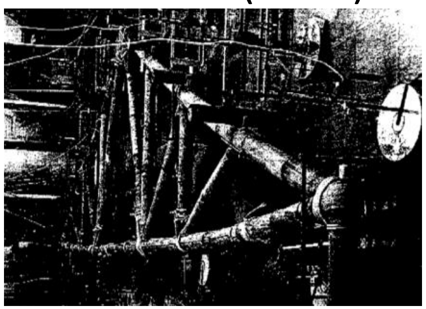
https://inhabitat.com/tag/bamboo-architecture/

state of the art

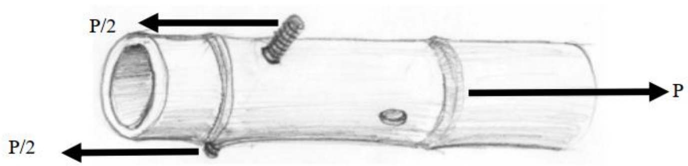
dowel-type connections

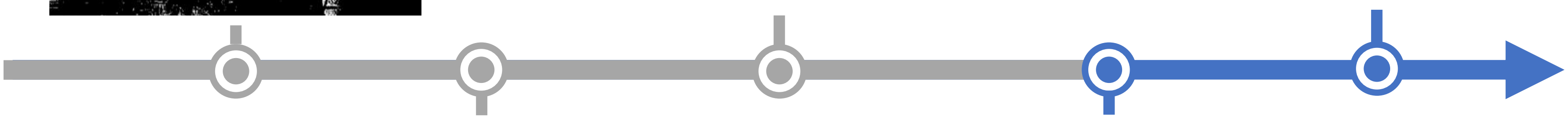
rational design
Wang & Yang (2019),
Correal et al. (2021)

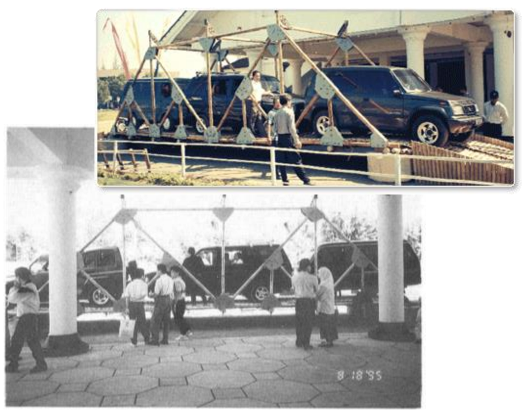
earliest systematic research
Janssen (1981)



empirical design
Columbian code
NSR-10 (2010)





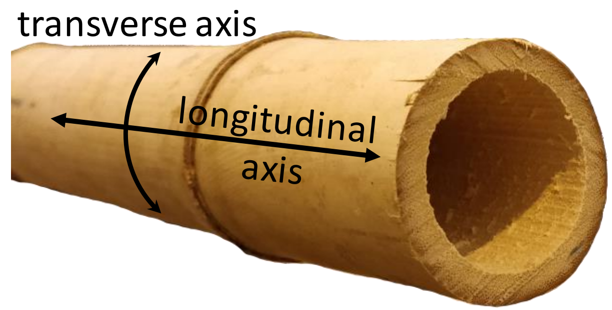


connections with strength
Morisco and Mardjono (1995)

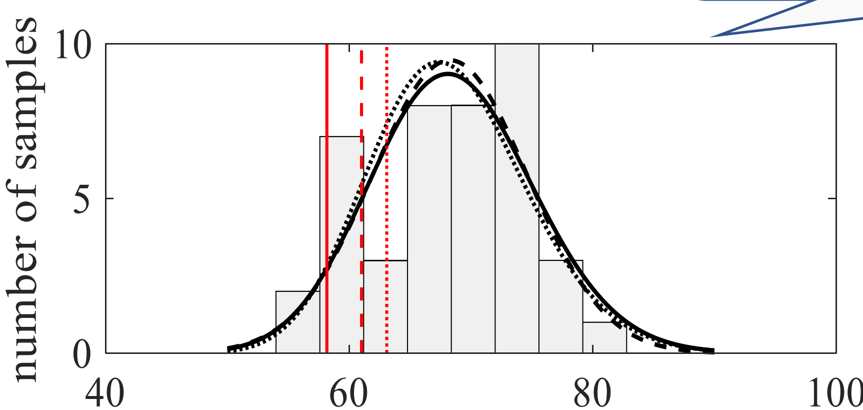
connections with ductility
Sassu et al. (2016)

question 1

axial member behaviour



how to cope with and design for the natural variability of the bamboo culms?



compressive strength MPa

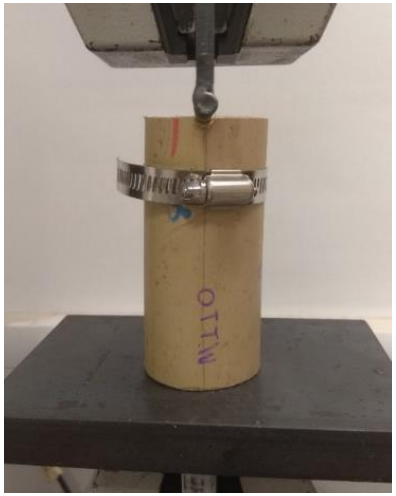
design for **variability**:

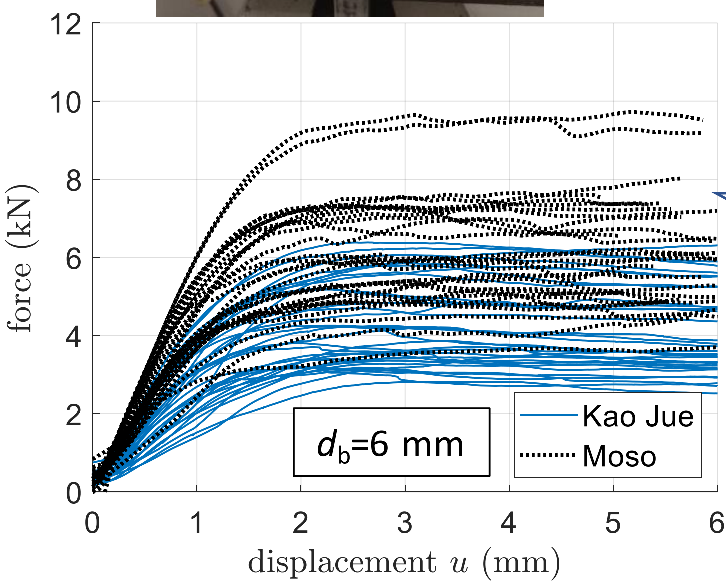
- **culm geometry**
  along the length (longitudinal axis), cross section, thickness

- **mechanical properties**
  … all of them, natural material, multiple species

question 2

embedment behaviour



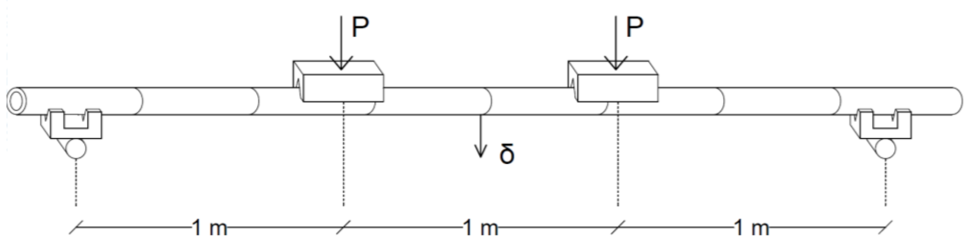


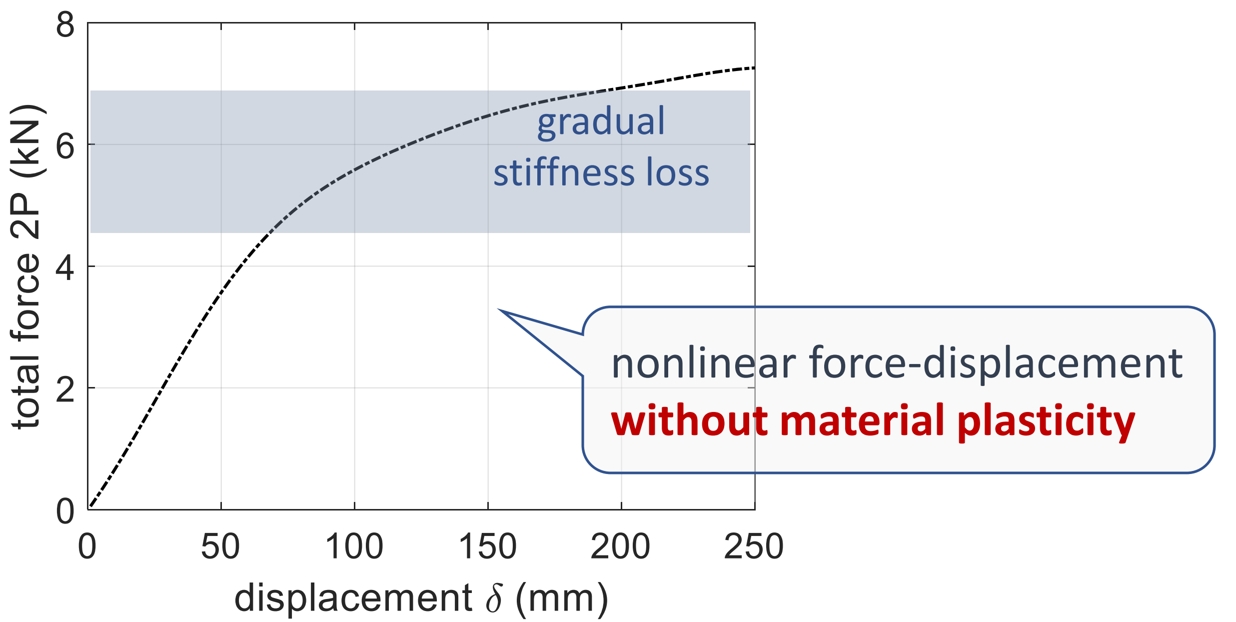
- **2 bamboo species** (Moso and Kao Jue)
- testing standard **ASTM D5764** for timber

experimental force-displacement curves exhibit **high variability** can we predict the behaviour?

question 3

bamboo culm flexure





[1]Lorenzo et al, CBM 2021, *Non-linear behavior and failure mechanism of bamboo poles in bending*
[2]Trujillo et al, ICE-Struct and Build 2017, *Flexural properties as a basis of bamboo strength grading*

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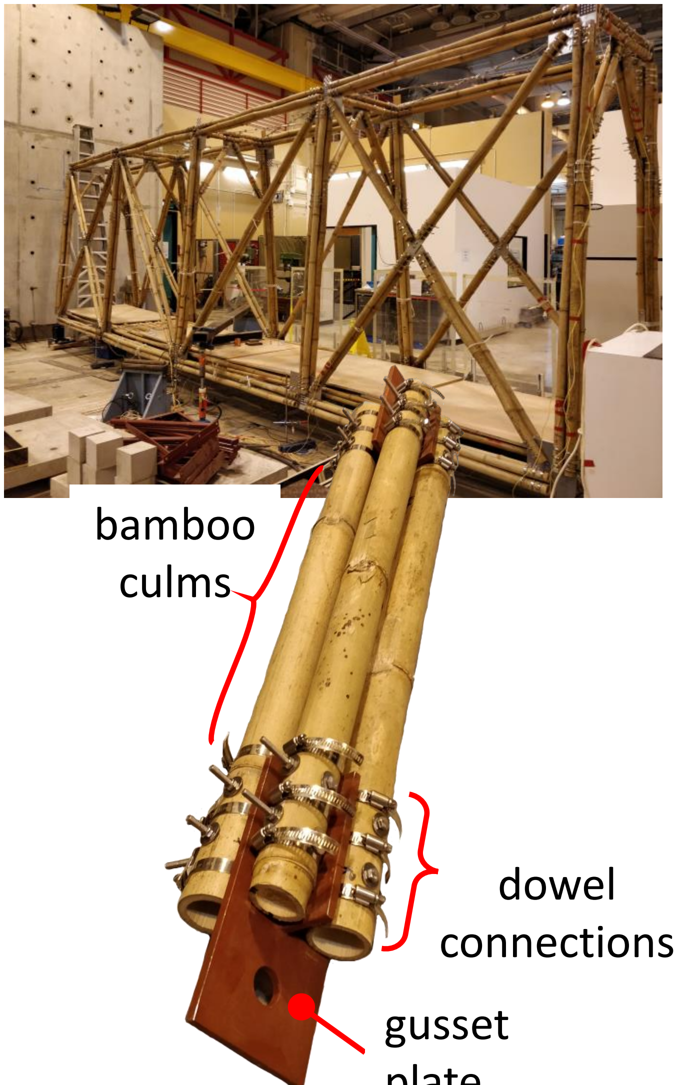
design premise

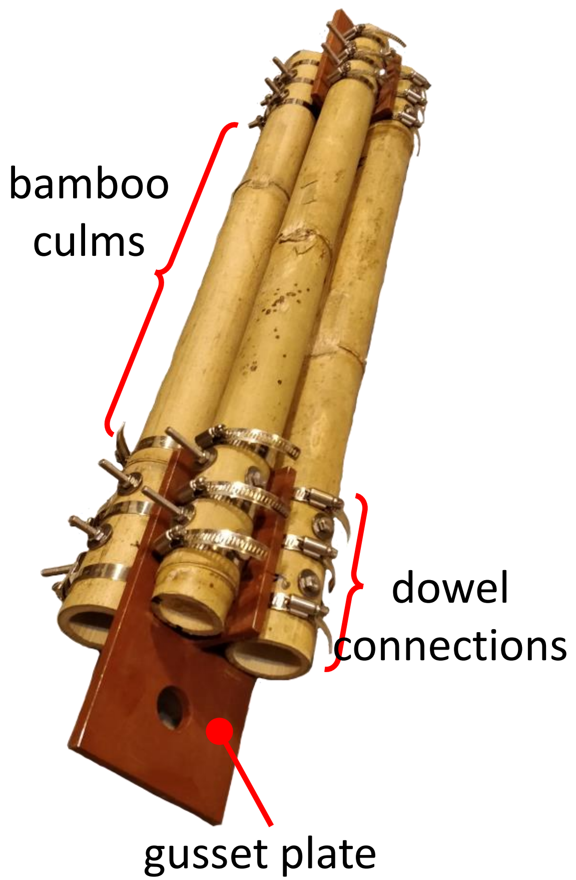
multi-culm bamboo member with steel connectors



- proposed structural members:
  multiple bamboo culms
  bolted on **steel connectors** at their ends
- multiple culms per member:
  more bamboo species
  increased **redundancy** on structural member
- steel ends enable the **steel-to-steel connection** of structural members,
  negating many design ambiguities
- thorough understanding of mechanical behaviour of the proposed structural members →
  emphasis on the **bolt embedment** phenomenon
- conventional structural forms (trusses) →
  facilitates adoption of **bamboo**

design premise

coping with variability



natural variability of bamboo culms
managed through an **original combination** of

i. grading
- unviable and defective culms removed
- use bamboo culms with
  eg 40 – 60 mm external diameters

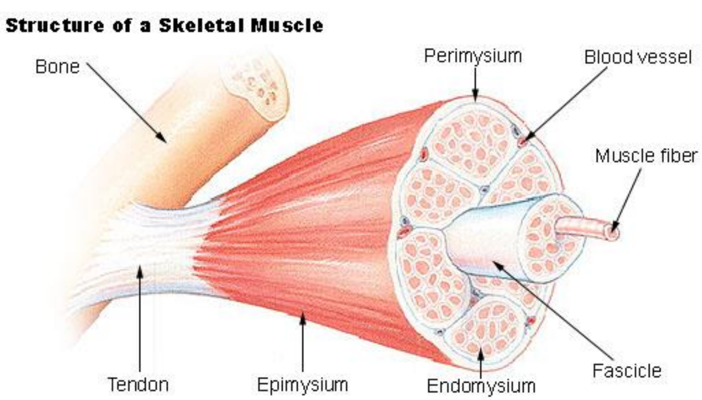
ii. multiple bamboo culms
- eg 4 bamboo culms combined
  into a single member

iii. capacity design principles
- establish a desired hierarchy of capacities

[Pradhan & Dimitrakopoulos ASCE *J. of Struc. Eng.,* 2021]

design premise

coping with variability



multiple parallel elements in a member is a common practice/ observed in nature

multiple culms - premise:

