VERIFICHE DI SICUREZZA DI STRUTTURE NUOVE ED ESISTENTI IN C.A. e C.A.P. CON IL METODO DEGLI ELEMENTI FINITI

8 July 2024

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Attività 2024

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Seminario in presenza e on line
Dipartimento di Ingegneria Civile e Ambientale
Politecnico di Milano - 29 aprile 2024

PROGETTAZIONE DI STRUTTURE IN CALCESTRUZZO FIBRORINFORZATO - ANNEX L

IN COLLABORAZIONE CON
aicap
ASSOCIAZIONE ITALIANA CALCESTRUZZO ARMATO E PRECOMPRESSO
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Partecipa al ciclo completo di eventi sull'EUROCODICE 2 organizzati da AICAP E CTE

29 Aprile, Milano — **Sede:** Politecnico di Milano
Tema: **PROGETTAZIONE DI STRUTTURE IN CALCESTRUZZO FIBRORINFORZATO - ANNEX L CONCEPTUAL DESIGN, EQUAZIONI DI VERIFICA ED ESEMPI APPLICATIVI**
Relatori: Marco di Prisco, Giovanni Plizzari e Liberato Ferrara

8 Luglio, Torino — **Sede:** Auditorium presso l'Energy Center del Politecnico di Torino
Tema: **VERIFICHE DI SICUREZZA DI STRUTTURE NUOVE ED ESISTENTI IN C.A. E C.A.P. CON IL METODO DEGLI ELEMENTI FINITI.**
Relatori: Paolo Castaldo e Elena Miceli, Giuseppe Mancini e Diego Gino, Beatrice Belletti e Simone Ravasini

Settembre, Roma — in collaborazione con l'Ordine di Roma ed il CNR
Tema: **LA ROBUSTEZZA STRUTTURALE: METRICHE DI MISURA E CASI ESEMPLIFICATIVI**
Relatori: Marco Savoia, Anna Saetta e Paolo Martinelli

13 Dicembre, Palermo — in collaborazione con l'Ordine di Palermo
Tema: **PROGETTAZIONE DEL RINFORZO DI STRUTTURE IN C.A. CON SISTEMI FRP**
Relatori: Lidia La Mendola, Maria Antonietta Aiello e Gianmarco De Felice

MEDIA PARTNER
ingenio

Enrico Nusiner
Franco Angotti

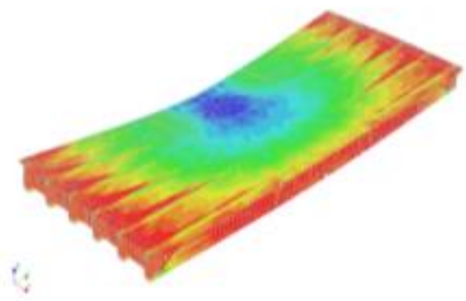
Marco Di Prisco

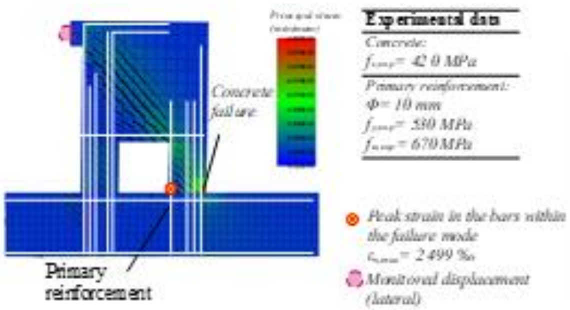
TEMA:

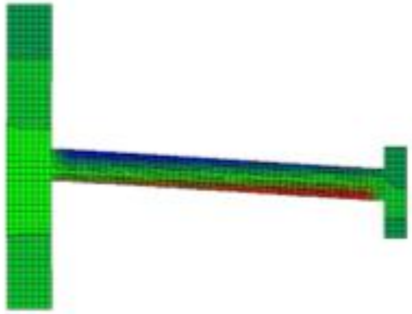
VERIFICHE DI SICUREZZA DI STRUTTURE NUOVE ED ESISTENTI IN C.A. E C.A.P. CON IL METODO DEGLI ELEMENTI FINITI

Relatori:

Paolo Castaldo, Beatrice Belletti, Giuseppe Mancini,
Diego Gino, Simone Ravasini, Elena Miceli







Metodologie di verifiche "Safety Formats" di strutture in c.a./c.a.p. secondo Annex F – EC2
Paolo Castaldo
9:00-10:00 1 ora

