ISUME

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A Risk Based Approach for the Robustness Assessment of Timber Roofs

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Collapse of wide span roofs

Siemens Arena Denmark 2003

Munch-Andersen

Exibition Hall Finland 2003

Frühwald et al.

Bad Reichenhall arena Germany 2006

Winter et al.

Denmark Club Hall, Denmark 2010

Pedersen et al.

Causes of failure

Report TVBK 2007 , Frühwald-Serrano-Toratti-Emilsson-Thelandersson, Lund University

Reference	Planning & design %	Con-struction %	Use/ main-tenance %	Other[a] %	Total %
Matousek [1]	37	35	5	23	98
Brand & Glatz [2]	40	40	-	20	100
Yamamoto & Ang [18]	36	43	21	-	100
Grunau [19]	40	29	31[b]	-	100
Reygaertz [20]	49	22	29[b]	-	100
Melchers, et al. [21]	55	24	21	-	100
Fraczek [22]	55	53	-	-	108[c]
Allen [23]	55	49	-	-	104c
Hadipriono [24]	19	27	33	20	99

[a] Includes cases where failure can not be associated with only one factor and may be due to several of them

[b] Building materials, environmental influences, service conditions

[c] Multiple errors for single failure case

Causes of failure

Report TVBK 2007 , Frühwald-Serrano-Toratti-Emilsson-Thelandersson, Lund University

The errors occurr more likely in the design phase, followed by the construction phase

Material deficiency or maintenance

	Planning & design %	Con-struction %	Use/ main-tenance %	Other[a] %	
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Robustness

= insensitivity to local failure and to progressive collapse

…..different measures

Redundancy factor, Robustness index, Reliability-Robustness index, Stiffness-Robustness index etc.

….several code references

- Danish Code of Practice for the Safety of Structures
- EUROCODE
- Joint Committee for Structural Safety

A Robustness Measure

Damage Limit Requirement in EN 1991-1-7:

A failure should not lead to an area failed that exceeds the minimum between

- 15% of the floor area

- 100m^2

Reliability & Risk

Reliability / Probability of failure

Probability of exceeding ultimate limit states for the structural system at any stage during its life

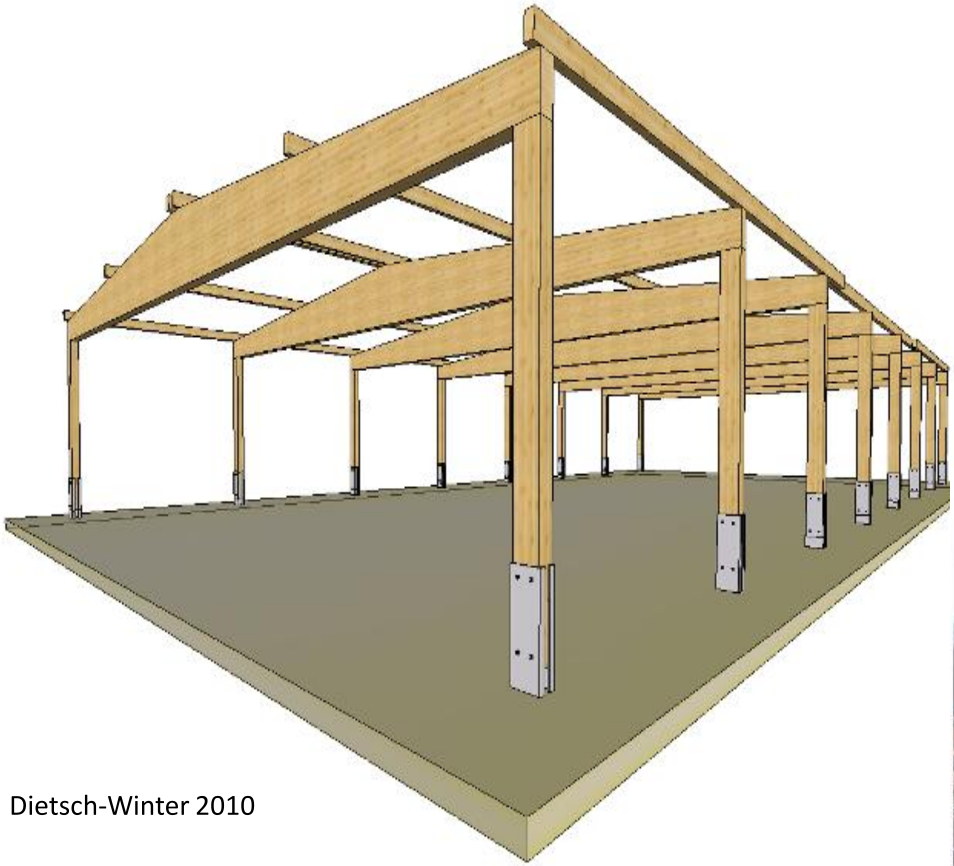
$$\Pr(F) = \int_{\Omega_F} f(x)\,dx = \Pr\left(g(\underline{X}) \leq 0\right)$$