- highly unlikely for multiple culms to possess unfavourable values of (e.g. geometric/material) properties simultaneously
- same average value:

$$\bar{X} = \sum_{i=1}^{N}(X_i/N)$$

- **variance reduces**:

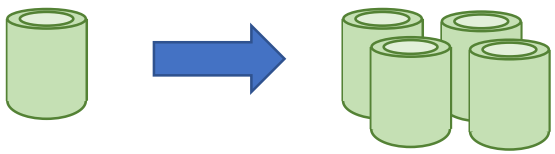
$$\sigma_{\bar{X}}^2 = \sum_{i=1}^{N}\sigma_{X_i/N}^2 = \sigma_X^2/N$$

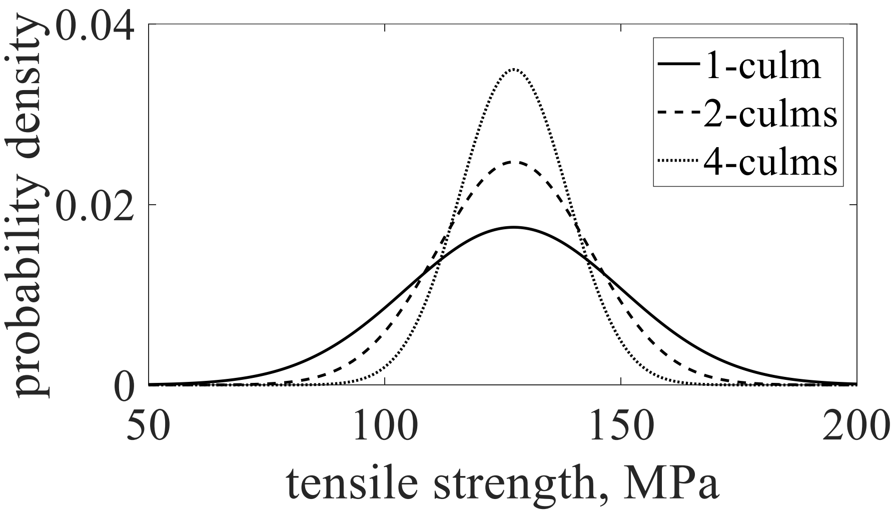
$$CV_{\bar{X}} = CV_{X_1}/\sqrt{N}$$

[Pradhan & Dimitrakopoulos ASCE *J. of Struc. Eng.*, 2021]

design premise

coping with variability





coping with variability - example:
tensile strength of bamboo (Kao Jue) culms

- found to be normally distributed
- expected value and variance of a **single** bamboo **culm**:

$$\mu_X = 127.33 \text{ MPa} \qquad \sigma_X^2 = 521.3$$

expected value and variance of average tensile strength in

- **2-culm** axial member

$$\mu_{\bar{X}} = 127.33 \text{ MPa} \qquad \sigma_X^2 / 2 = 260.6$$

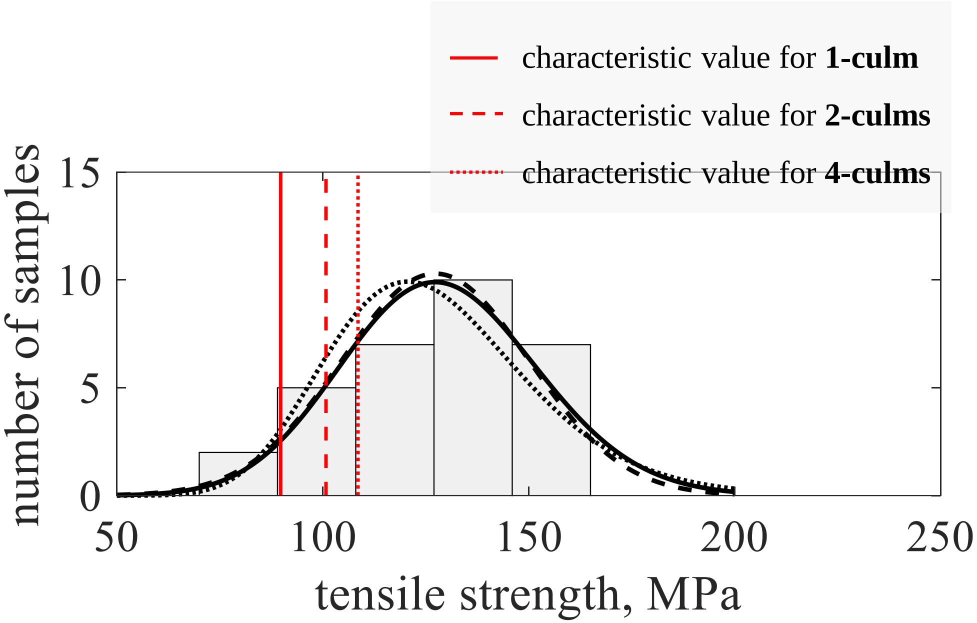
- **4-culm** axial member

$$\mu_{\bar{X}} = 127.33 \text{ MPa} \qquad \sigma_X^2 / 4 = 130.3$$

[Pradhan & Dimitrakopoulos ASCE *J. of Struc. Eng.*, 2021]

design premise

coping with variability



number of culms	$\bar{x}_{0.05}$	$\gamma_{\bar{X},m}$
1 culm	89.8 MPa	1.58
2 culm	100.8 MPa	1.30
4 culm	108.6 MPa	1.18

characteristic values as per EN 1990:2002:

- 5^{th} ($\bar{x}_{0.05}$) and 95^{th} ($\bar{x}_{0.95}$) percentile values

design values

- 0.1^{th} ($\bar{x}_{0.001}$) percentile values of material properties

- ***material partial safety factor*** for N-culm member:

$$\gamma_{\bar{X},m} = \frac{\bar{x}_{0.05}}{\bar{x}_{0.001}}$$

- the specific percentile values and material partial safety factors become **less conservative** as number of bamboo culms N increases in the member

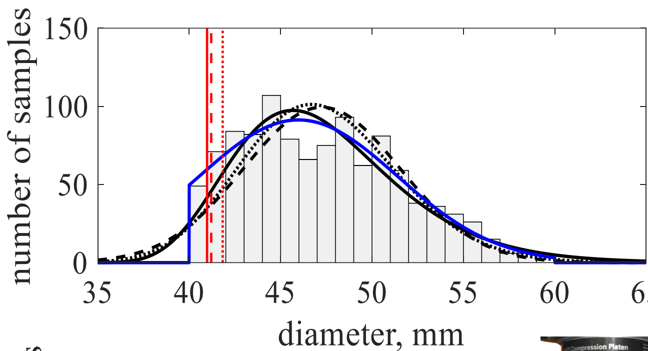
[Pradhan & Dimitrakopoulos ASCE *J. of Struc. Eng.*, 2021]

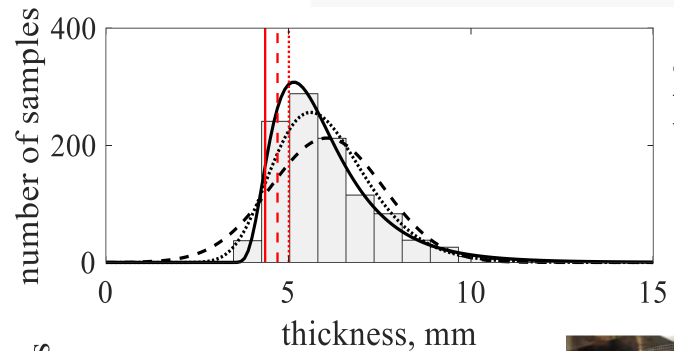
design premise

coping with variability

characteristic value for **1-culm**
characteristic value for **2-culms**
characteristic value for **4-culms**

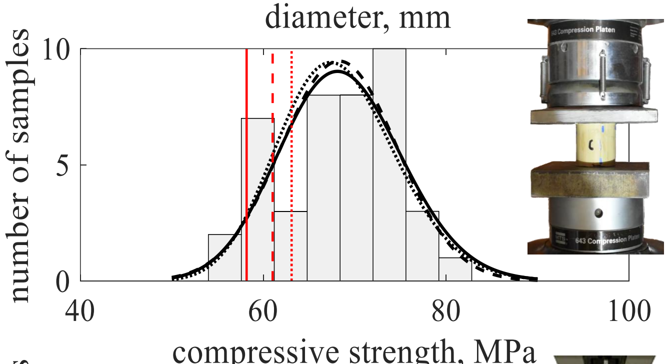
adopted fit: truncated normal

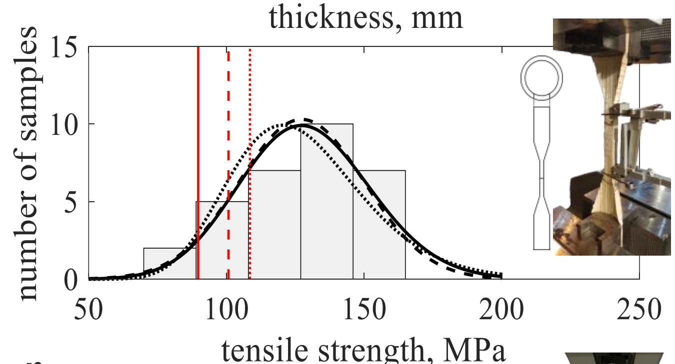




adopted fit: log3

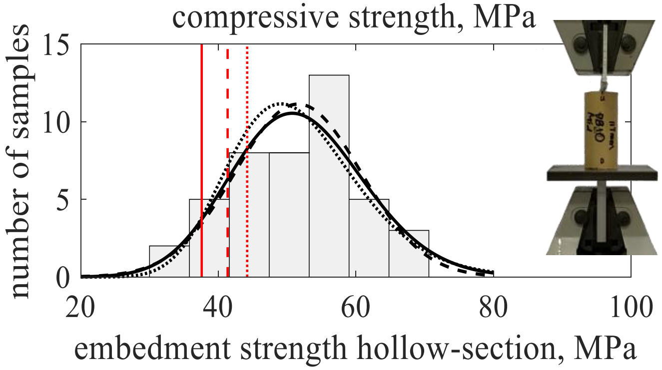
adopted fit: log-normal

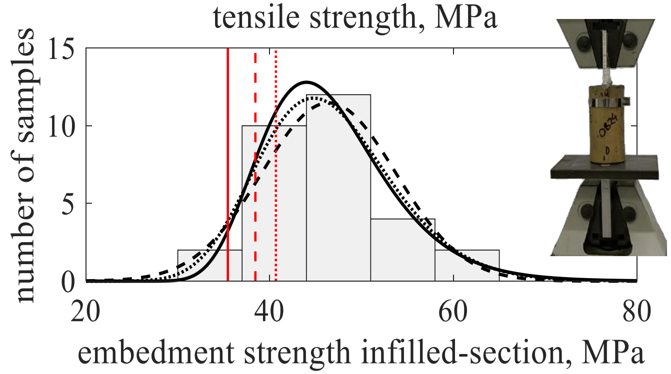




adopted fit: normal

adopted fit: log-normal



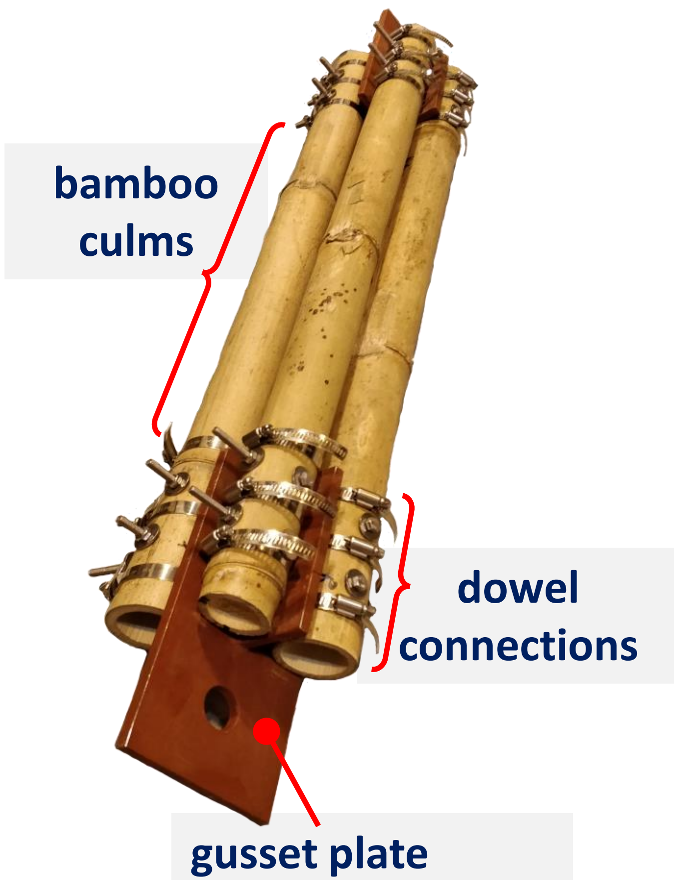


adopted fit: log-normal

[Pradhan & Dimitrakopoulos ASCE *J. of Struc. Eng.*, 2021]

design premise

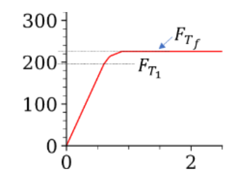
coping with variability



capacity design to achieve **reliable** and predictable mechanical **performance**, including a **desirable failure** mode

premise: establish a **desired hierarchy** of capacities

I. **dowel connections** yielding
   - predictable and ductile → **should fail first !**



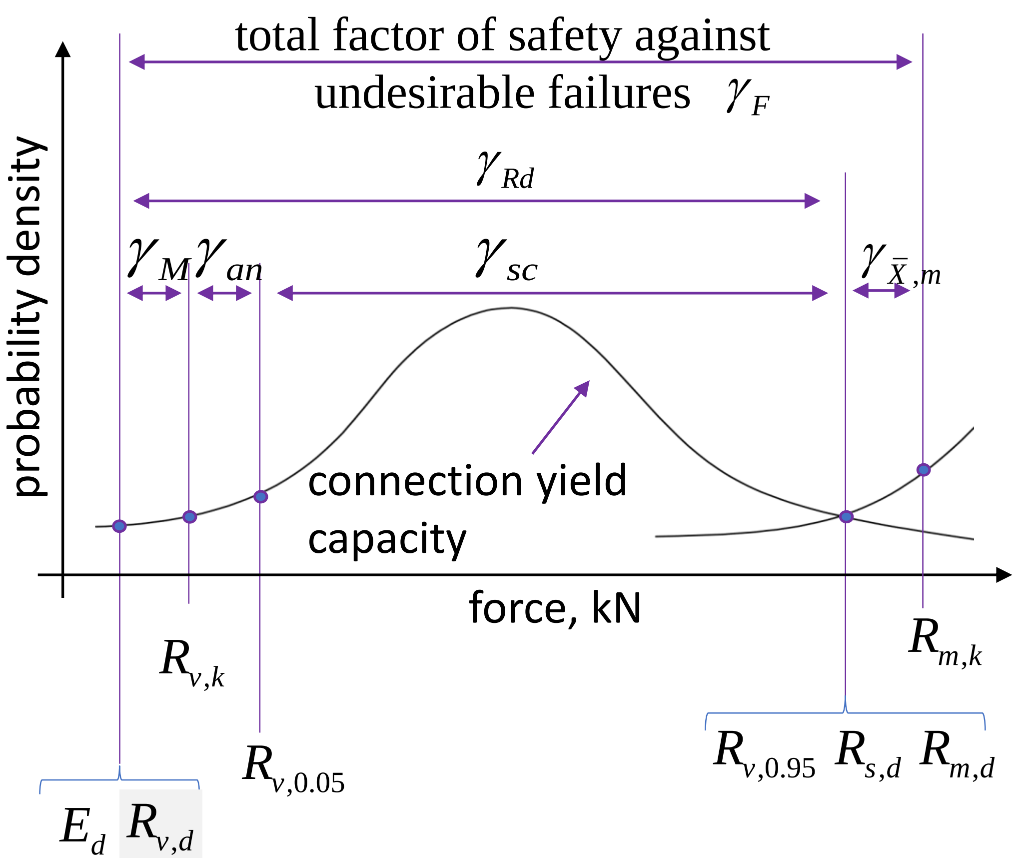
II. **bamboo culms** are **brittle**
   - designed stronger than the dowels
   - **confinement** (hose-clamps) to prevent premature failure by longitudinal splitting