Modellazione agli elementi finiti di strutture in c.a./c.a.p.: ipotesi e validazione
Beatrice Belletti
10:00-11:00 1 ora

Progetto delle strutture in c.a./c.a.p. con elementi shell
Giuseppe Mancini
11:00-12:00 1 ora

Confronto tra analisi locale e globale agli elementi finiti di strutture in c.a./c.a.p.: esempi
Diego Gino
12:00-13:00 1 ora

Pausa pranzo
13:00-15:00

Valutazione della sicurezza statica e sismica di strutture in c.a. mediante i safety formats: esempi
Simone Ravasini
15:00-16:00 1 ora

Valutazione della sicurezza di ponti ed edifici mediante i safety formats: esempi
Elena Miceli
16:00-17:00 1 ora

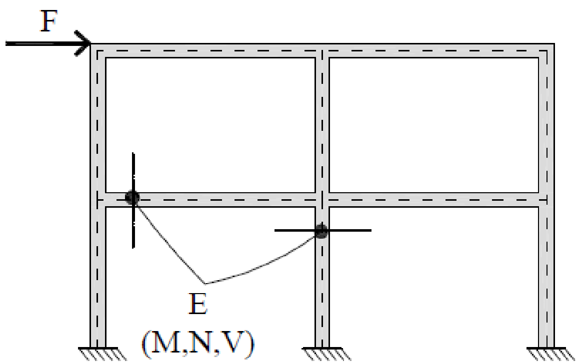
Metodologie di verifiche “Safety Formats” di strutture in c.a./c.a.p. secondo Annex F – EC2

GLOBAL RESISTANCE FORMAT (GRF)

fib MODEL CODE 2010 and 2020

"LOCAL" ANALYSIS

$$E_d \leq R_d$$



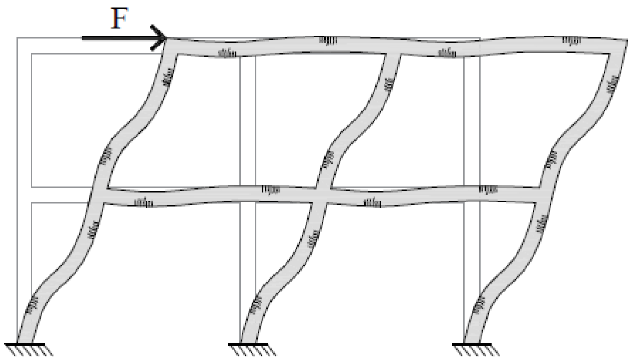
F : agent external actions

E_d : design value of effects of actions evaluated with linear elastic analysis

R_d : sectional resistance in terms of internal actions (M,N,V) (design)