Risk

Defined as the ***"expected adverse consequences"***

$$Risk = \mathrm{E}[A_F] = \int_0^{A_{roof}} a\, f_{A_F}(a)\,da$$

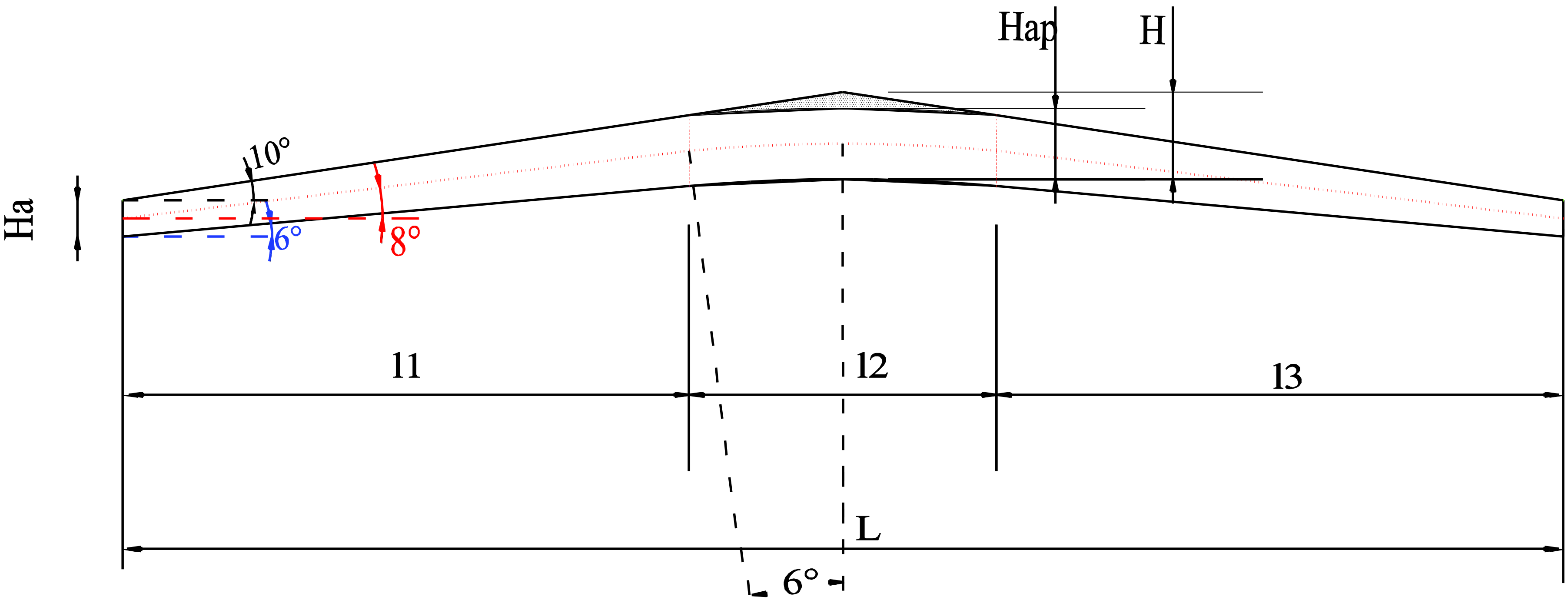
Case study



Dietsch-Winter 2010

Holzbau web Gallery

Timber Primary Beams



Span: L= 20.0 m

Distance between the beams: e = 6.0 m

Width: b = 180mm;

Height at Support: h_a = 600mm

Angle upper Edge: δ = 10°

Angle lower edge: β= 6°;

Inner Radius: r = 20 m

Lamella thickness: t = 32 mm

Height in Apex: h_{ap} = 1163mm

GLULAM TIMBER GL24c

Beam Failure Mechanism

- **Bending**
  - Purlins: Loss of the support
  - Other beams: Redistribution of the load (30-40%)
- **Tension Orthogonal to the grain**
  - Purlins: Displacement of the support
  - Other beams: None
    Beam 'failed': Stiffness reduction
- **Shear**
  - Purlins: Displacement of the support
  - Other beams: None
    Beam 'failed': Stiffness reduction

Beam Failure Mechanism

Trigger for progressive collapse

- **Bending**
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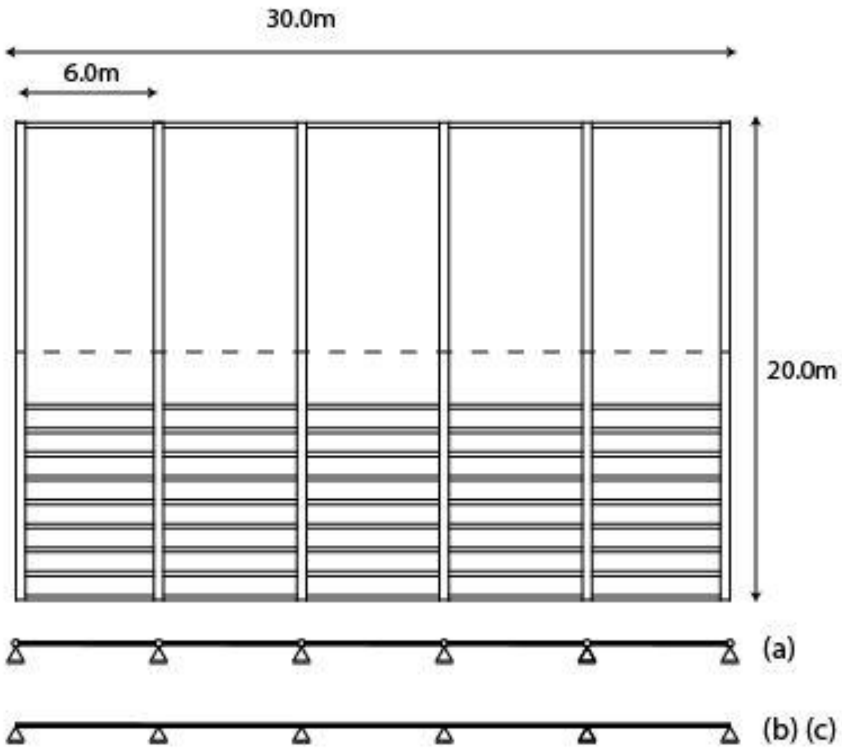
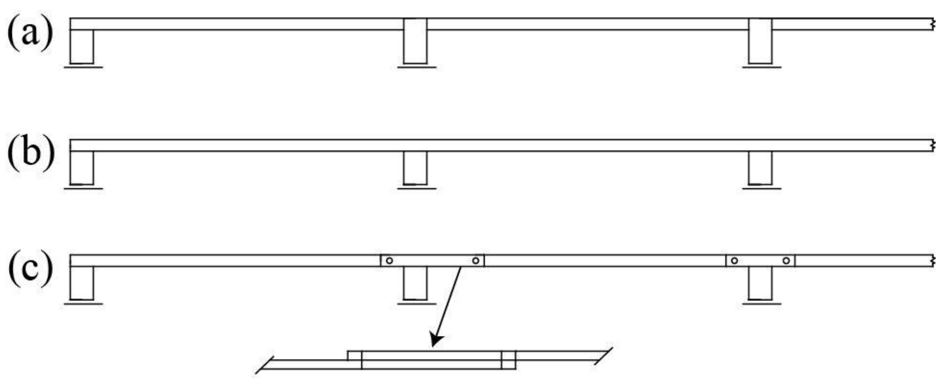
Timber Secondary Structure