III. **gusset plates**
   - for joint integrity Gusset plates should be designed stronger than dowel connection

[Pradhan & Dimitrakopoulos ASCE *J. of Struc. Eng.*, 2021]

design premise

capacity design principle: hierarchy of failure modes



only the experimental distribution of connection yield capacity required

(1) design capacity of

bamboo culms: $R_{m,d} \geq R_{v,0.95}$

steel gusset plate: $R_{s,d} \geq R_{v,0.95}$

↓

(2) experimental yield capacity of dowel-type connection

95th percentile: $R_{v,0.95} = \gamma_{sc} R_{v,0.05}$

5th percentile: $R_{v,0.05} = \gamma_{an} R_{v,k}$

↓

(3) characteristic yield capacity of dowel-type connection

$R_{v,k} = \gamma_M R_{v,d}$

↓

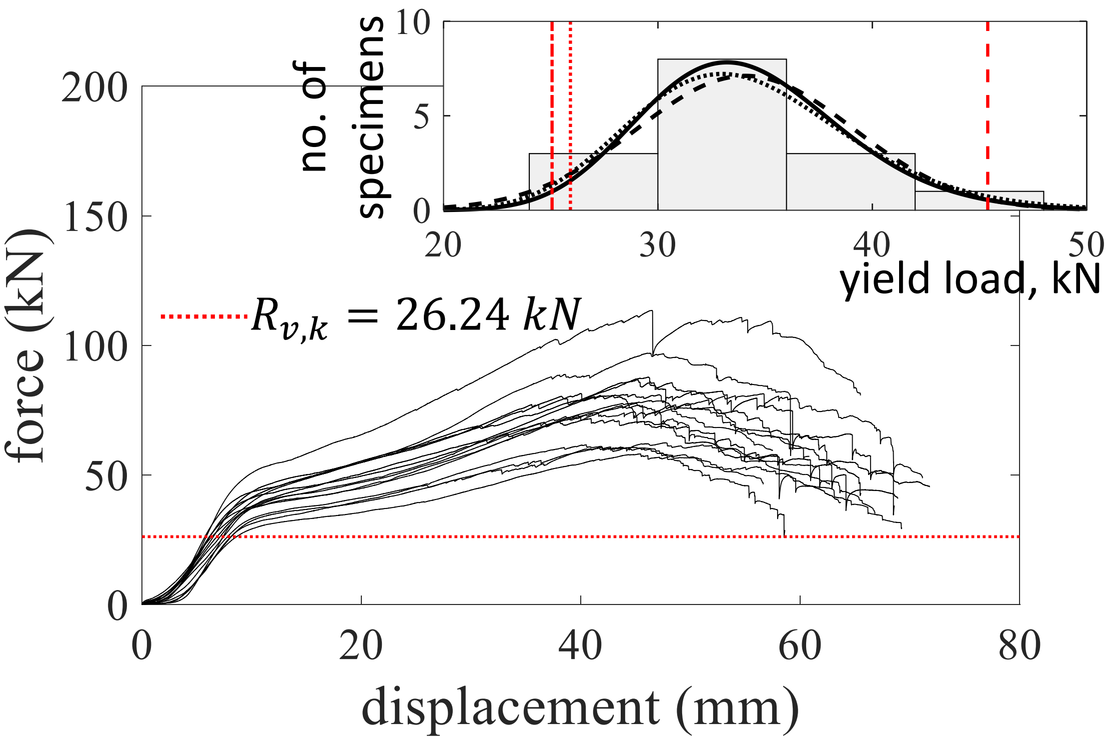
(4) design capacity of dowel-type connection

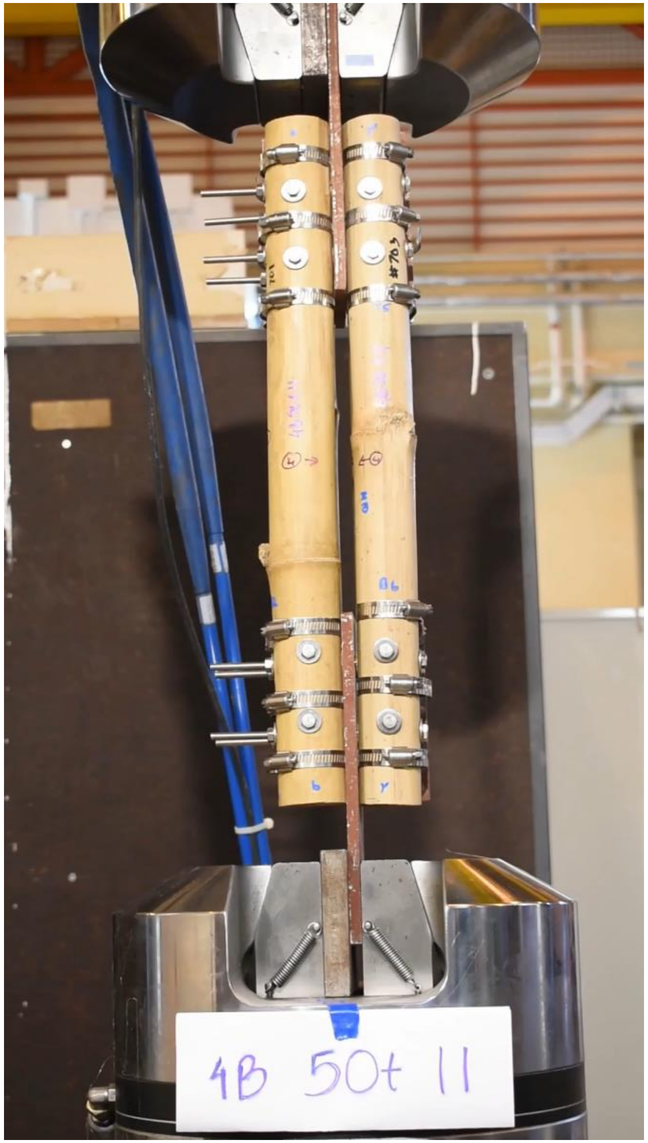
$R_{v,d} \geq E_d$

[Pradhan & Dimitrakopoulos ASCE *J. of Struc. Eng.,* 2021]

experimental program

hollow section tension (Type B)



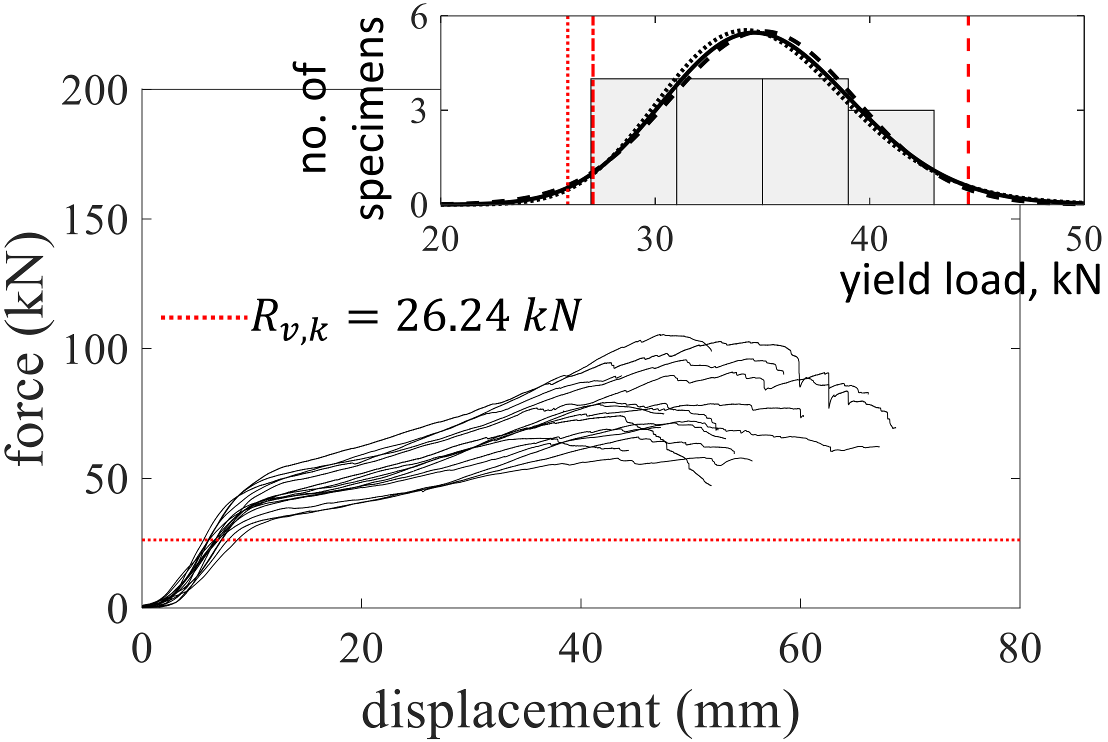


- average yield capacity: $34.11\ kN$
- average maximum capacity: $78.33\ kN$
- average ductility: 7.44
- 15 samples

[Pradhan & Dimitrakopoulos ASCE *J. of Struc. Eng.*, 2021]

experimental program

hollow section compression (Type B)

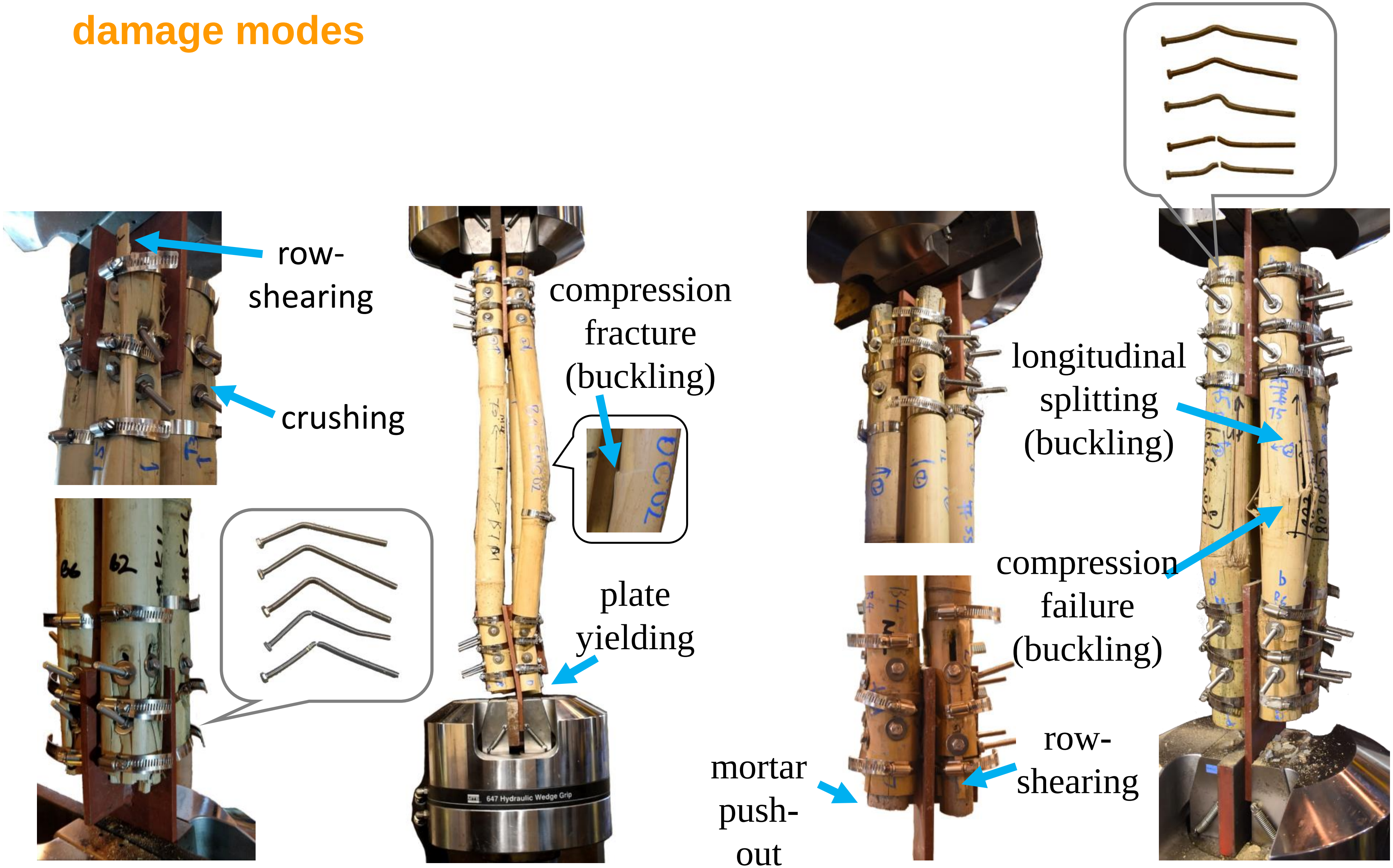


- average yield capacity: 35.04 kN
- average maximum capacity: 79.95 kN
- average ductility: 7.94
- 15 samples

[Pradhan & Dimitrakopoulos ASCE *J. of Struc. Eng.*, 2021]

experimental program

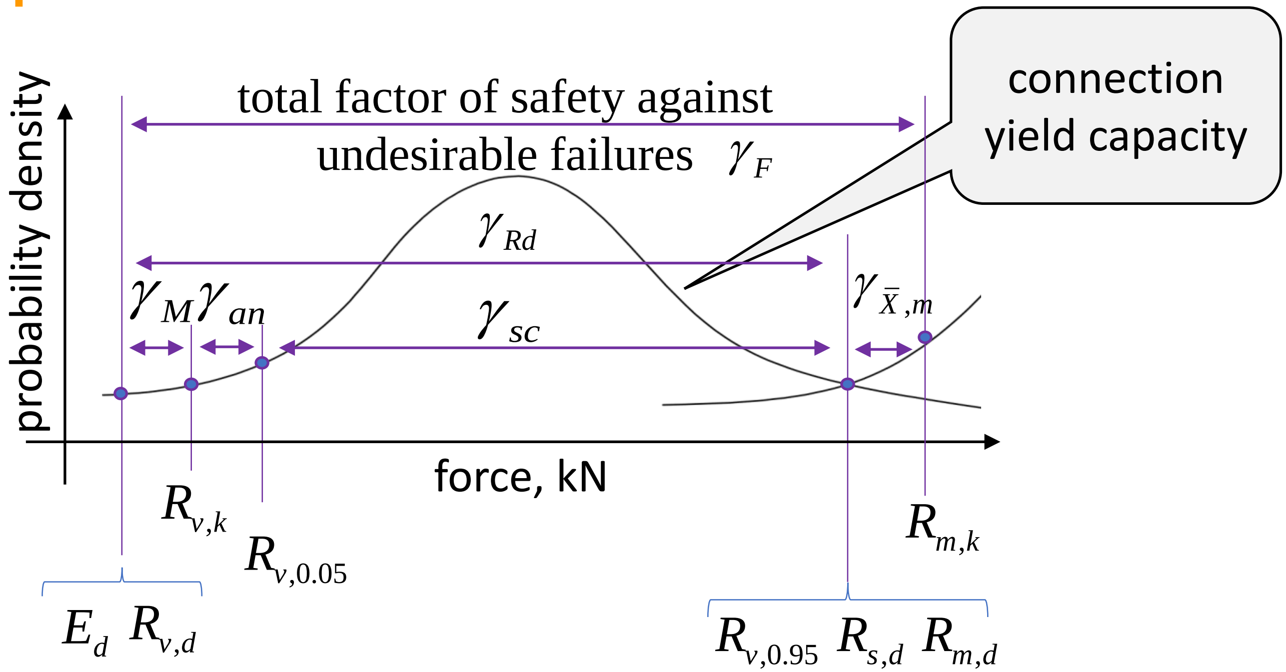
damage modes



[Pradhan NPN & Dimitrakopoulos EG, ASCE *J. of Struc. Eng.*, 2021]