"GLOBAL" ANALYSIS

$$F_d \leq R_d$$



F : agent external actions

F_d : design value of external actions

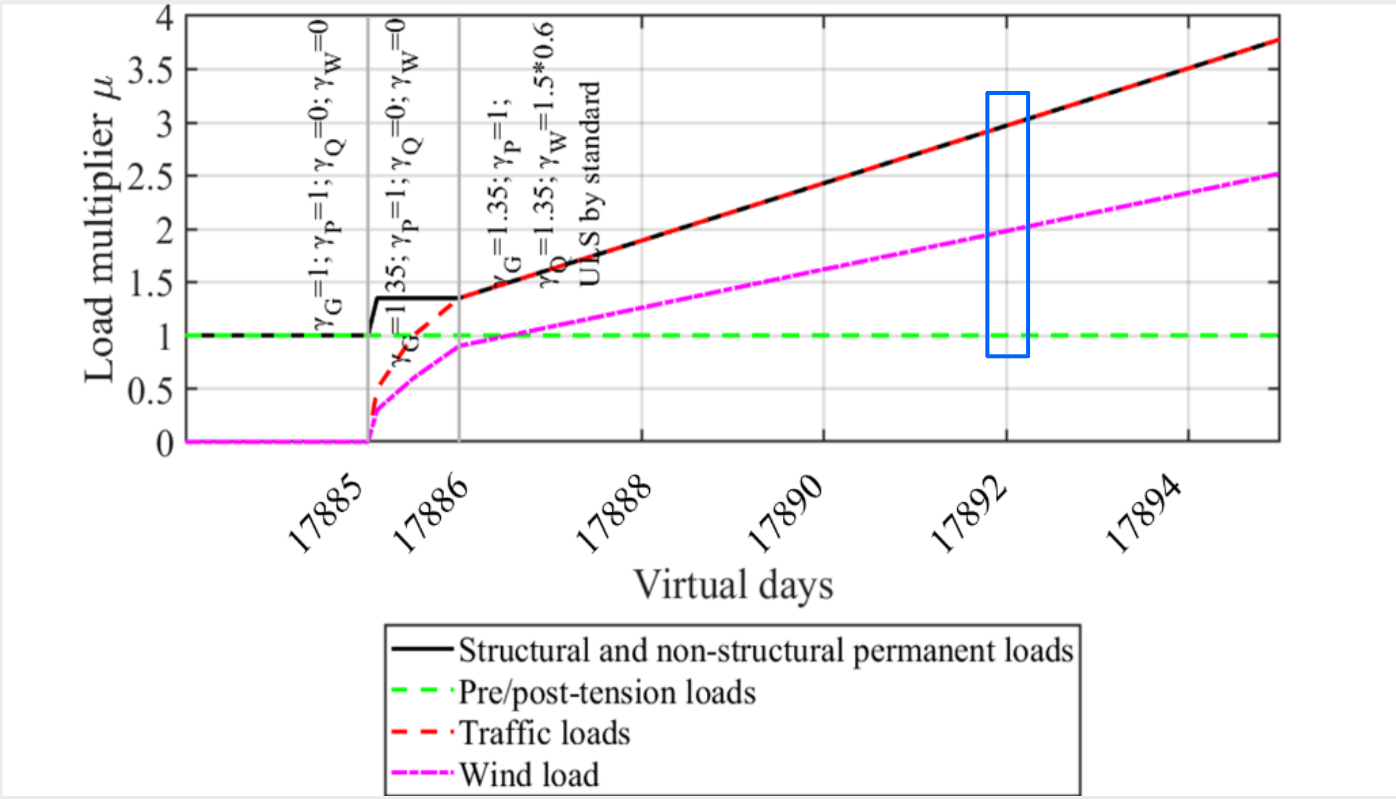
R_d : global design resistance of the structure to the external action evaluated with non-linear analysis (design)

(NLNA: Non-Linear Numerical Analysis)

GLOBAL RESISTANCE FORMAT (GRF)

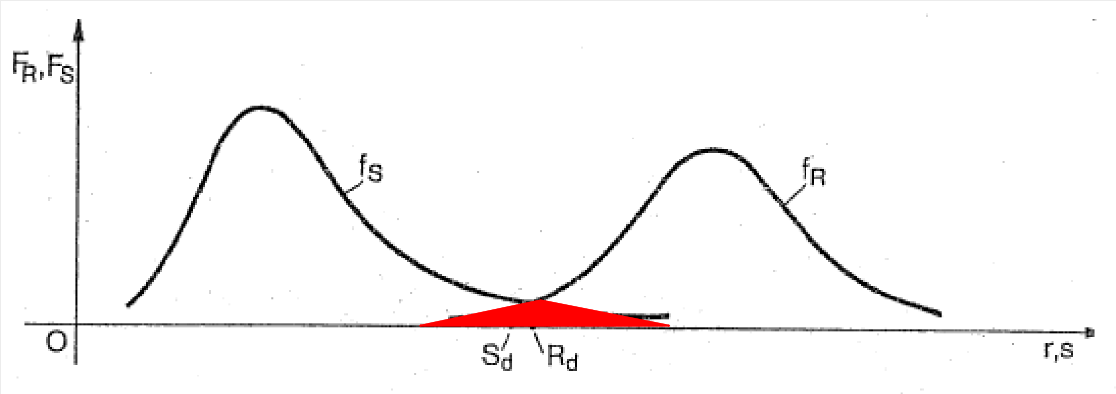
fib MODEL CODE 2010 and 2020

Global Structural Resistance



GLOBAL RESISTANCE FORMAT (GRF)