SOLID TIMBER
C24

- same utilization f $0.9 < \eta < 1$
- same reliability of critical sections

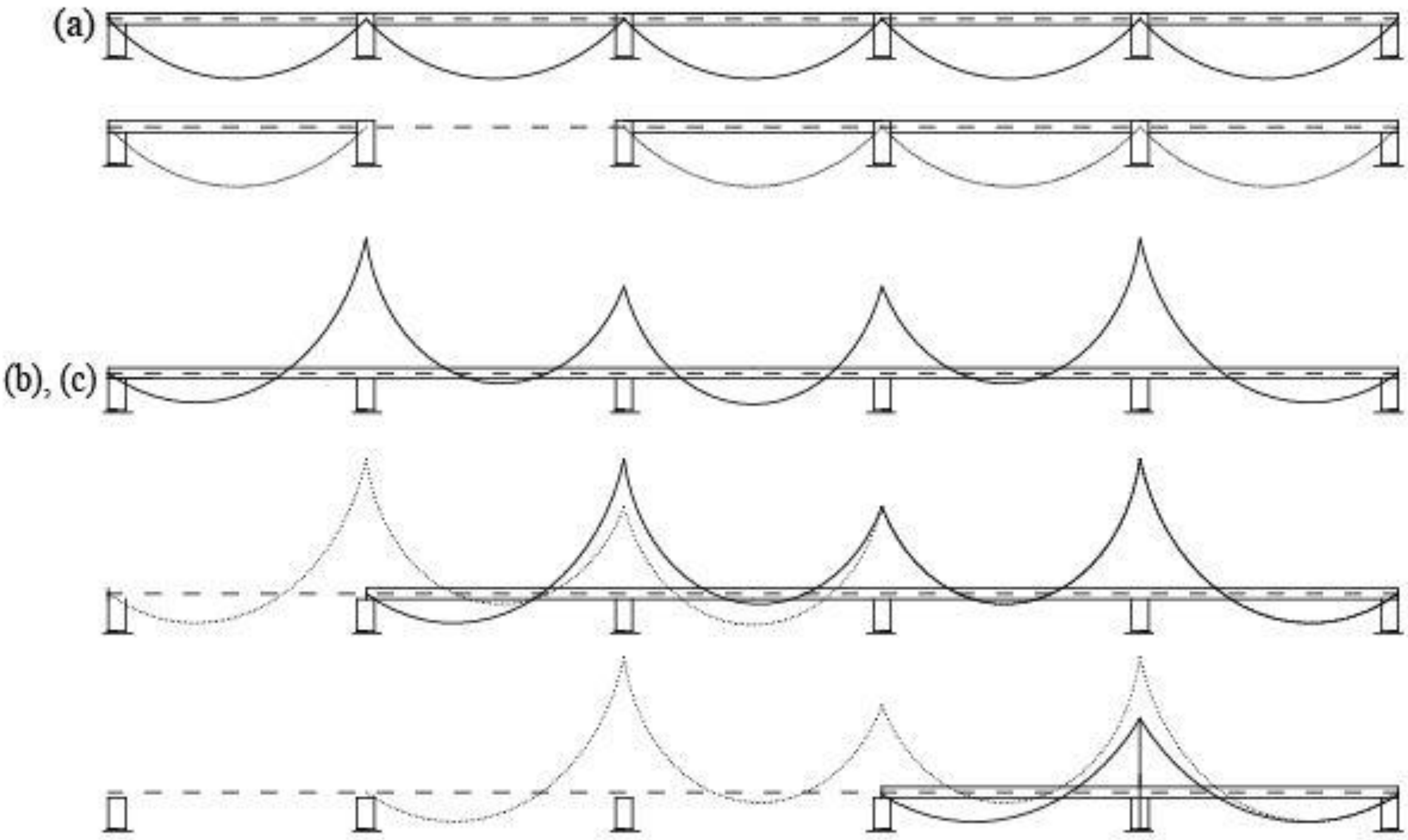


Simply supported

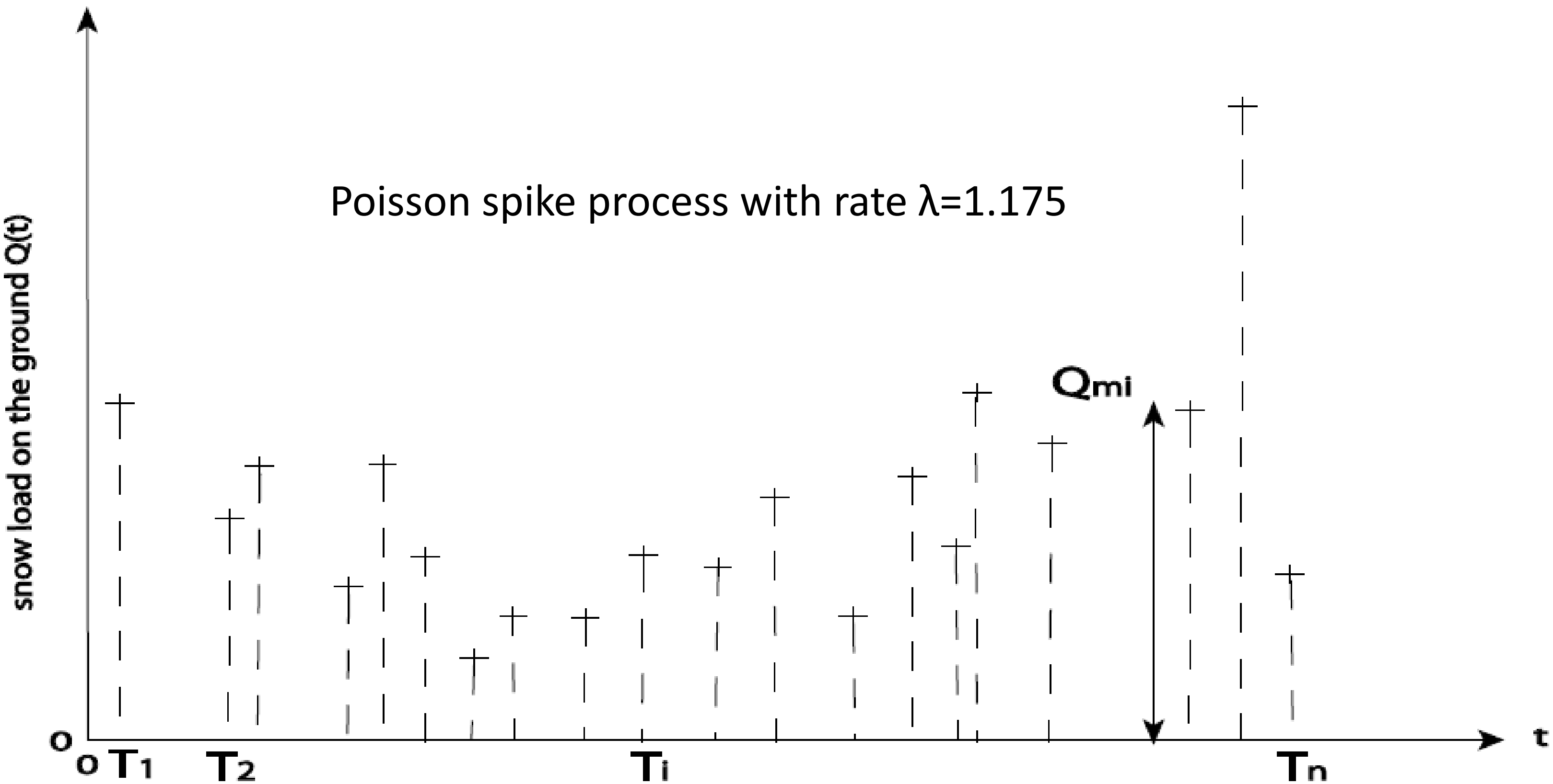
Continuous

Lap-Jointed

Secondary Structure Failure Scenario



Stochastic model of the snow load