capacity design

calibration of partial factors



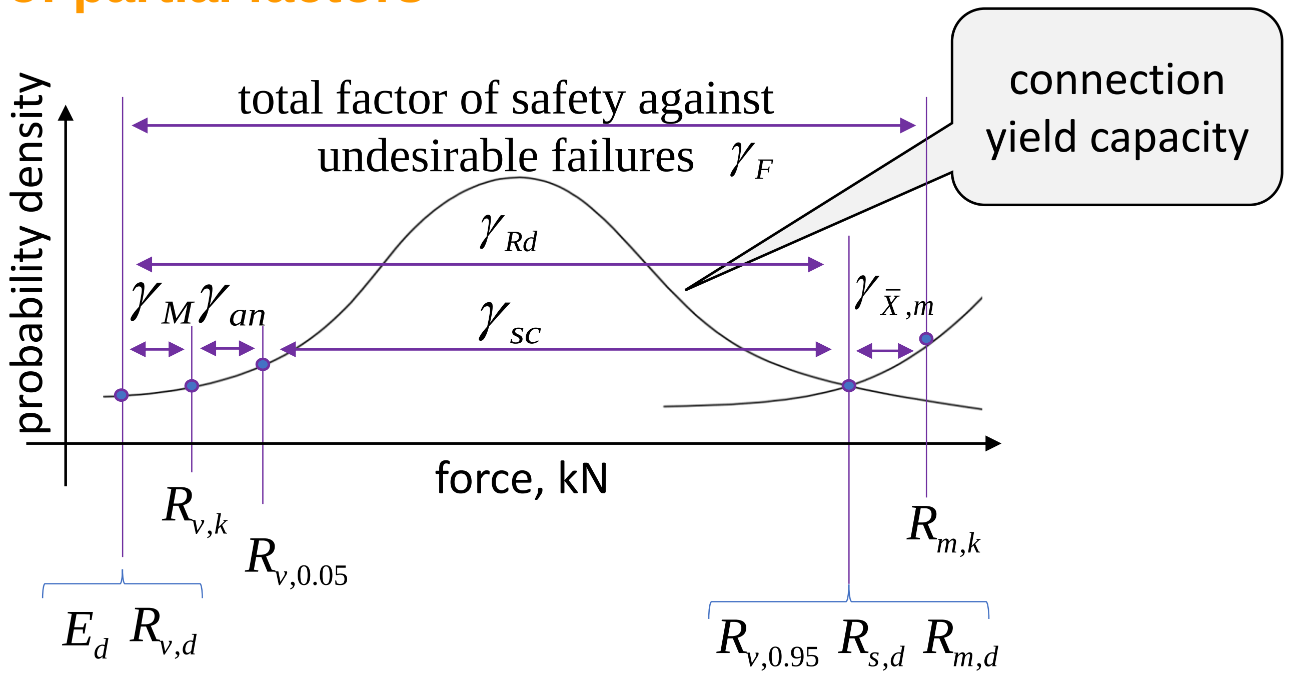
overstrength factor: $\gamma_{Rd} = \gamma_{sc} \times \gamma_{an} \times \gamma_M$

- $\gamma_{sc} = R_{v,0.95}/R_{v,0.05}$ = scatter in experimental yield capacity
- $\gamma_{an} = R_{v,0.05}/R_{v,k}$ = error in analytical prediction of yield capacity
- $\gamma_M = R_{v,k}/R_{v,d}$ = safety factor of resistance

- $R_{v,k}$ is estimated analytically using European Yield Model equations
- $R_{v,d} = R_{v,0.001}$ as per EN1990

[Pradhan NPN & Dimitrakopoulos EG, ASCE *J. of Struc. Eng.*, 2021]

calibration of partial factors



total factor of safety against undesirable failure is:

$$\gamma_F = \gamma_{Rd} \times \gamma_{\bar{X},m}$$

- $\gamma_{\bar{X},m}$ is the pertinent average material partial factor of safety for N-culm member

[Pradhan NPN & Dimitrakopoulos EG, ASCE *J. of Struc. Eng.*, 2021]

design premise

calibration of partial factors

type	$\bar{\gamma}_{sc}$	$\bar{\gamma}_{an}$	$\bar{\gamma}_{M}$	$\bar{\gamma}_{Rd}$
hollow-section	1.65	**1.02**	1.31	2.20
infilled-section	2.05	**0.97**	1.61	3.09

$\gamma_{sc} = \frac{R_{v,0.95}}{R_{v,0.05}}$ → variability

$\gamma_{an} = \frac{R_{v,0.05}}{R_{v,k}}$ → error in analytical prediction of **EYM equations**

$\gamma_{M} = \frac{R_{v,k}}{R_{v,d}}$ → safety factor to achieve desired probability of failure

- $\gamma_{an} \approx 1$, i.e. $R_{v,k} \approx R_{v,0.05}$
    - analytical approach can predict experimental yielding
    - this is partial verification of proposed approach
- $\bar{\gamma}_M = 1.31$ for hollow-section specimens,
  is same as that recommended for timber connections (i.e. $\gamma_M = 1.30$ in EN 1995)
- partial factors are **larger** for mortar infilled specimens
    - larger variability compared to hollow-section specimens

Pradhan & Dimitrakopoulos, *Journal of Structural Engineering* (2021)

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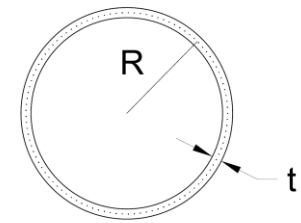
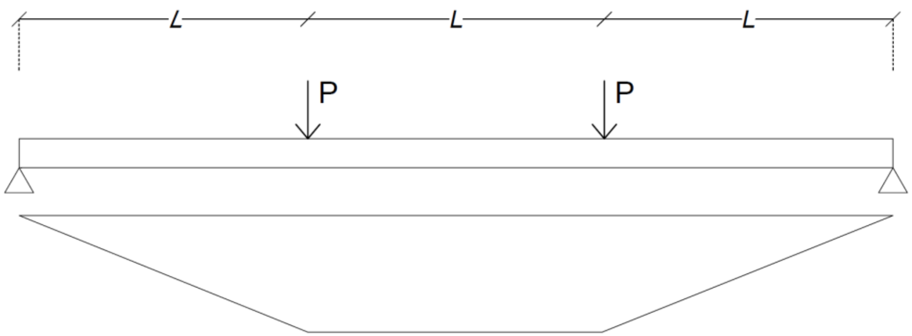
falure load prediction

$$\phi = \frac{R}{t}$$





$E_{\|}$: Young's modulus parallel to the fibers

$E_{\perp}$: Young's modulus perpendicular to the fibers

$\sigma_{c\|}$: compressive strength parallel to the fibers

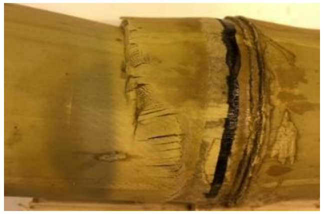
$\sigma_{t\perp}$: tensile strength perpendicular to the fibers

Brazier moment (local kinking):

$$\frac{M_B}{A^{3/2}} = \frac{1}{9\sqrt{\pi}}\left(\frac{E_{\|}E_{\perp}}{\phi}\right)^{1/2}$$

longitudinal compression:

$$\frac{M_l}{A^{3/2}} = \frac{1}{\sqrt{8\pi}}\sigma_{c\|}\phi^{1/2}$$



circumferential tension:

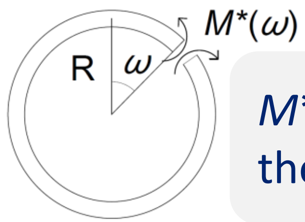
$$\frac{M_o}{A^{3/2}} = 0.18\left(\sigma_{t\perp}E_{\|}\right)^{1/2}\left[1-1.24\left(\frac{\sigma_{t\perp}}{E_{\perp}}\right)\phi\right]$$

shear failure?

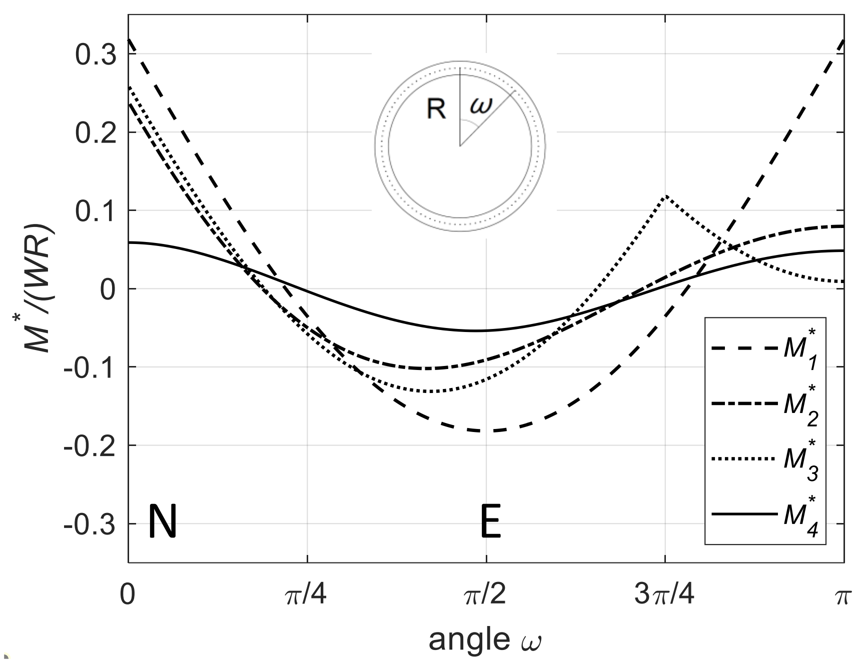
Wegst & Ashby, JMS 2007, *The structural efficiency of orthotropic stalks, stems and tubes*

bamboo culm flexure

falure load prediction: **circumferential tension**

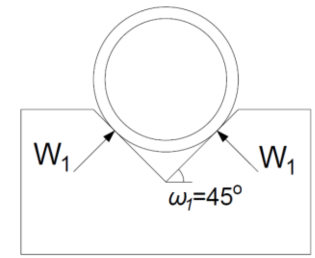


*M**: bending moment in the cross-section plane

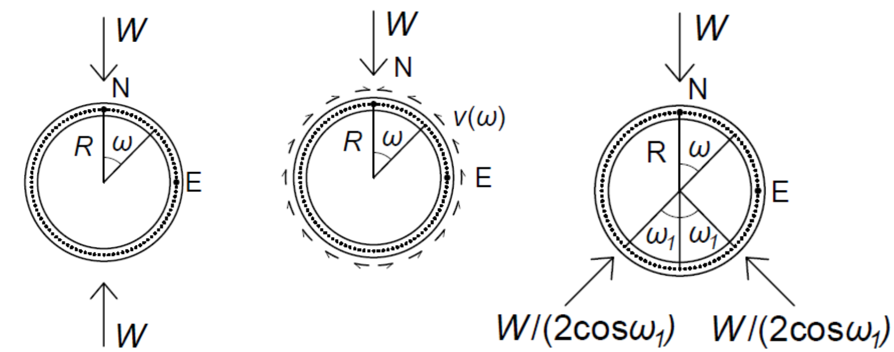


maximum *M** at pont N

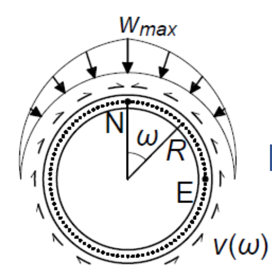
four load cases:



Case 1 (M^*_1) Case 2 (M^*_2) Case 3 (M^*_3)



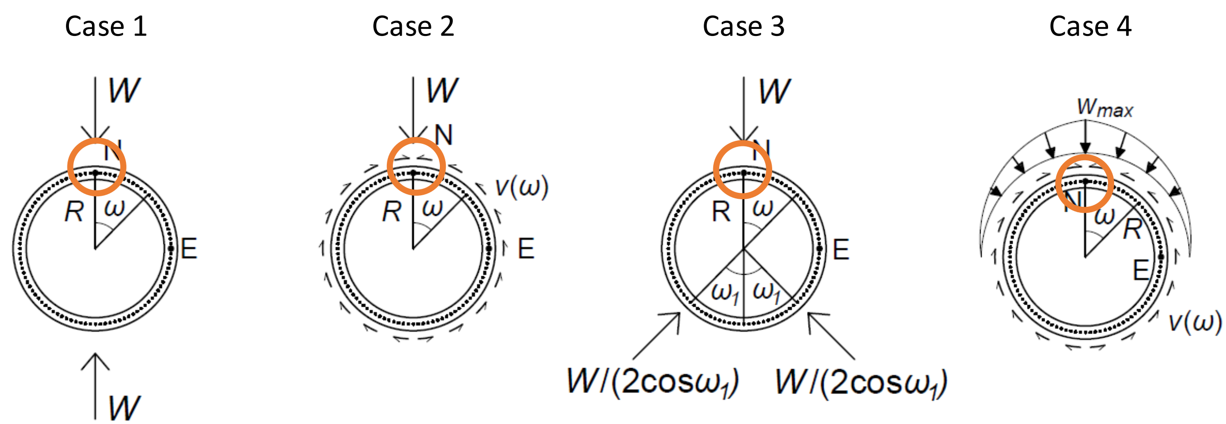
Case 4 (M^*_4)

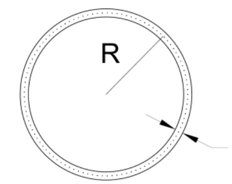


$$v(\omega) = \frac{W \sin \omega}{\pi R}, \qquad W = \frac{4 w_{max} R}{\pi}$$

bamboo culm flexure

falure load prediction: **circumferential tension**





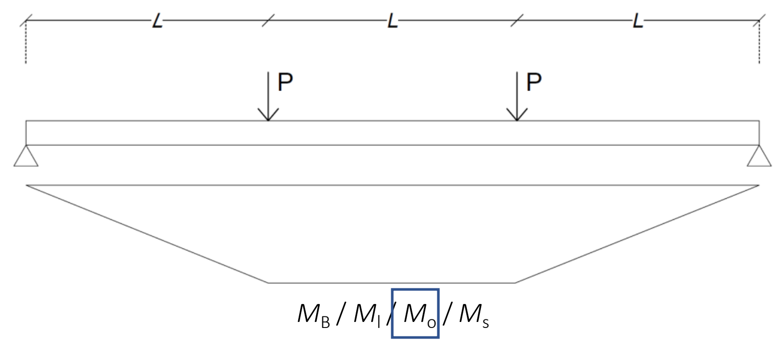
$$\phi = \frac{R}{t}$$

$$\frac{M_{o,1}}{A^{3/2}} = 0.1364\left(\sigma_{t\perp}E_{\parallel}\right)^{1/2}\left[1-0.7012\left(\frac{\sigma_{t\perp}}{E_{\perp}}\right)\phi\right]$$

$$\frac{M_{o,2}}{A^{3/2}} = 0.1114\left(\sigma_{t\perp}E_{\parallel}\right)^{1/2}\left[1-0.4680\left(\frac{\sigma_{t\perp}}{E_{\perp}}\right)\phi\right]$$

$$\frac{M_{o,3}}{A^{3/2}} = 0.1041\left(\sigma_{t\perp}E_{\parallel}\right)^{1/2}\left[1-0.4086\left(\frac{\sigma_{t\perp}}{E_{\perp}}\right)\phi\right]$$

$$\frac{M_{o,4}}{A^{3/2}} = 0.1547\left(\sigma_{t\perp}E_{\parallel}\right)^{1/2}\left[1-0.9024\left(\frac{\sigma_{t\perp}}{E_{\perp}}\right)\phi\right]$$