fib MODEL CODE 2010 and 2020



Partial safety factors

aleatory uncertainties { actions; materials and geometry

epistemic uncertainties { modelling hypotheses

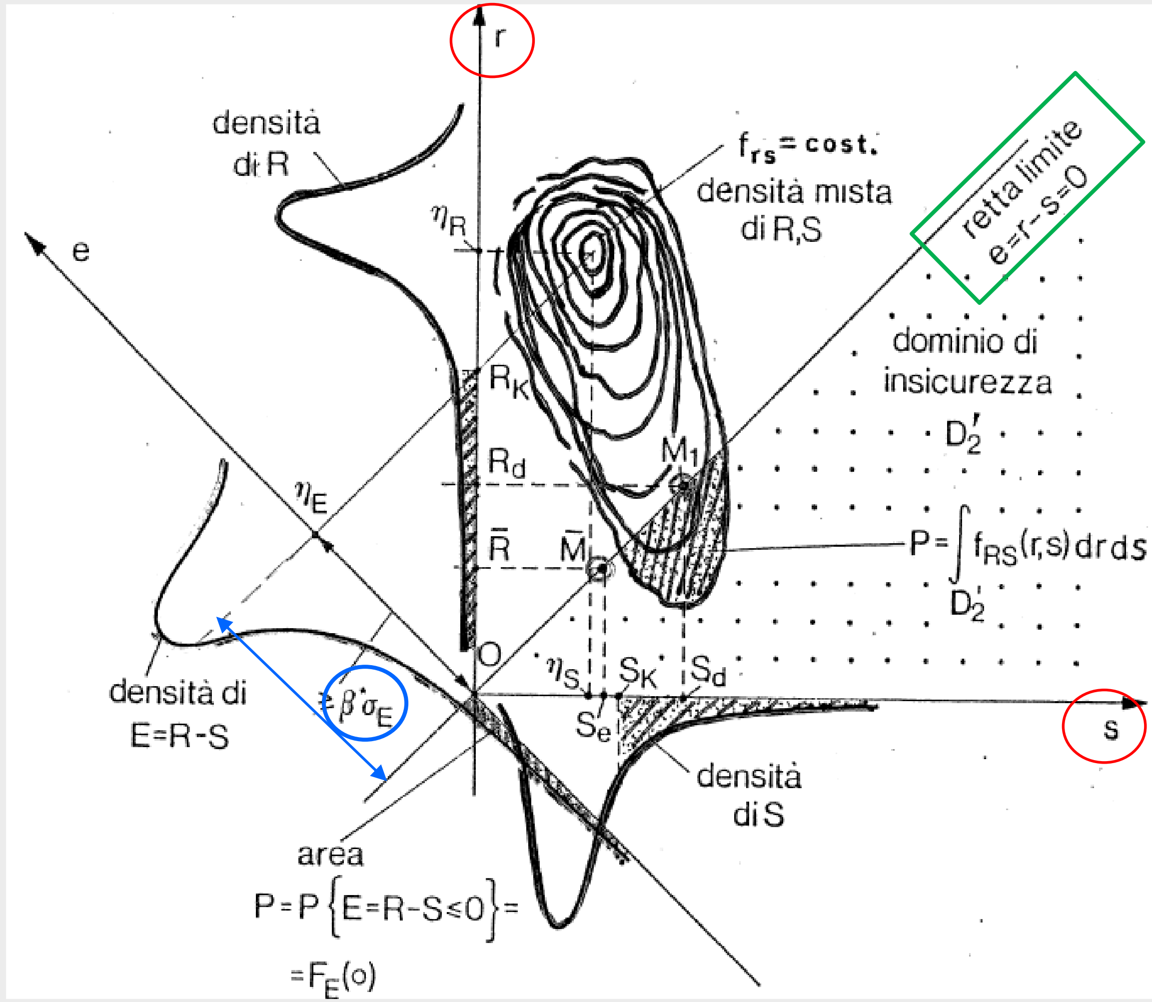
↓

Probability of failure p_f

GLOBAL RESISTANCE FORMAT (GRF)

fib MODEL CODE 2010 and 2020

R=resistenza
S=azione



(A. Migliacci)

GLOBAL RESISTANCE FORMAT (GRF)

fib MODEL CODE 2010 and 2020

Probability of failure p_f

↓

$$p_f = \Phi(-\beta) \qquad \beta = -\Phi^{-1}(p_f)$$

GLOBAL RESISTANCE FORMAT (GRF)

fib MODEL CODE 2010 and 2020

Probability of failure

↓

β

P_f	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-6}
β	1.28	2.32	3.09	3.72	4.75

GLOBAL RESISTANCE FORMAT (GRF)

fib MODEL CODE 2010 and 2020

Classi di consequenza CC

CC	Qualitative description	Examples
CC1	Small number of persons at risk, and negligible economic or environmental losses.	Buildings where people do not normally enter (e.g. storage buildings, greenhouses). Low rise buildings with only few people. Bridges - short-span structures such as culverts, short river crossings.
CC2	All buildings not classified as CC1 or CC3	Residential and office buildings. Most buildings up to 15 stories. Bridges not in other consequence classes.
CC3	Large number of persons at risk, or substantial economic or environmental losses.	Buildings where people may congregate (e.g. grandstands, concert halls), buildings designated as essential facilities (e.g. hospitals, schools) or buildings whose failure could pose a substantial hazard to a community (e.g. facilities for manufacture or storage of hazardous substances). High-rise buildings. Railway bridges, bridges over railways. Bridges over or under major roads.