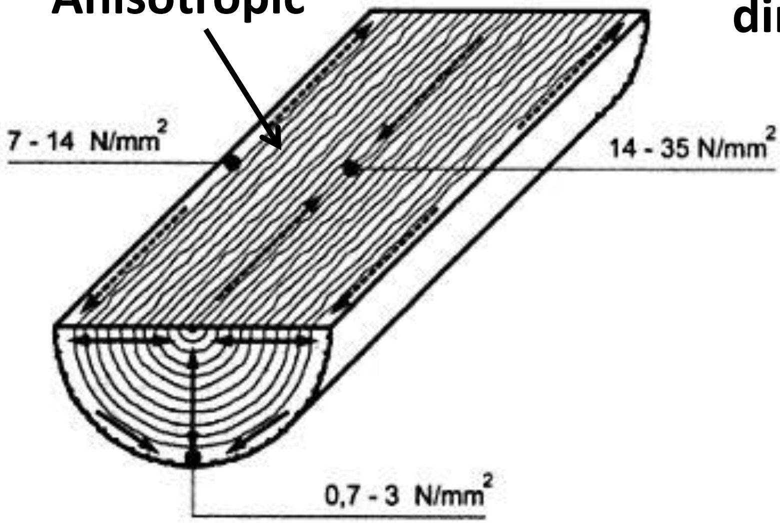


$$F_{Q_{max}}(q) = \sum_{i=0}^{\infty} \left[F_{Q_m}(q)\right]^n \cdot p_N(n)$$

$$F_{Q_{max}}(q) = \exp\left\{\lambda T\left[\exp\left[-\exp\left(-\frac{q-b}{a}\right)\right]-1\right]\right\}$$

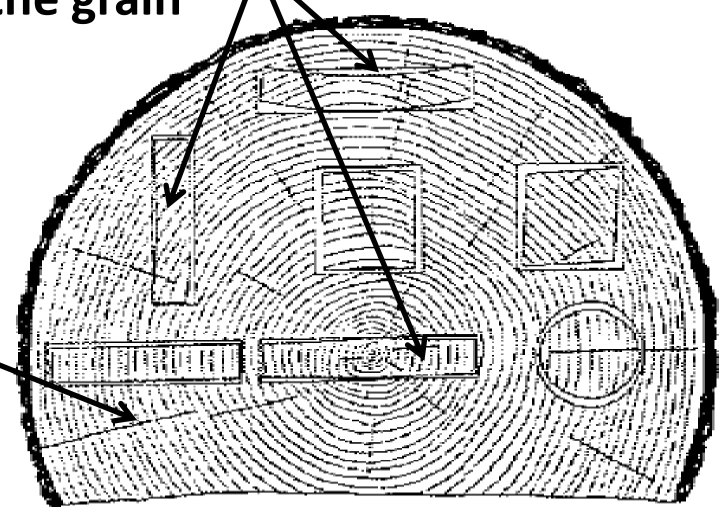
Strength of timber (Solid, Glulam)