$E_{\parallel}$: Young's modulus parallel to the fibers

$E_{\perp}$: Young's modulus perpendicular to the fibers

$\sigma_{t\perp}$: tensile strength perpendicular to the fibers

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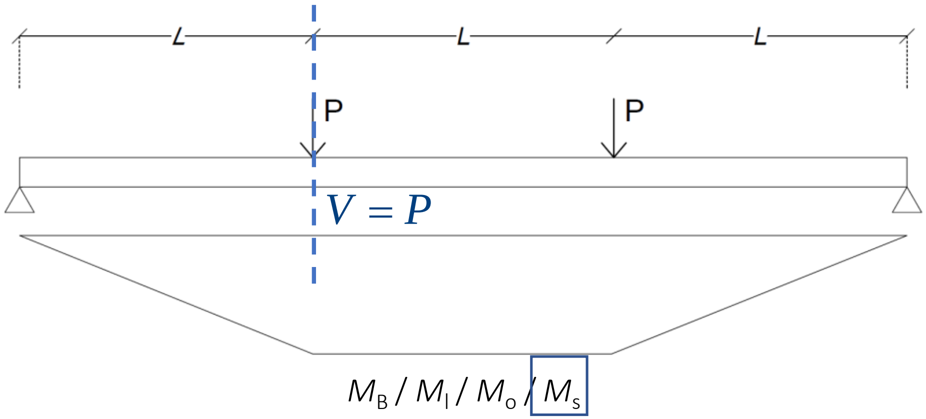
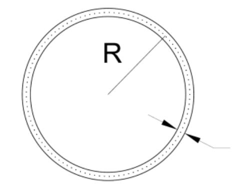
bamboo culm flexure

falure load prediction: **shear failure**



$$\phi = \frac{R}{t}$$



accounts for shear stress concentrations in thick-walled sections

maximum shear stress in the cross-section:

$$\tau_{\max} = \left(2 + \frac{1}{\phi}\right)\frac{V}{A} \; *$$

V = shear force
A = cross-section area

failure moment:

$$\frac{M_s}{A^{3/2}} = \frac{n\tau_{u\|}\sqrt{2}}{\left(2 + \frac{1}{\phi}\right)\sqrt{\pi}}\sqrt{\phi}$$

$\tau_{u\|}$: shear strength parallel to the fibers

$n = \frac{L}{2R}$: normalized with culm diameter shear span length

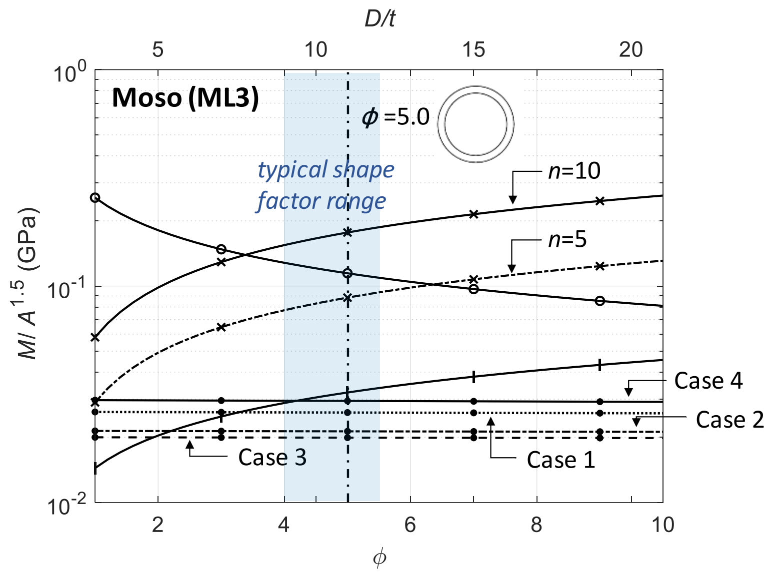
*Hoogenboom & Spaan, 2005, *Shear stiffness and maximum shear stress of tubular members*

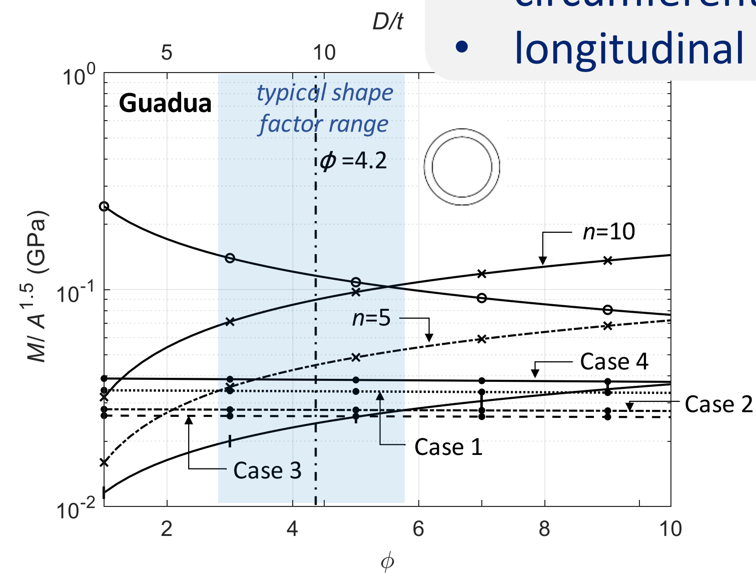
bamboo culm flexure

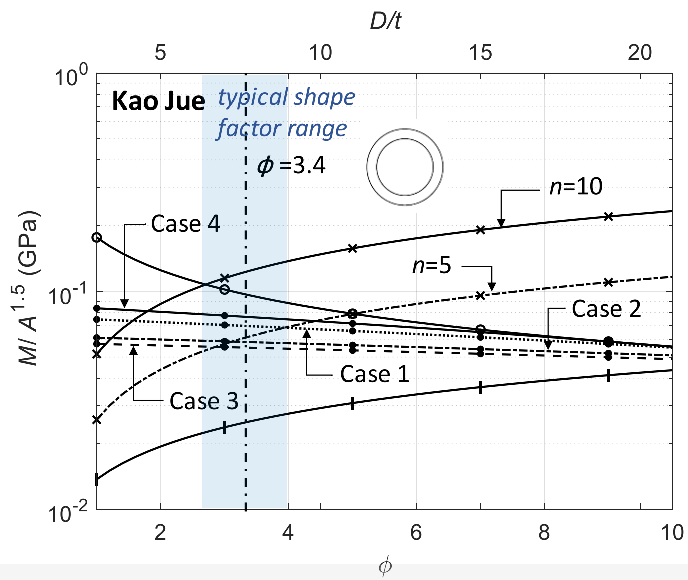
falure load prediction: **failure maps**

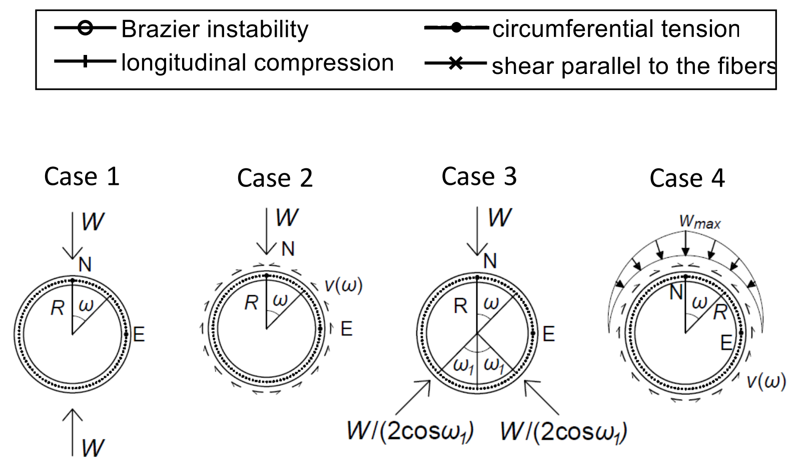
critical failure modes:

- circumferential tension
- longitudinal compression





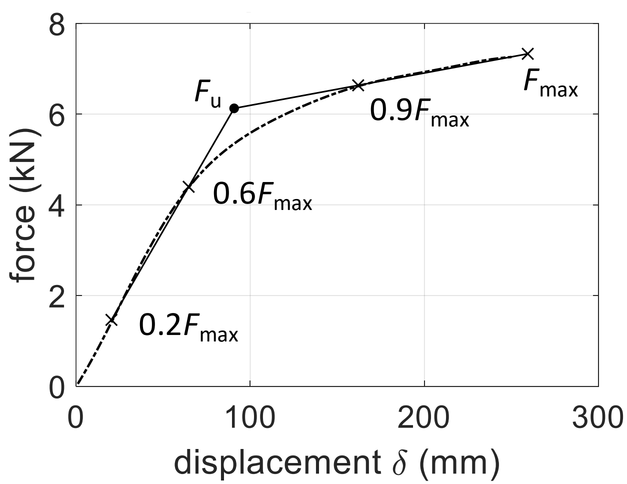


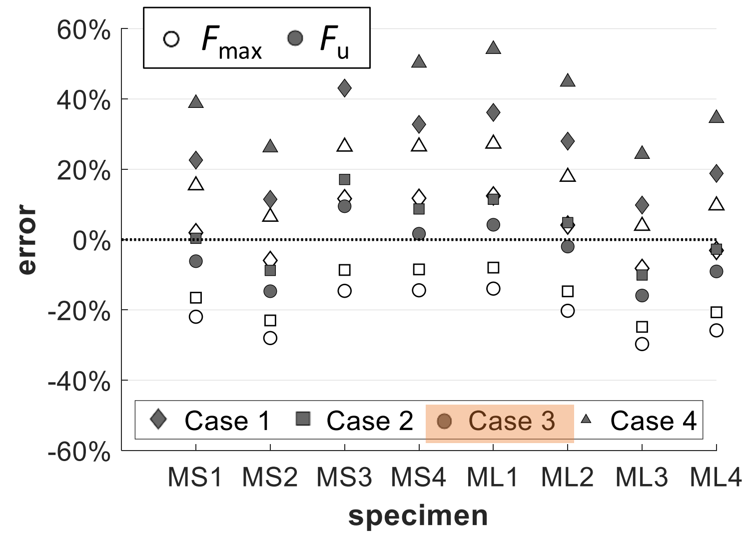


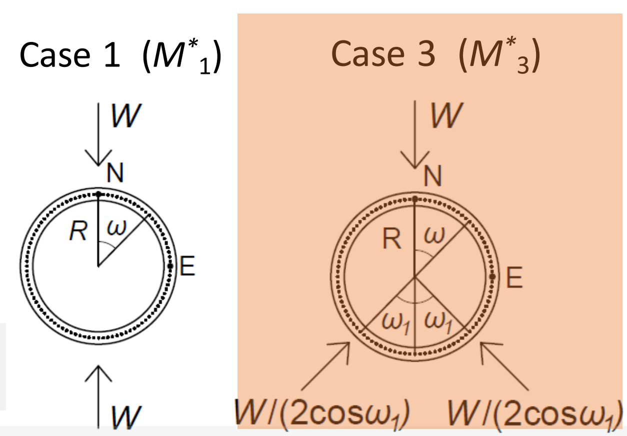
bamboo culm flexure

falure load prediction: **comparison with experimental data**

Moso







Moso (*circumferential tension* failure)

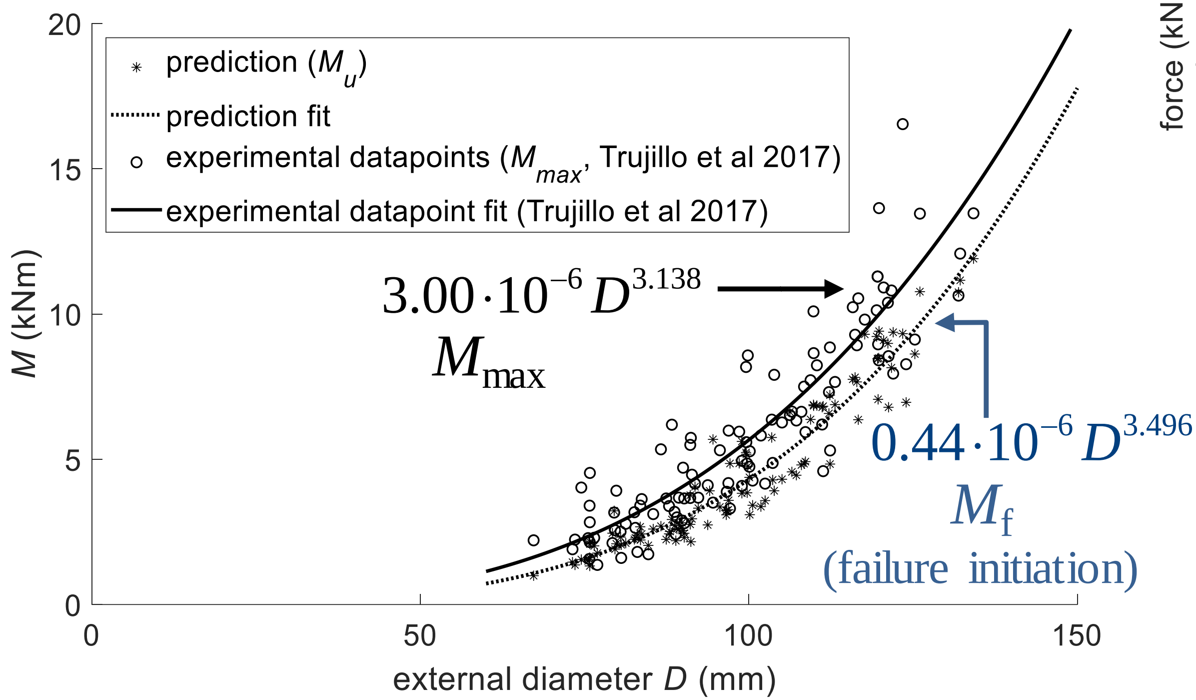
- prediction of Case 3 is closer to F_u
- prediction of Case 1 is closer to F_{max}

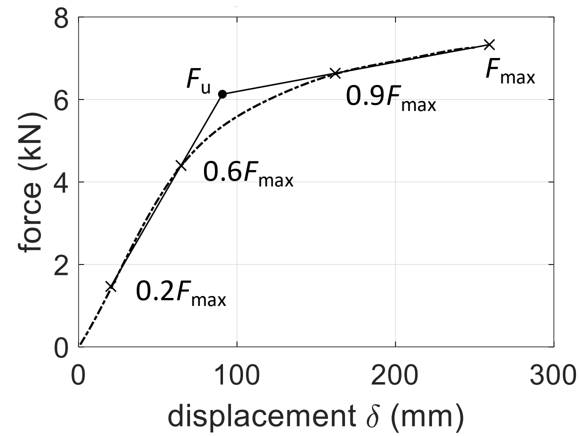
experimental data from:
Lorenzo et al, CBM 2021, *Non-linear behavior and failure mechanism of bamboo poles in bending*

bamboo culm flexure

falure load prediction: **comparison with experimental data**

Guadua





Guadua: failure either because of ***longitudinal compression*** or because of ***circumferential tension***

experimental data from:
Trujillo et al, ICE-Struct and Build 2017, *Flexural properties as a basis of bamboo strength grading*

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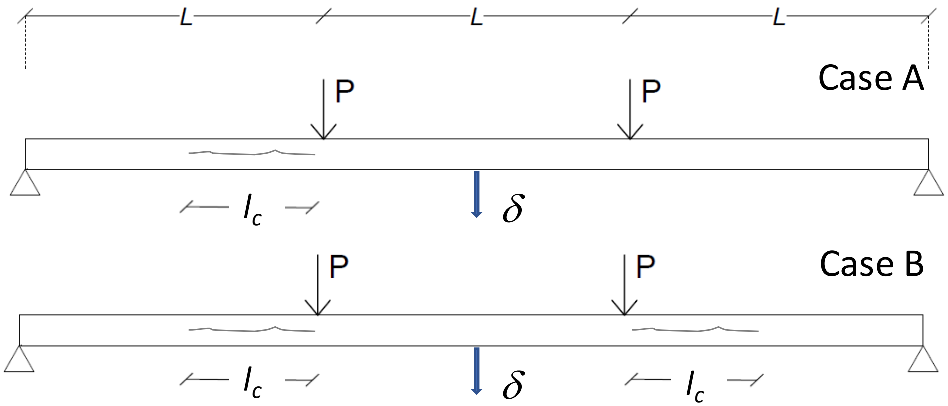
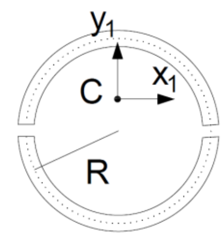
bamboo culm flexure

stiffness loss prediction: **two parallel cracks**



cracked cross-section:



cross-section moment of inertia:

$$\frac{I_{CC}}{I} = 1 - \frac{64}{9\pi^2} = 0.28$$

I_{CC} : cracked cross-section

I : intact cross-section

stiffness loss (virtual work method):

stiffness of cracked culm

$$\frac{K_{c,i}}{K_b} = \left[1 + b_i n_1 \left(n_1^2 - 3n_1 + 3\right)\right]^{-1}, \quad K = \frac{2P}{\delta}$$