GLOBAL RESISTANCE FORMAT (GRF)

fib MODEL CODE 2010 and 2020

Classi di consequenza CC

β in 1 anno

Relative cost of safety measure	Consequence Class		
	CC1	CC2	CC3
Large (A)	3.1	3.3	3.7
Normal (B)	3.7	**4.2**	4.4
Small (C)	4.2	4.4	4.7

β in 50 anni

Consequence Class		
CC1	CC2	CC3
3.3	**3.8**	4.3

GLOBAL RESISTANCE FORMAT (GRF)

fib MODEL CODE 2010 and 2020 – EC2 - ANNEX F

Modello numerico non lineare

Resistenza Globale = valore «incrementato» della combinazione di azioni esterne

Sicurezza strutturale (incertezze elatorie ed epistemiche - β)

↓

Metodologie di verifica – Safety formats

GLOBAL SAFETY FORMATS AND SAFETY FACTORS

fib MODEL CODE 2010 and 2020 – EC2 - ANNEX F

GLOBAL RESISTANCE FORMAT (GRF)		
fib MODEL CODE 2010		*fib* MODEL CODE 2020 – EC2 - ANNEX F
PFM – Partial Factor Method		PFM – Partial Factor Method
GRMs – Global Resistance Methods	GRF – Global Resistance Factor	GFM – Global Factor Method
	ECoV – Estimation of Coefficient of Variation	
	GSF – Global Safety Factor	
PM – Probabilistic Method		PM – Probabilistic Method

GLOBAL SAFETY FORMATS AND SAFETY FACTORS

fib MODEL CODE 2010 and 2020

1. **Partial Factor Method (PFM) (*fib* Model Code 2010, 2013);**

2. **Global Resistance Methods (GRMs):**

- **2.a Global Resistance Factor (GRF) (*fib* Model Code 2010, 2013);**
- **2.b Method of Estimating the Coefficient of Variation of the structural resistance (ECoV) (*fib* Model Code 2010, 2013);**
- **2.c Global Safety Factor (GSF) based on mean values of material properties (Allaix, Carbone & Mancini, 2013);**

3. The general probabilistic approach is considered the Probabilistic Method (PM) (*fib* Model Code 2010, 2013).

GLOBAL SAFETY FORMATS AND SAFETY FACTORS

fib MODEL CODE 2010 and 2020

aleatory uncertainties

1 **PFM – Partial Factor Method**

N°of simulations required: ***1***

$\mathbf{R_{NLNA}(f_d)}$

$$R_d = \frac{R_{NLNA}(X_d; a_d)}{\gamma_{Rd}}$$

epistemic uncertainties

2.a **GRF – Global Resistance Factor** (EN 1992-2)

N°of simulations required: ***1***

$\mathbf{R_{NLNA}(f_{cmd}, f_{ym})}$

$$f_{cmd} = 0.85 f_{ck}$$

$$f_{ym} = 1.1 f_{yk}$$

$$R_d = \frac{R_{NLNA}(f_{cmd}, f_{ym}; a_{nom})}{\gamma_{GL}}$$

$$\gamma_{GL} = \gamma_R \gamma_{Rd} \quad (=1.27)$$

GLOBAL SAFETY FORMATS AND SAFETY FACTORS

fib MODEL CODE 2010 and 2020

2.b ECoV – Estimation of Coefficient of Variation

N°of simulations required:

2 → **1 $R_{NLNA}(f_k)$**, **1 $R_{NLNA}(f_m)$**

$$V_R = \frac{1}{1.65} \ln \left(\frac{R_{NLNA}(X_m; a_{nom})}{R_{NLNA}(X_k; a_{nom})} \right)$$