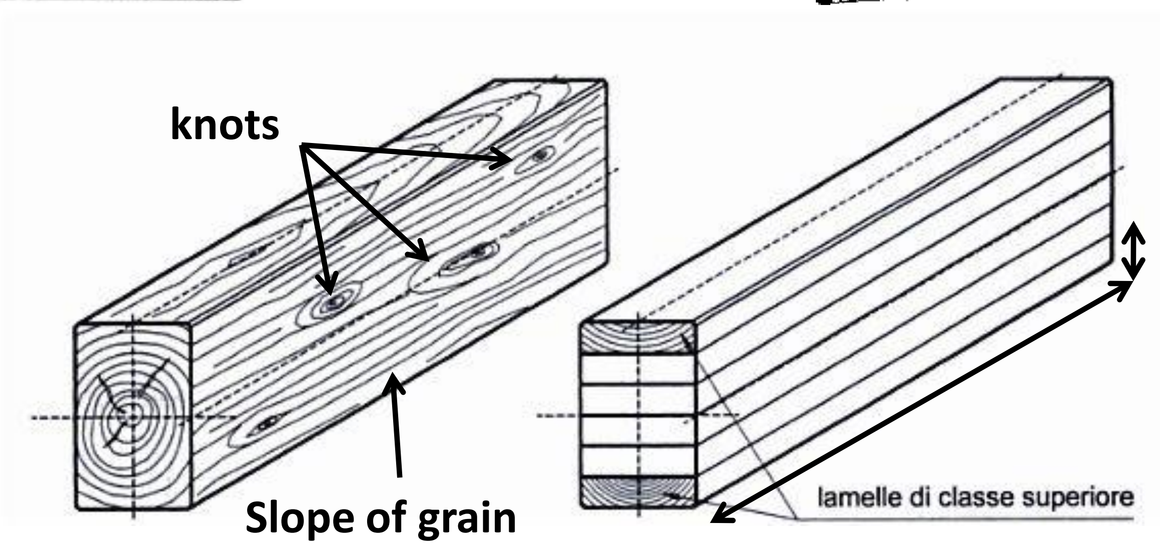
Anisotropic



Strength depends on direction of the grain

rupture





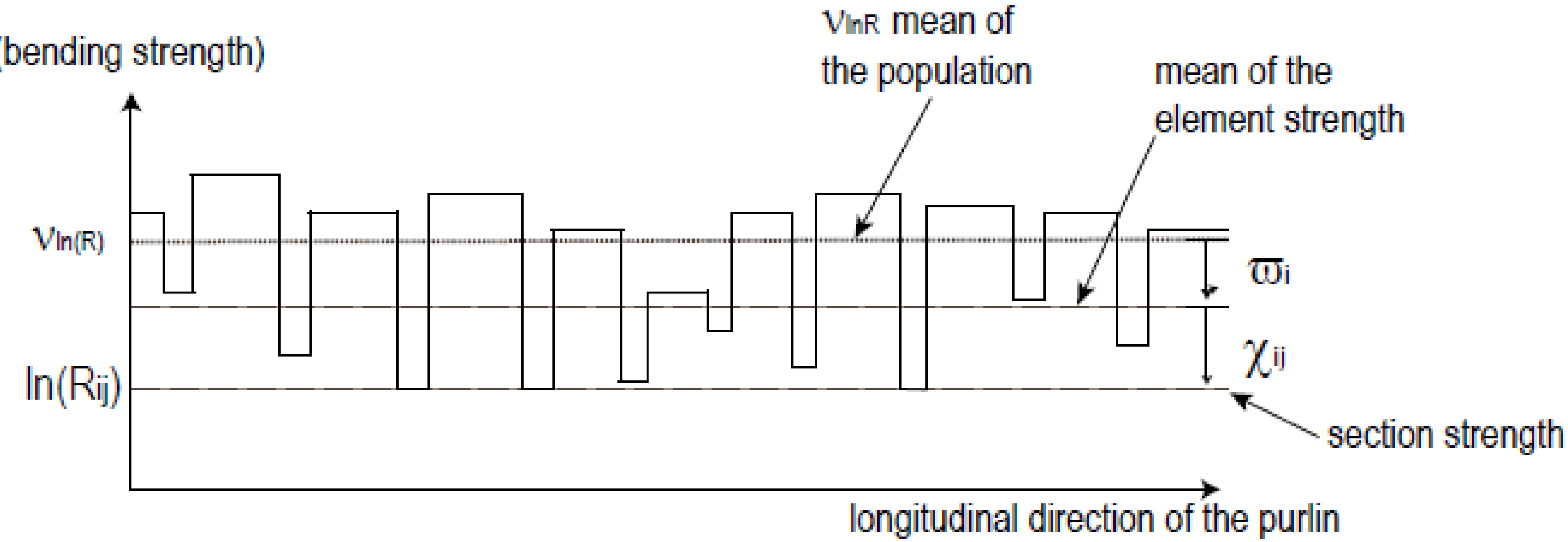
- -Bark pockets
- -Resin pocket
- -decay

Strength depends on size

Stochastic model of the strength

Bending Resistance: Isaksson's model

$$R_{ij} = \exp\left[\nu + \varpi_i + \chi_{ij}\right]$$



- Short **weak zones** (knots or clusters) connected by sections of clear wood (series system)
- Strength is a correlated r.v.
- Bending Resistance is Lognormal r.v.

Systematic weaknesses

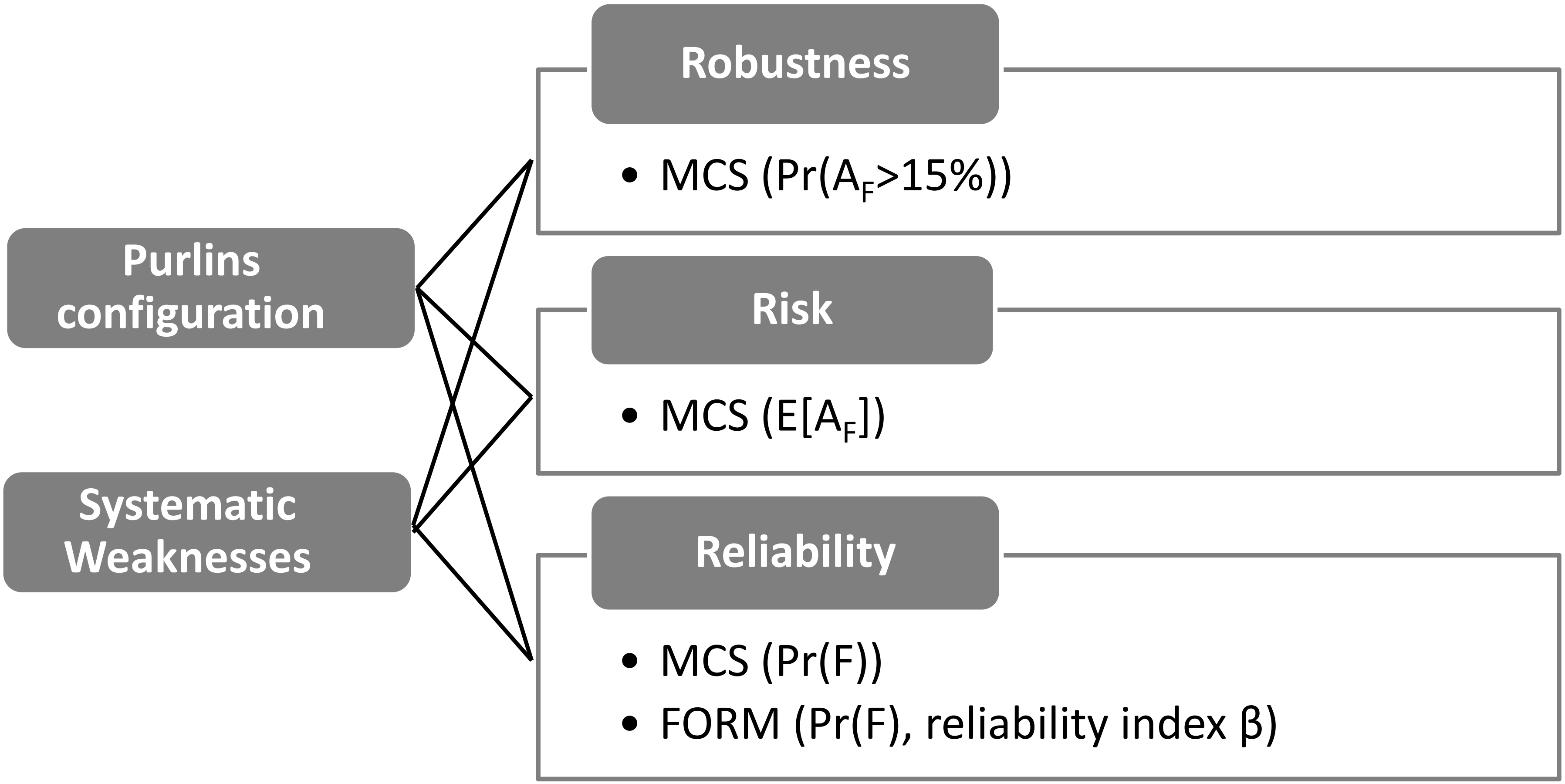
Causes of weaknesses	Reduction of the resistance
Design errors	20%
Wrong cross section	18-20%
Wrong strength grade	17-20%
Bad execution of holes	20%
Bad execution of finger joints	20%