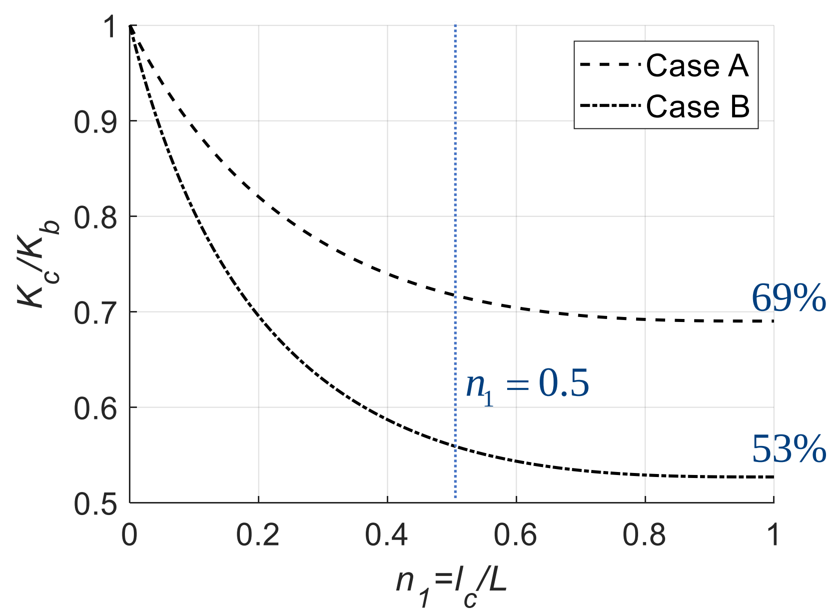
stiffness of intact culm

$$n_1 = \frac{l_c}{L}$$

l_c → crack length

L → shear span length

$$b_i = \begin{cases} 0.45 & \text{for Case A} \\ 0.90 & \text{for Case B} \end{cases}$$



outline

intro & motivation

design for variability

explain flexural behavior

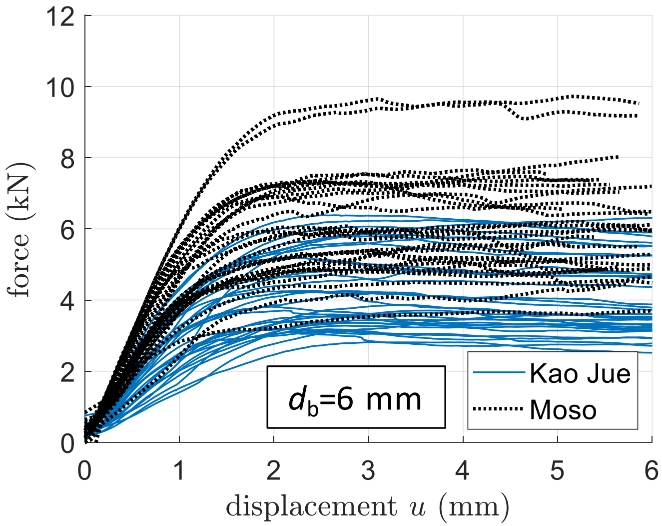
predict embedment behavior

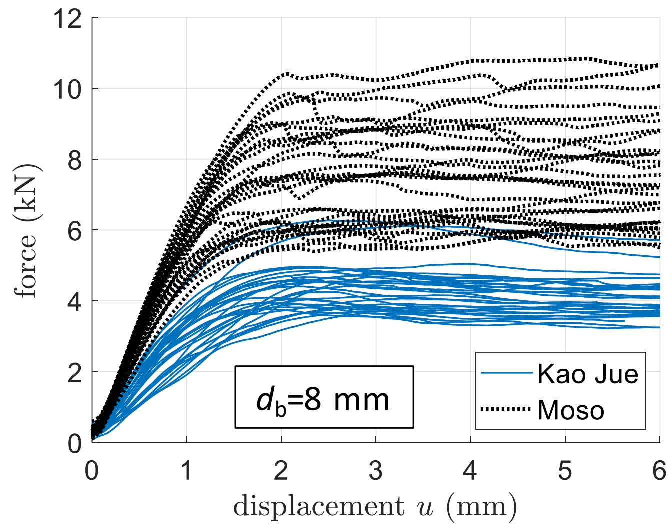
full-scale bamboo footbridge

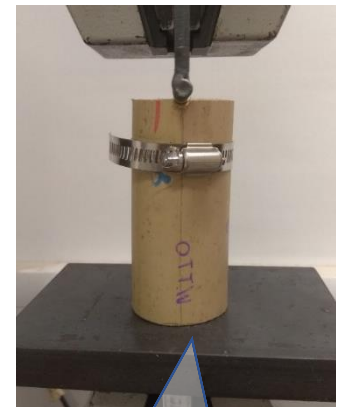
conclusions

bolted connections: **embedment property prediction**

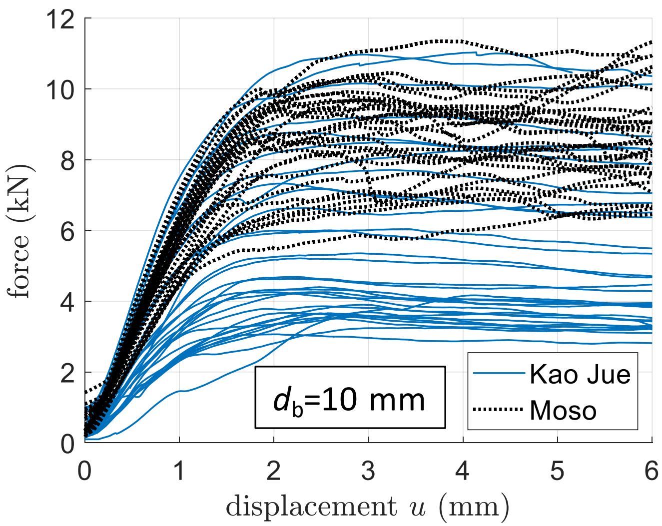
experimental program







confinement to prevent early splitting



- **two bamboo species** (Moso and Kao Jue)
- **three bolt diameters** (6 mm, 8 mm and 10 mm)
- testing standard **ASTM D5764** for timber

experimental force-displacement curves exhibit **high variability**

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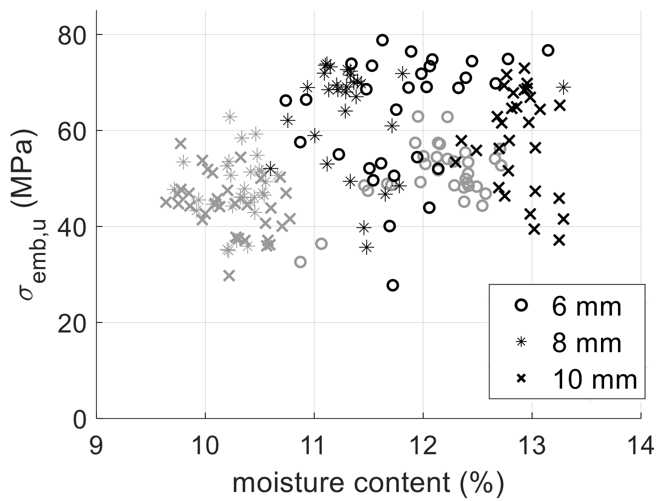
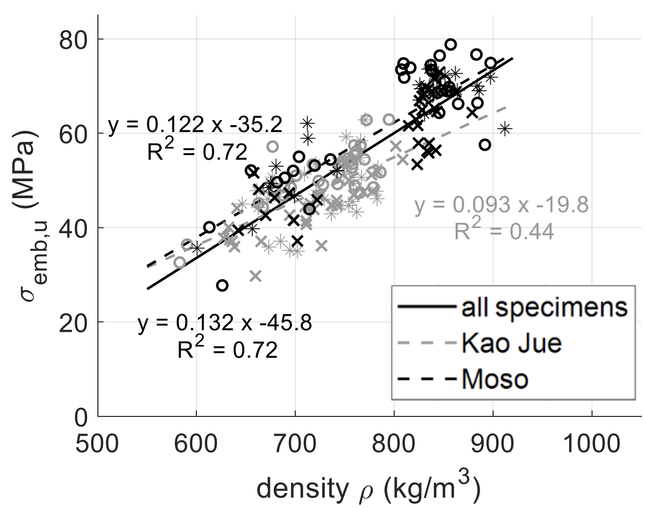
embedment property prediction

based on individual parameters





embedment strength

$$\sigma_{emb,u} = \frac{F_y}{2d_b t}$$

F_y : experimental "yield" force (5%-offset method)

K_{emb} : slip modulus

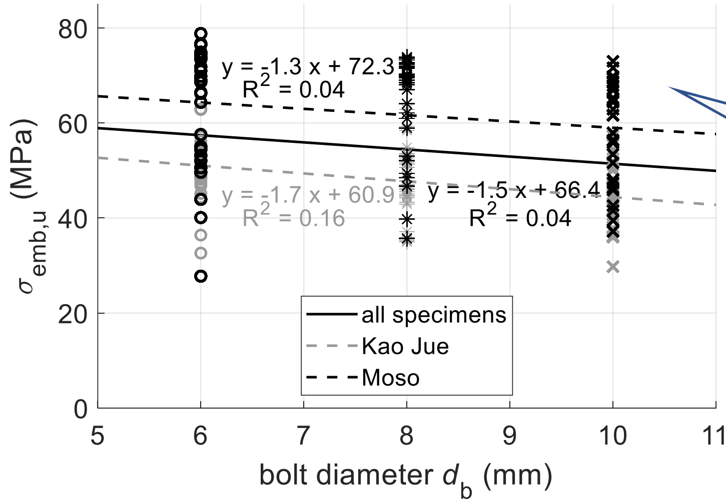
d_b : bolt diameter

t : culm thickness

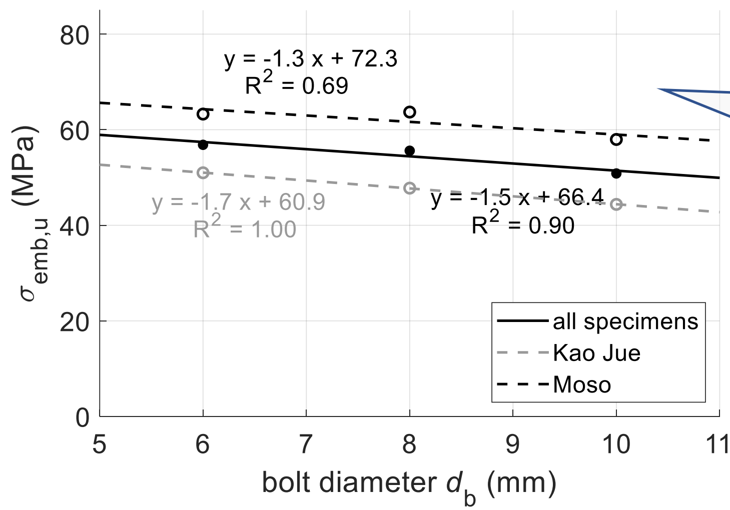
- **moisture content** has **minimal effect**
- **density** is **determining** parameter

embedment property prediction

based on individual parameters



bolt diameter predicts **poorly** the **individual datapoints**



bolt diameter **accurately** predicts **average** property values

but expressions are…

- **not dimensionally consistent**
- **species-specific**

embedment property prediction

dimensional analysis

embedment property determining parameters:
- **bolt diameter d_b**
- **material density ρ**
- **culm thickness t**

general dimensionless product

$$\Pi_{Gen,K} = K_{emb}^{x_1} \times (\rho g)^{x_2} \times t^{x_3} \times d_b^{x4}$$

gravity acceleration (for dimensional consistency)

2 **fundamental`**,
linearly independent **solutions**

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = a \begin{bmatrix} 1 \\ -1 \\ 0 \\ 2 \end{bmatrix} + b \begin{bmatrix} 0 \\ 0 \\ 1 \\ -1 \end{bmatrix} \Rightarrow$$

2 **dimensionless products**

$$\Pi_K = \frac{K_{emb}}{\rho g d_b^{\,2}}, \quad \bar{t} = \frac{t}{d_b}$$

Buckingham's theorem[1]

$$f\left(\Pi_K, \frac{t}{d_b}\right) = 0 \Rightarrow \Pi_K = \Psi_K\left(\frac{t}{d_b}\right)$$

$$K_{emb} = \Psi_K\left(\frac{t}{d_b}\right) \cdot \rho g d_b^{\,2}$$

$$E_{emb} = \Psi_E\left(\frac{t}{d_b}\right) \cdot \rho g d_b,$$

$$\sigma_{emb,u} = \Psi_\sigma\left(\frac{t}{d_b}\right) \cdot \rho g d_b$$

$$\Psi\left(\frac{t}{d_b}\right) = a_1\left(\frac{t}{d_b}\right)^n + a_2$$

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embedment property prediction

dimensional analysis

$$\Psi\left(\frac{t}{d_b}\right) = a_1\left(\frac{t}{d_b}\right)^n + a_2$$

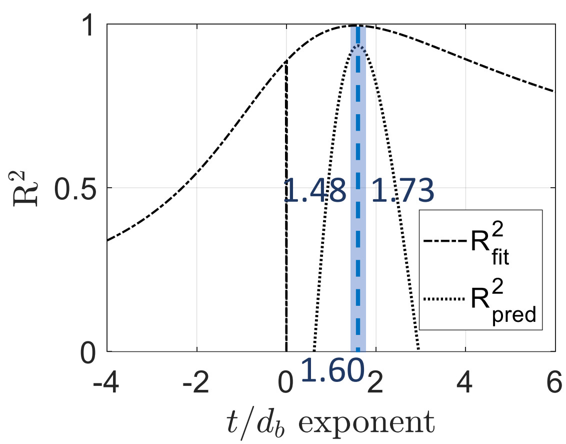
average property prediction

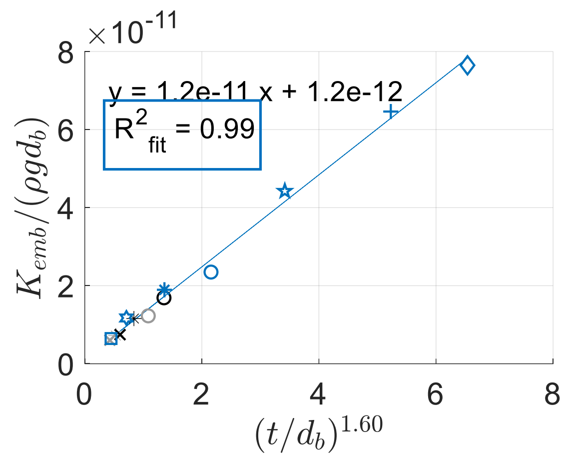
bolt diameter:

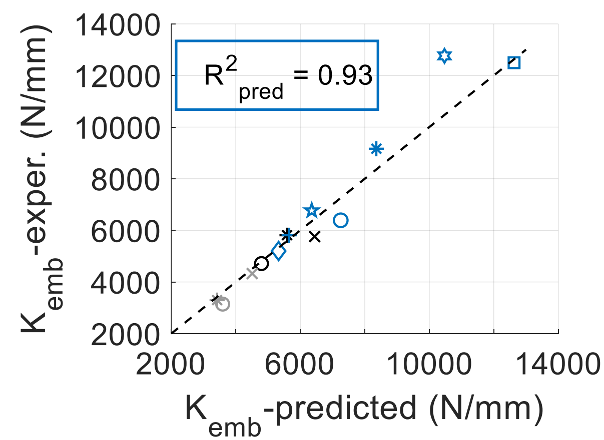
◊ 3 mm + 3.45 mm ★ 4.5 mm o 6 mm
✱ 8 mm × 10 mm ✡ 12 mm □ 16 mm

species:

o Kao Jue o Moso o Guadua[1]







specific exponent range for which both R^2_{fit} and R^2_{pred} are maximum

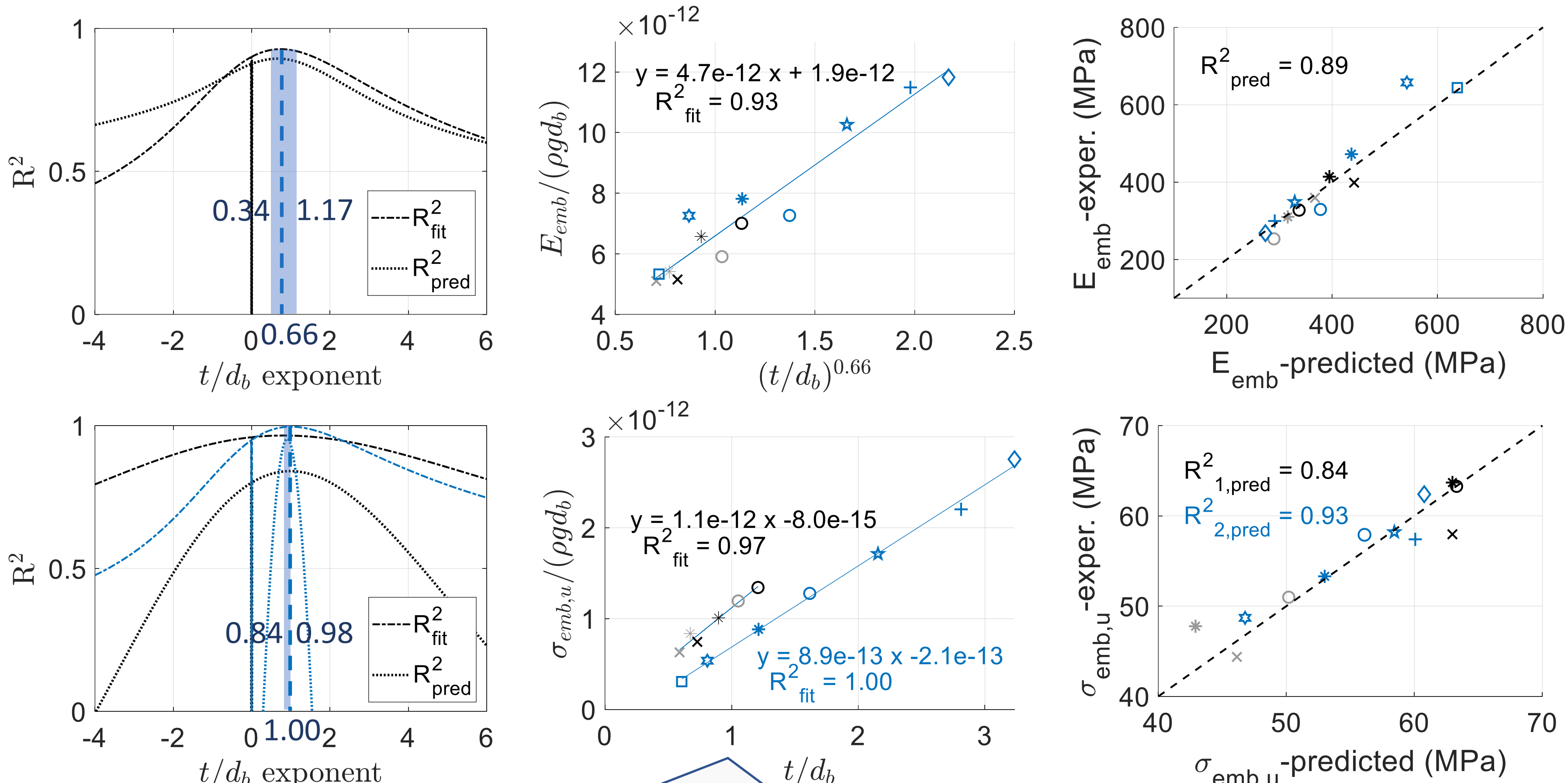
$$\Psi_K\left(\frac{t}{d_b}\right) = 1.2\cdot 10^{-11}\left[\left(\frac{t}{d_b}\right)^{1.60} + 0.10\right]$$

species-independent slip modulus prediction equation (**combined datasets** for Moso, Kao Jue and Guadua[1])

[1]Trujillo & Malkowska, CBM 2018, *Empirically derived connection design properties for* Guadua *bamboo*

embedment property prediction

dimensional analysis



separate equations for Moso-Kao Jue and for Guadua because of difference in experimental setup (**confinement**)

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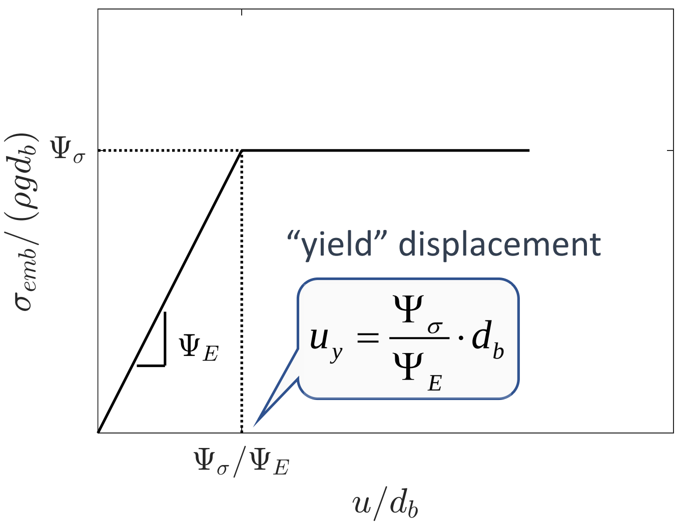
embedment property prediction

dimensional analysis

dimensionless bilinear embedment stress-displacement curve



$$\Psi_E\left(\frac{t}{d_b}\right) = 4.7\cdot 10^{-12}\left[\left(\frac{t}{d_b}\right)^{0.66} + 0.40\right]$$

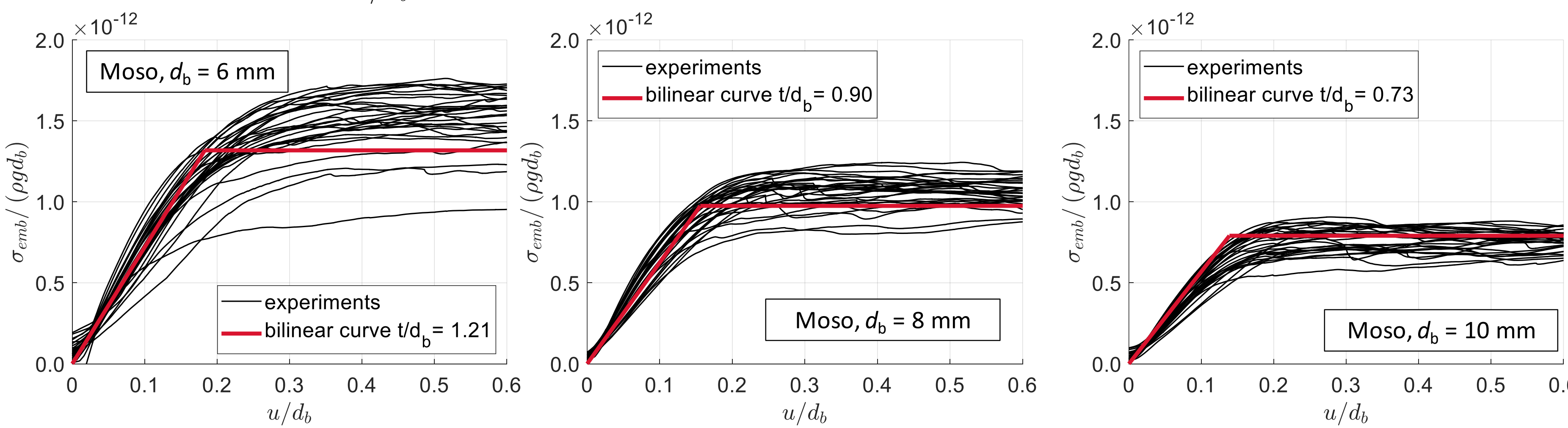
species-independent

$$\Psi_\sigma^{(KM)}\left(\frac{t}{d_b}\right) = 1.1\cdot 10^{-12}\left(\frac{t}{d_b} - 0.01\right)$$

Kao Jue and Moso

$$\Psi_\sigma^{(G)}\left(\frac{t}{d_b}\right) = 0.9\cdot 10^{-12}\left(\frac{t}{d_b} - 0.24\right)$$

Guadua



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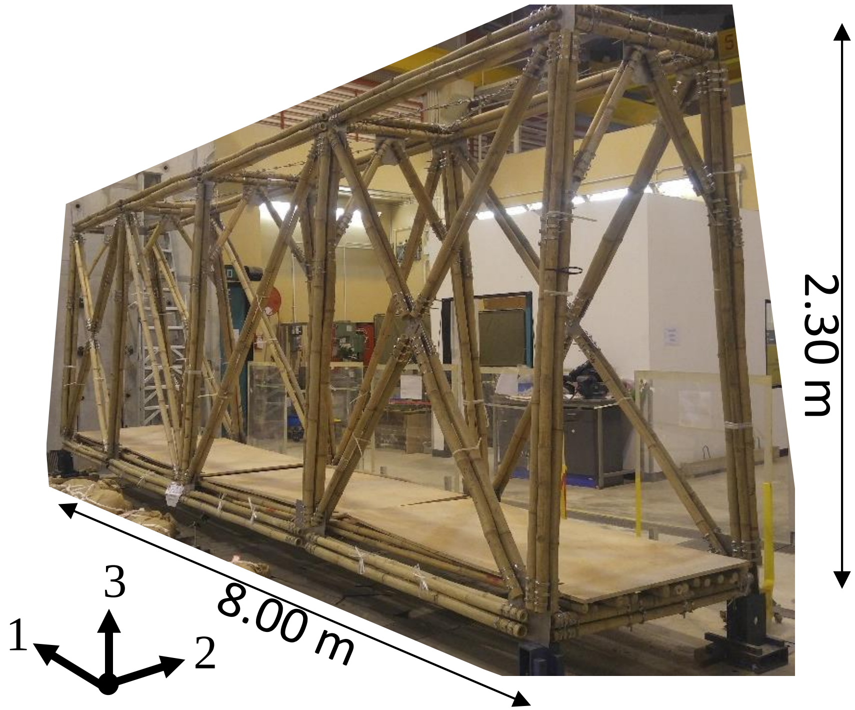
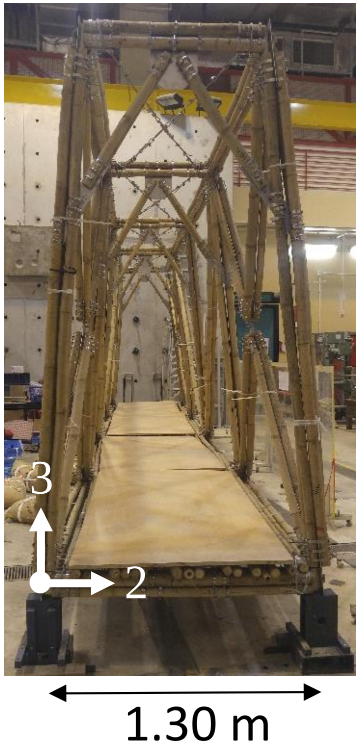
full-scale bamboo footbridge

conclusions

full-scale bamboo footbridge

description



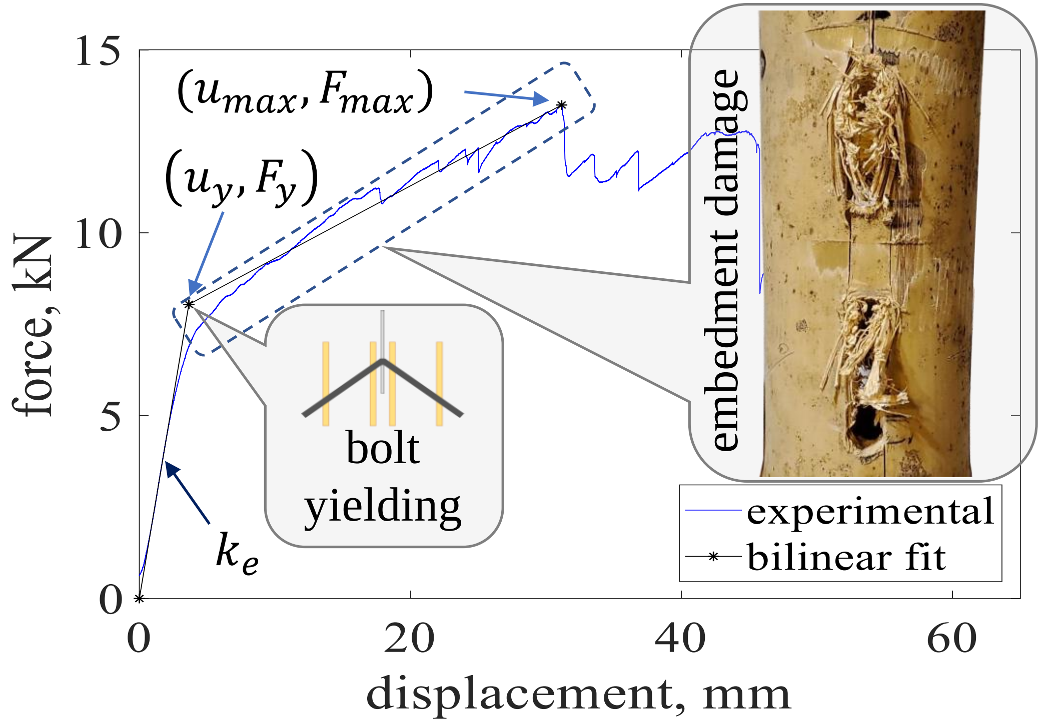


- Kao Jue bamboo (*Bambusa pervariabilis*)
- stainless steel gusset plates (3 mm)
- M6 bolts of A2-70 grade
- hose-clamps (40-63 mm)