$$\gamma_R = \exp(\alpha_R \cdot \beta \cdot V_R)$$

Log-normality assumption

$$R_d = \frac{R_{NLNA}(X_m; a_{nom})}{\gamma_R \cdot \gamma_{Rd}}$$

aleatory uncertainties

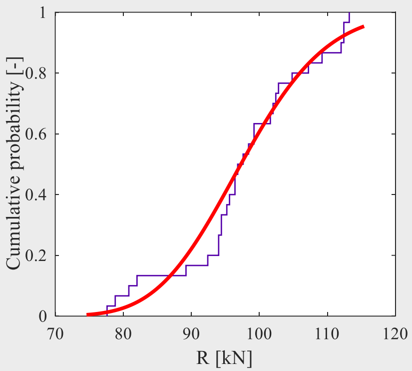
epistemic uncertainties

GLOBAL SAFETY FORMATS AND SAFETY FACTORS

fib MODEL CODE 2010 and 2020

2.c GSF – Global Safety Factor

- **Reduced Monte Carlo simulation: Latin Hypercube Sampling (LHS)**



V_R

N°of simulations required:

(e.g., around ***30***)

Then:

$$\gamma_R = \exp(\alpha_R \cdot \beta \cdot V_R)$$

Log-normality assumption

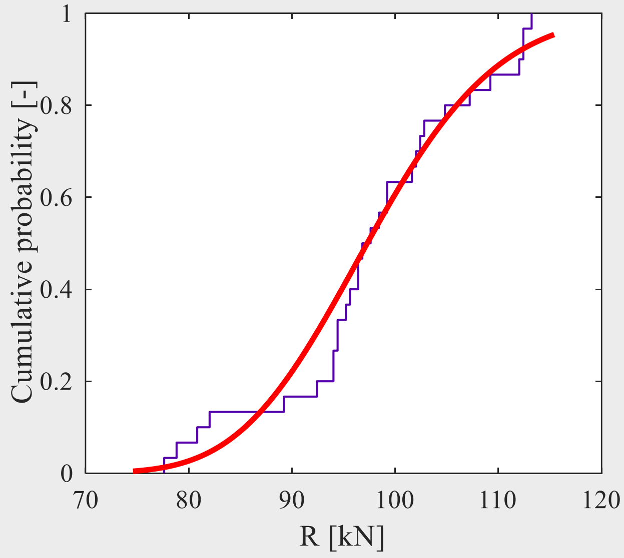
$$R_d = \frac{R_{NLNA}(X_m; a_{nom})}{\gamma_R \cdot \gamma_{Rd}}$$

aleatory uncertainties

epistemic uncertainties

3 PM – Probabilistic Method

- **Reduced Monte Carlo simulation: Latin Hypercube Sampling (LHS)**



N°of simulations required:

(e.g., around ***30***)

The distribution (which can be generic) is characterized.

GLOBAL SAFETY FORMATS AND SAFETY FACTORS

fib MODEL CODE 2010 and 2020 – EC2 - ANNEX F

GLOBAL RESISTANCE FORMAT (GRF)		
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GRMs – Global Resistance Methods	GRF – Global Resistance Factor	GFM – Global Factor Method
	ECoV – Estimation of Coefficient of Variation	
	GSF – Global Safety Factor	
PM – Probabilistic Method		PM – Probabilistic Method

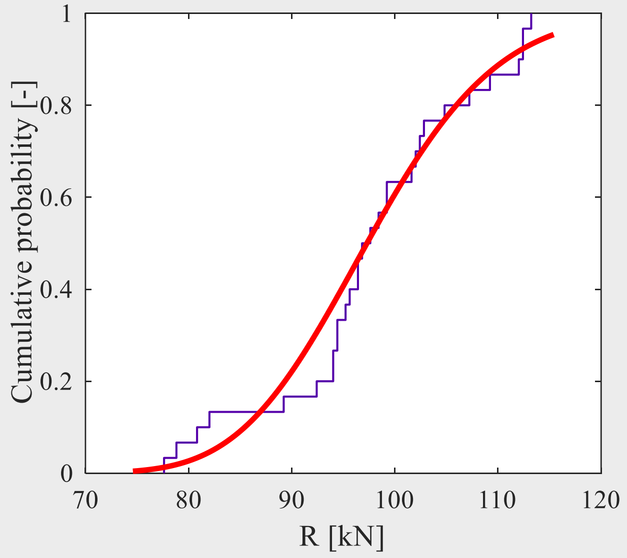
PROBABILISTIC METHOD (PM)

fib MODEL CODE 2010 and 2020

EUROCODICE 2 - Annex F

3 PM – Probabilistic Method

- **Reduced Monte Carlo simulation: Latin Hypercube Sampling (LHS)**



N°of simulations required:

(e.g., around ***30***)

The distribution (which can be generic) is characterized.