- **Weakened sections** occur as Bernoulli process with **p=0.30**
- **Bending strength** of the weak-element $\mathbf{R_D}$ is **Lognormal** distributed with **20% lower** mean value
- **Bending strengths** of weak-elements $\mathbf{R_D}$ are **strongly correlated** (**ρ=0.95**)

Random Variables of the model

	r.v.	Distribution	μ	COV
Snow load on the ground [kN/m²]	Q	Gumbel	0.384	0.40
Occurrence [1/y]	T	Poisson	1.175	0.92
Shape Factor [\]	C	Gumbel	0.78	0.35
Density [kN/m³]	G	Normal	4.20	0.10
Permanent load [kN/m²]	P	Normal	0.4	0.10
Bending strength [MPa]	R_{ij}	Lognormal	36.97	0.25
Bending strength [MPa]	R_{Dij}	Lognormal	29.57	0.25

Methods of Analysis



Monte Carlo simulations

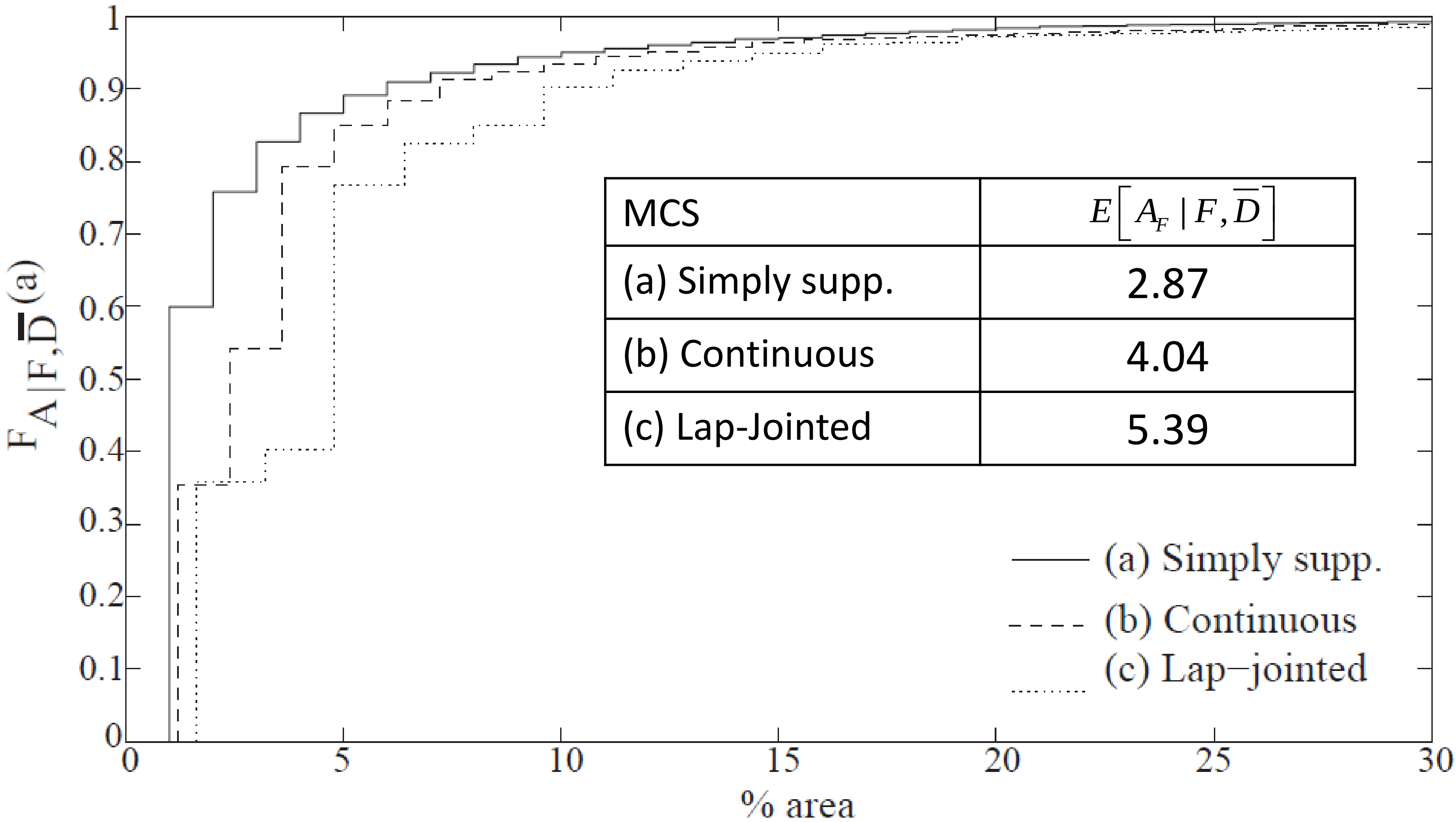
MCS (confience interval 95%)	$\Pr\left(F\left(50yr\right) \mid \overline{D}\right)$
(a) Simply supp.	$4.51 \div 4.76 \cdot 10^{-2}$
(b) Continuous	$1.75 \div 1.92 \cdot 10^{-2}$
(c) Lap-Jointed	$1.39 \div 1.54 \cdot 10^{-2}$

→ **β value 2.3-2.7**

MCS (confience interval 95%)	$\Pr\left(F\left(50yr\right) \mid D\right)$ (p=0.30)
(a) Simply supp.	$9.38 \div 9.5710^{-2}$
(b) Continuous	$5.21 \div 5.50 \cdot 10^{-2}$
(c) Lap-Jointed	$2.94 \div 3.15 \cdot 10^{-2}$