[Pradhan, Paraskeva, Dimitrakopoulos *EngStr 2022*]

full-scale bamboo footbridge

bilinear model of axial member



from **structural element tests**, back-calculate

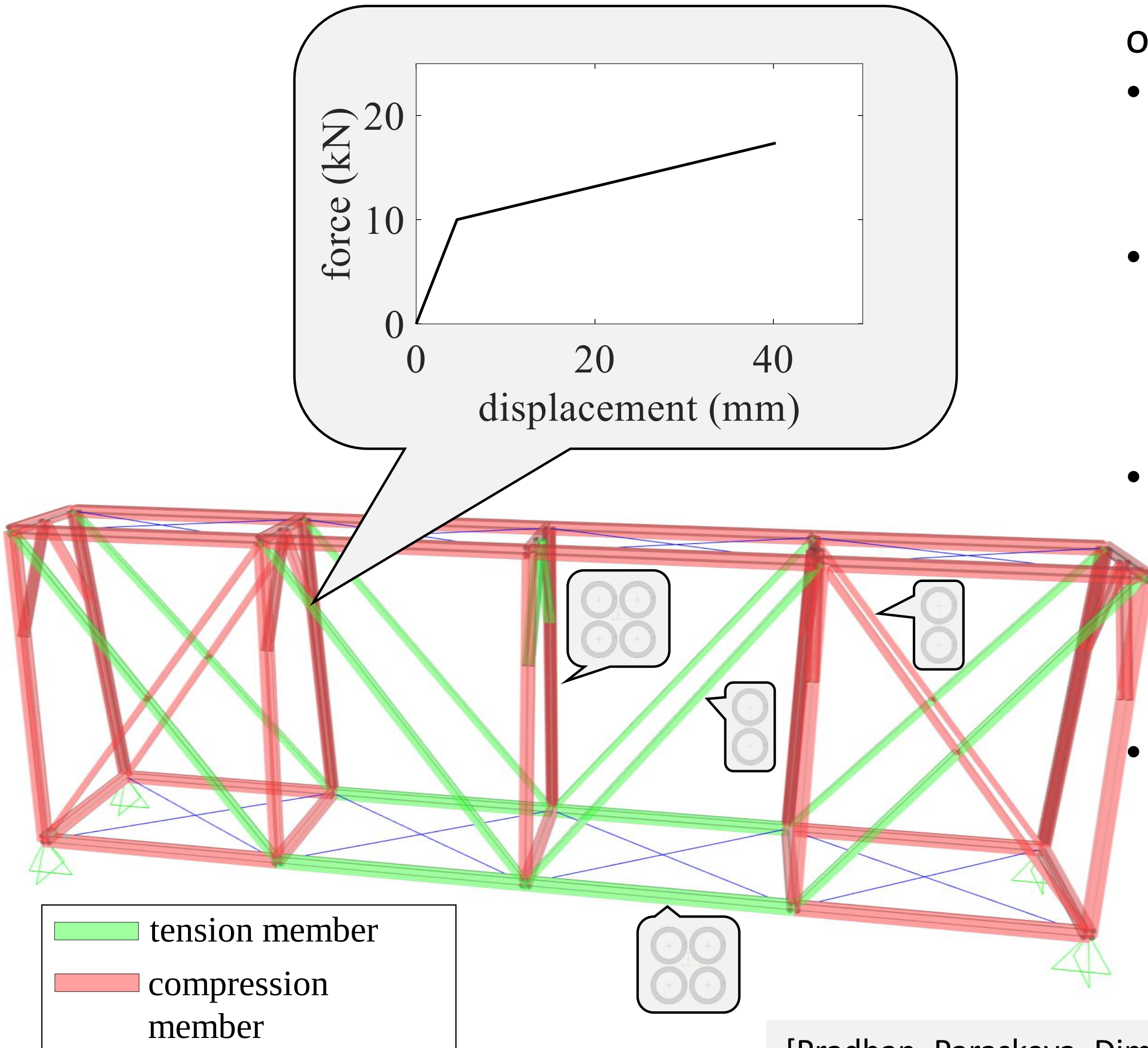
- connection yielding (u_y, F_y) and maximum (u_{max}, F_{max}) states
- connection elastic stiffness $k_{c,e}$ and plastic stiffness $k_{c,p}$

estimate elastic stiffness of bamboo culms k_m from **material strength tests**

[Pradhan, Paraskeva, Dimitrakopoulos *EngStr 2022*]

full-scale bamboo footbridge

bilinear model of axial member



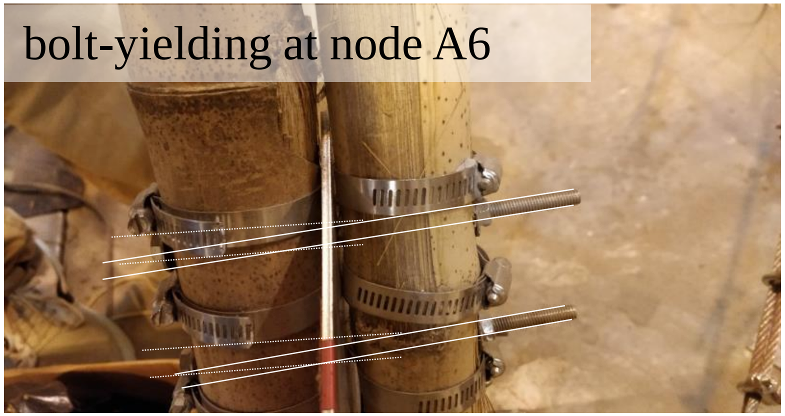
SAP2000 implementation/validation of the **model**

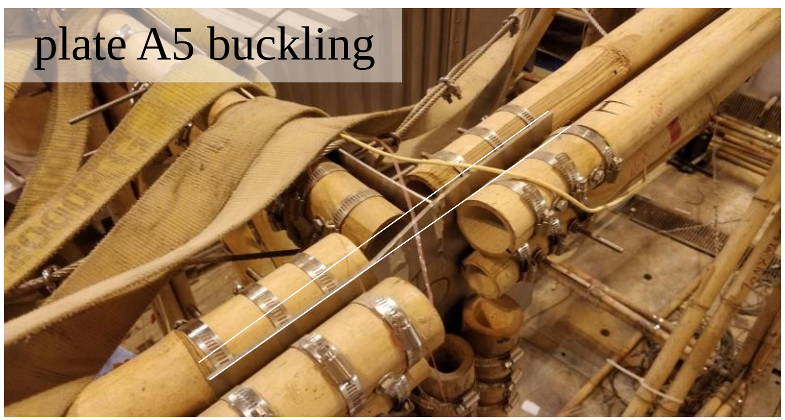
- a single frame element develops the total elastic stiffness k_e
- connection plastic behavior developed by means of plastic hinges
- validated numerical model is implemented on 2-culm and 4-culm members of truss footbridge
- non-linear response and damage progression simulated in SAP2000

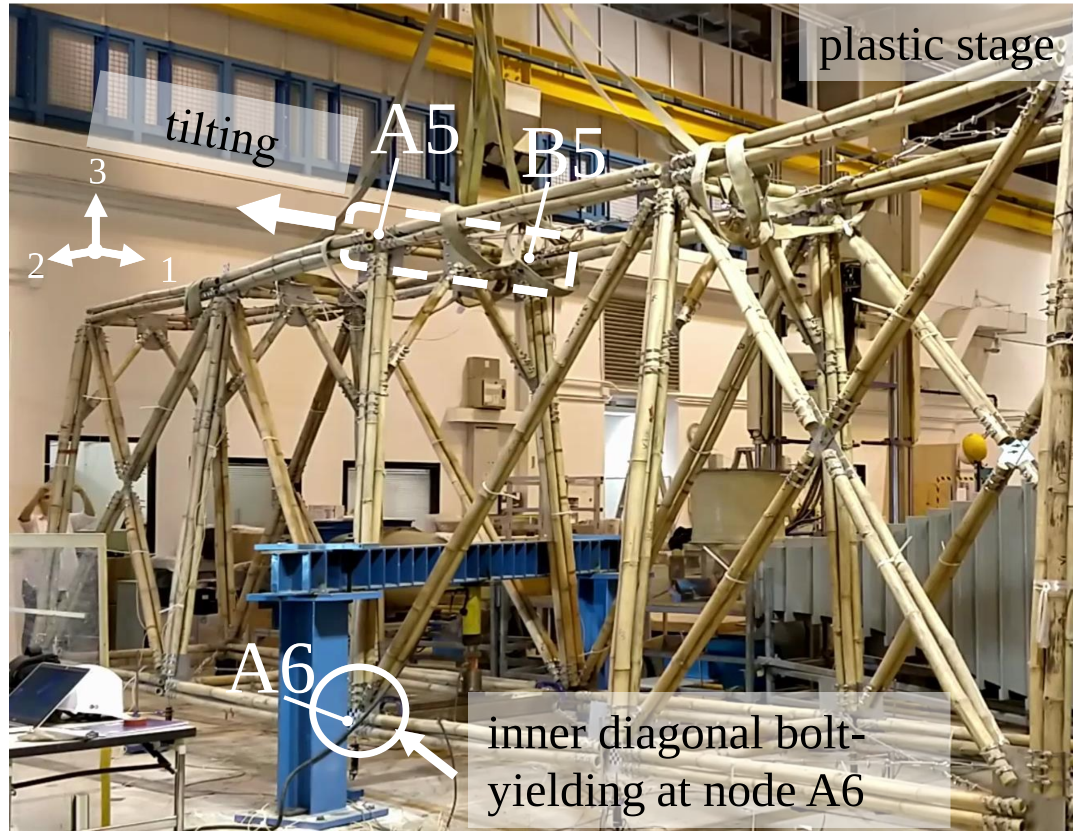
[Pradhan, Paraskeva, Dimitrakopoulos *EngStr 2022*]

full-scale bamboo footbridge

experimental testing





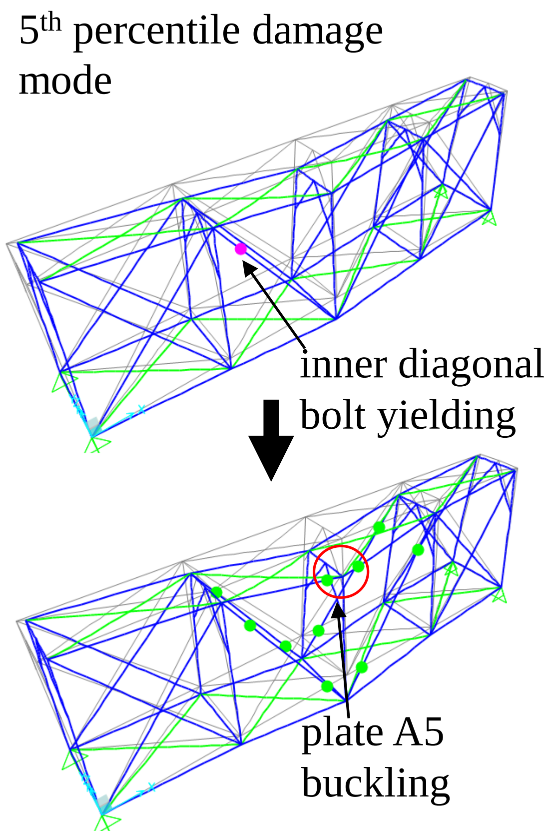


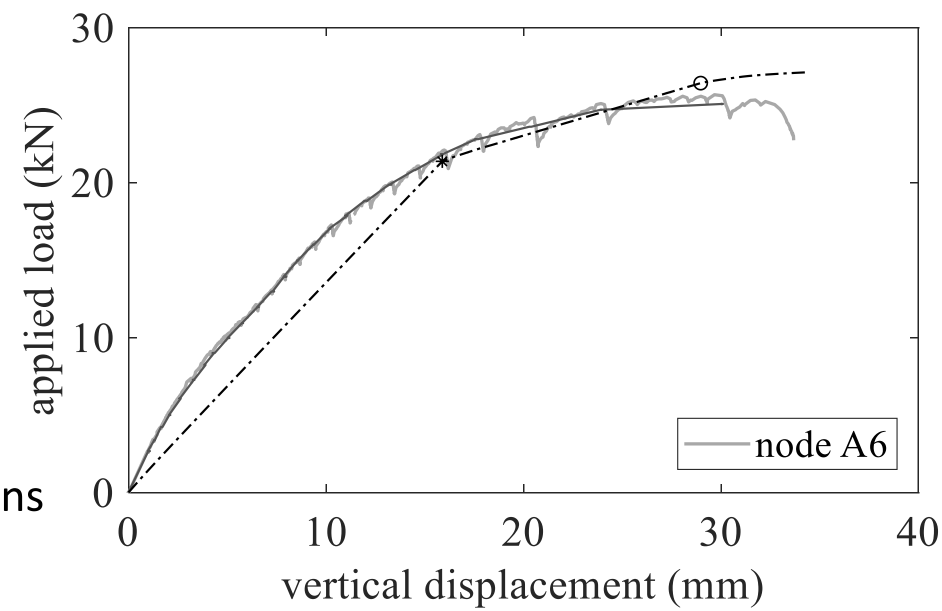
- first failure by yielding of bolted connections
- further loading results in buckling of steel plate, causing tilting of upper story nodes A5-B5

[Pradhan, Paraskeva, Dimitrakopoulos *EngStr 2022*]

full-scale bamboo footbridge

numerical simulation vs experiment





- first failure by yielding of bolted connections
- further loading results in buckling of steel plate,
  causing unbounded displacement of nodes

[Pradhan, Paraskeva, Dimitrakopoulos *EngStr 2022*]

outline

connection design

design premise

experimental program

capacity design

implementation of full-scale bamboo footbridge

embedment simulation

conclusions

conclusions

connection design

- proposed method **manages variability** of bamboo culms through (i) grading, (ii) use of multiple culms, and (iii) capacity design principles
- axial members display high **ductility** and **predictability** owing to dowel yielding before other components
- characteristic values of average material/geometric properties can predict 5^{th} percentile yielding of dowel connections

implementation on an original footbridge

- proposed bilinear model of axial member can simulate the non-linear behavior of bolted connections
- numerical simulation of the footbridge predicts correctly the non-linear response and damage sequence of the experimental structure

relevant publications

Mouka Th, **Dimitrakopoulos** EG, Lorenzo R (**2022**) "Effect of a longitudinal crack on the flexural performance of bamboo culms" **Acta Mechanica** doi: 10.1007/s00707-022-03314-3

Mouka Th, **Dimitrakopoulos** EG (**2022**) "Prediction of bamboo culm embedment properties parallel to grain via dimensional analysis" **Construction and Building Materials** doi: 10.1016/j.conbuildmat.2022.128434

Mouka Th, **Dimitrakopoulos** EG, Lorenzo R (**2022**) "Insight into the behavior of bamboo culms subjected to bending" **Journal of the Royal Society Interface** doi: 10.1098/rsif.2021.0913.

Pradhan NPN, Paraskeva TS, **Dimitrakopoulos** EG (**2022**) "Simulation and experimental verification of an original full-scale bamboo truss" **Engineering Structures** doi: 10.1016/j.engstruct.2022.113965

Pradhan NPN, **Dimitrakopoulos** EG (**2021**) "Pilot study on capacity-based design of multiculm bamboo axial members with dowel type connections" **ASCE Journal of Structural Engineering** doi: 10.1061/(ASCE)ST.1943-541X.0002995

Mouka Th, **Dimitrakopoulos** EG (**2021**) "Simulation of embedment phenomena on bamboo culms via a modified foundation modelling approach" **Construction and Building Materials** doi: 10.1016/j.conbuildmat.2020.122048

Pradhan NPN, Paraskeva TS, **Dimitrakopoulos** EG (**2020**) "Quasi-static reversed cyclic testing of multi-culm bamboo members with steel connectors" **Journal of Building Engineering** doi: 10.1016/j.jobe.2019.100983

Paraskeva TS, Pradhan NPN, Stoura CD, **Dimitrakopoulos** EG (**2019**) "Monotonic loading testing and characterization of new multi-full-culm bamboo to steel connections" **Construction and Building Materials** doi: 10.1016/j.conbuildmat.2018.12.198

Paraskeva TS, Grigoropoulos G, **Dimitrakopoulos** EG (**2017**) "Design and experimental verification of easily constructible bamboo footbridges for rural areas" **Engineering Structures** doi: 10.1016/j.engstruct.2017.04.044

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PhD Nischal P N PRADHAN

PhD Theodora MOUKA

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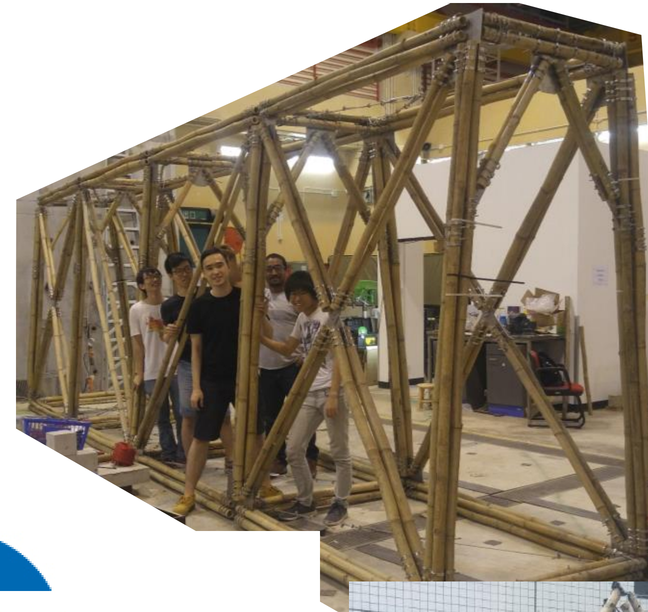

thank you for your kind attention!

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https://ilias.people.ust.hk/

Department of Civil and Environmental Engineering

The Hong Kong University of Science and Technology