PARTIAL FACTOR METHOD (PFM)

EUROCODICE 2 - Annex F

1 **PFM – Partial Factor Method**

design structural resistance

$$R_d = \frac{R_{NLNA}(X_d ; a_d)}{\gamma_{Rd}}$$

structural resistance by means of 1 NLNA considering the design values (assuming a target reliability index - prEN 1990:2020 and prEN 1992-1-1:2020 - Annex A) for the material and geometrical properties

partial safety factor for the resisting model uncertainties (between and within)

GLOBAL FACTOR METHOD (GFM)

EUROCODICE 2 - Annex F

2 **GFM – Global Factor Method (ECoV)**

design structural resistance

$$R_d = \frac{R_{NLNA}(X_m; a_{nom})}{\gamma_R \gamma_{Rd}}$$

structural resistance by means of 1 NLNA considering the mean and nominal values, respectively, for the material and geometrical properties (actual failure mode)

partial safety factor accounting for both the aleatory uncertainties of the material and geometrical properties

partial safety factor for the resisting model uncertainties (between and within)

GLOBAL FACTOR METHOD (GFM)

fib MODEL CODE 2010 and 2020

EUROCODICE 2 - Annex F

Aleatory uncertainties:

$$R_d = \frac{R_{NLNA}\left(X_m ; a_{nom}\right)}{\gamma_R \gamma_{Rd}}$$

γ_R: partial safety factor accounting for both the aleatory uncertainties of the material and geometrical properties

GLOBAL FACTOR METHOD (GFM)

fib MODEL CODE 2010 and 2020

EUROCODICE 2 - Annex F

$$\gamma_R = \frac{\exp(\alpha_R \beta_t \cdot V_R)}{\delta_R} \geq 1.00$$

α_R: sensitivity factor: set equal to 0.8 in line to the assumption of dominant resistance variable within the reliability analysis

V_R: the coefficient of variation (CoV) of the global structural resistance

δ_R: is related to the bias factors of geometrical properties deviations $\delta_{R,g}$ and to the mean-to-mean deviation $\delta_{R,m}$ ($\delta_R=\delta_{R,g}\cdot\delta_{R,m}$)≃1

β_t: the target reliability index and can be adopted in compliance to: prEN 1990:2020 and prEN 1992-1-1:2020 Annex A

GLOBAL FACTOR METHOD (GFM)

fib MODEL CODE 2010 and 2020

EUROCODICE 2 - Annex F

The coefficient of variation of the global resistance:

$$V_R = \sqrt{V_{R,m}^2 + V_{R,g}^2} \quad with\ V_R \leq 0.3$$

$V_{R,m}$ represents the coefficient of variation associated to the material uncertainties (=0.15) or according to ECoV method:

$$V_{R,m} = \frac{1}{1.65} \ln \left(\frac{R_{NLNA}\left(X_m; a_{nom}\right)}{R_{NLNA}\left(X_k; a_{nom}\right)} \right)$$

the same NLNA

a second NLNA considering the characteristic and nominal values, respectively, for the material and geometrical properties

$V_{R,g}$ denotes the coefficient of variation related to the geometrical uncertainties = 0.05

PARTIAL FACTOR METHOD (PFM)
GLOBAL FACTOR METHOD (GFM)

fib MODEL CODE 2010 and 2020

EUROCODICE 2 - Annex F

Modelling uncertainties:

$$R_d = \frac{R_{NLNA}(X_d; a_d)}{\gamma_{Rd}}$$

γ_{Rd} → ?

$$R_d = \frac{R_{NLNA}\left(X_m; a_{nom}\right)}{\gamma_R \gamma_{Rd}}$$

γ_{Rd} → ?

PARTIAL FACTOR FOR THE RESISTING MODEL UNCERTAINTIES

experimental test

$$R_i \approx \vartheta_i \; R_{NLNA,i}$$

NLNA result

resisting model uncertainties (random variable)