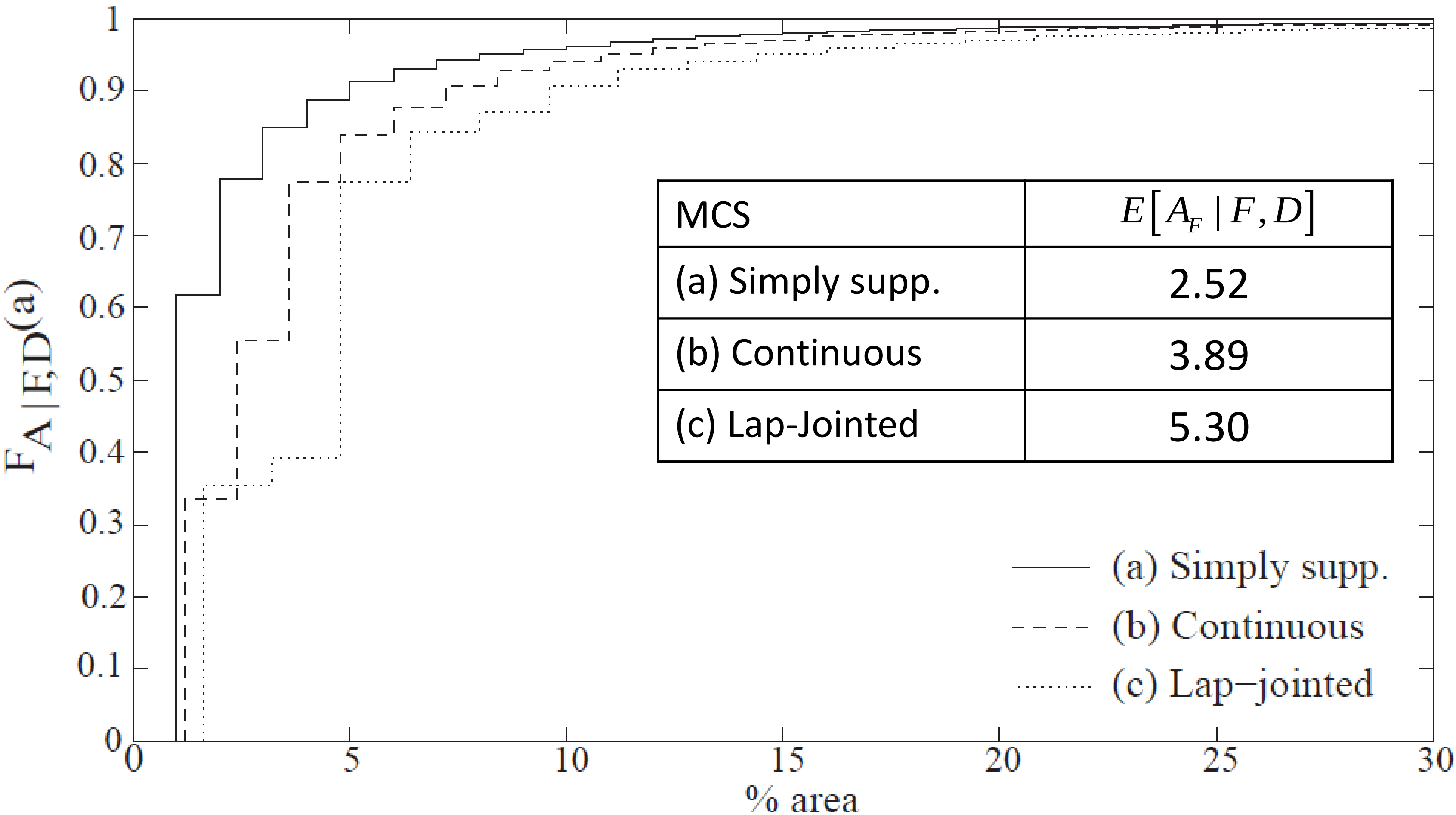
→ **β value 1.3-2.3**

Monte Carlo simulations



MCS	$E\left[A_F \mid F, \bar{D}\right]$
(a) Simply supp.	2.87
(b) Continuous	4.04
(c) Lap-Jointed	5.39

Monte Carlo simulations

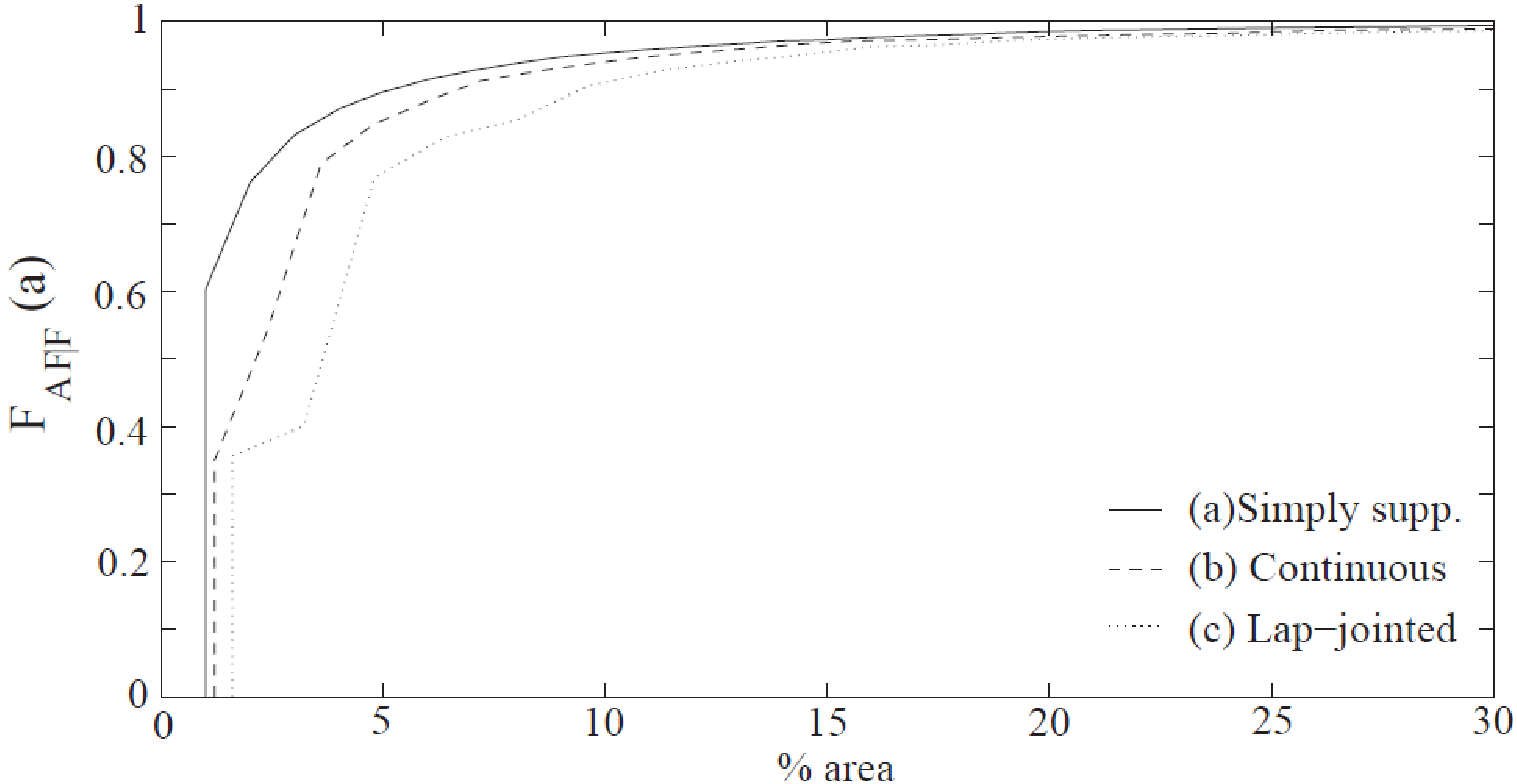


MCS	$E[A_F \mid F, D]$
(a) Simply supp.	2.52
(b) Continuous	3.89
(c) Lap-Jointed	5.30

Monte Carlo simulations

The limit of A_F as robustness requirement

$$F_{A_F|F}(a) = F_{A_F|F,\bar{D}}(a) \cdot Pr(\bar{D}|F) + F_{A_F|F,D}(a) \cdot Pr(D|F)$$



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The limit of A_F as robustness requirement

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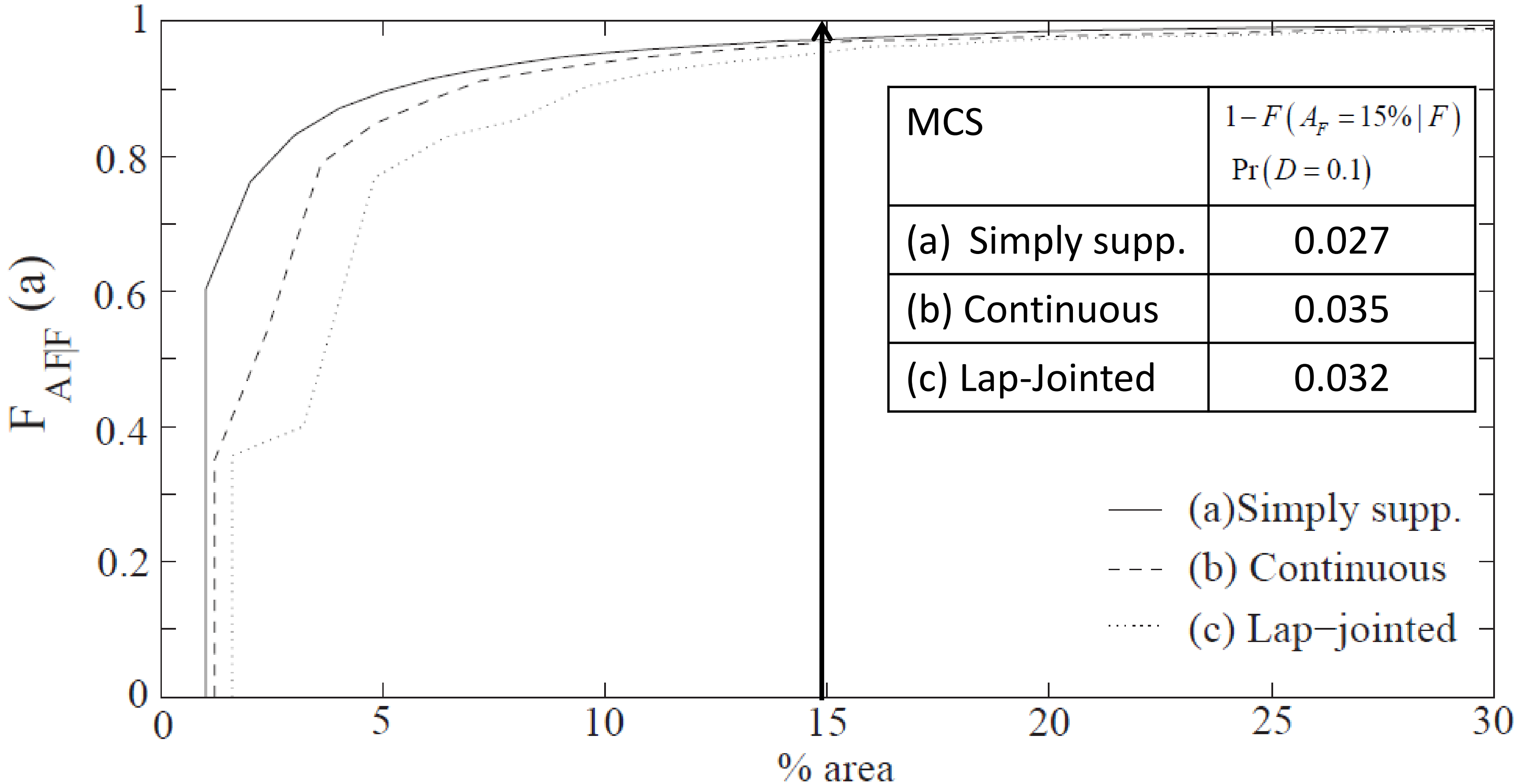

MCS	$1 - F(A_F = 15\% \mid F)$ $\Pr(D = 0.1)$
(a) Simply supp.	0.027
(b) Continuous	0.035
(c) Lap-Jointed	0.032

Risk

$$Risk = \mathrm{E}[A_F] = \int_0^{A_{roof}} a \cdot f_{A_F}(a)\ da$$

MCS	$\mathrm{E}[\mathrm{A_F}], \mathrm{Pr}(\mathrm{D}) = 0.01$	$\mathrm{E}[\mathrm{A_F}], \mathrm{Pr}(\mathrm{D}) = 0.10$
(a) Simply supp.	$1.34 \cdot 10^{-3}$	$1.43 \cdot 10^{-3}$
(b) Continuous	$0.75 \cdot 10^{-3}$	$0.88 \cdot 10^{-3}$
(c) Lap-Jointed	$0.79 \cdot 10^{-3}$	$0.87 \cdot 10^{-3}$

Results Purlins Assessment

Results	Reliability $Pr(F_{50y})$	Robustness $Pr(A_F>15\%\|F)$	Risk $E[A_F]$
(a) Simply supp.	$4.51 \div 4.76 \cdot 10^{-2}$	0.027	$1.34 \cdot 10^{-3}$
(b) Continuous	$1.75 \div 1.92 \cdot 10^{-2}$	0.035	$0.75 \cdot 10^{-3}$
(c) Lap-Jointed	$1.39 \div 1.54 \cdot 10^{-2}$	0.032	$0.79 \cdot 10^{-3}$

Conclusions Purlins Assessment

- Statically Determined (Simply supp.) secondary system is more robust

- Statically undetermined (Continuous and Lap-Jointed) secondary system have the lowest Pr(F) and Risk

The more robust configuration might be not the optimal one

Conclusions Purlins Assessment

- Statically Determined (Simply supp.) secondary system is more robust

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References

Dietsch P., Winter S. (2010). Robustness of Secondary Structures in wide-span Timber Structures. Proceedings WCTE 2010, Riva del Garda, Italy

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