μ_ϑ the mean value of the resisting model uncertainties

V_ϑ the coefficient of variation of the resisting model uncertainties

Under the log-normality hypothesis, the partial safety factor representative of the resisting model uncertainties can be determined, according to JCSS Probabilistic Model Code (2001), as follows:

$$\gamma_{Rd} = \frac{1}{\mu_\vartheta \cdot \exp(-\alpha_R \cdot \beta \cdot V_\vartheta)}$$

the sensitivity factor, equal to 0.32 for non-dominant resistance variable

the reliability index

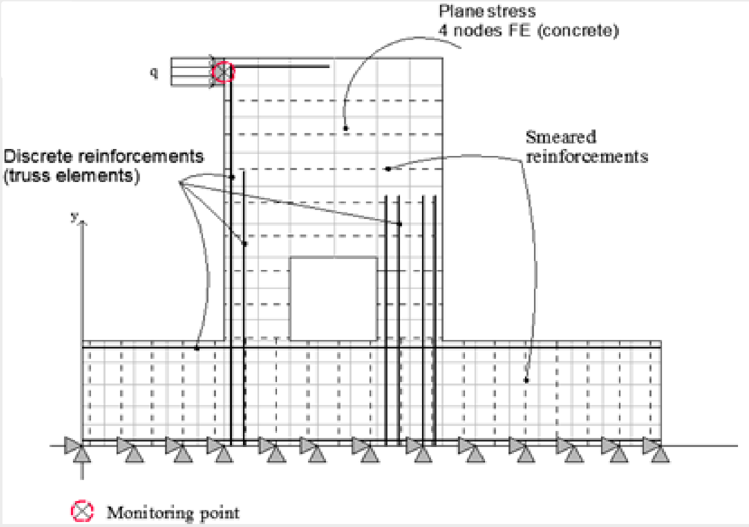
the coefficient of variation associated to the epistemic uncertainties

EXPERIMENTAL TESTS

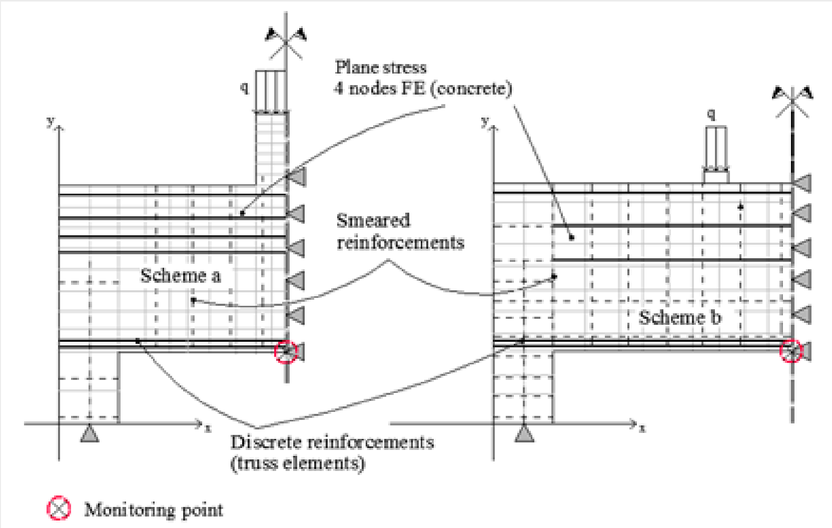
The experimental results reported in the scientific literature (Filho 1995, Foster and Gilbert 1998, Lefas and Kotsovos 1990, Leonhardt and Walther 1966, Vecchio and Collins 1982) and related to 25 different typologies of structural members are considered and assumed as benchmark test set.

(four shear panels, five deep beams and eleven walls)

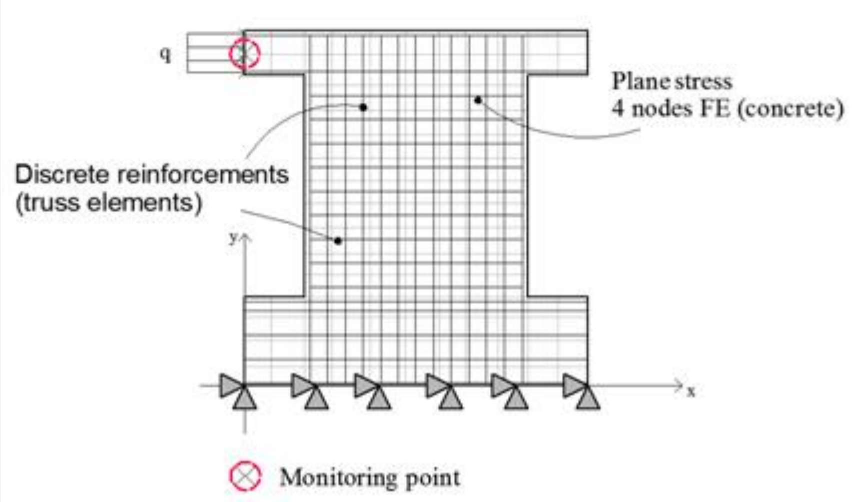
Filho 1995



Foster and Gilbert 1998

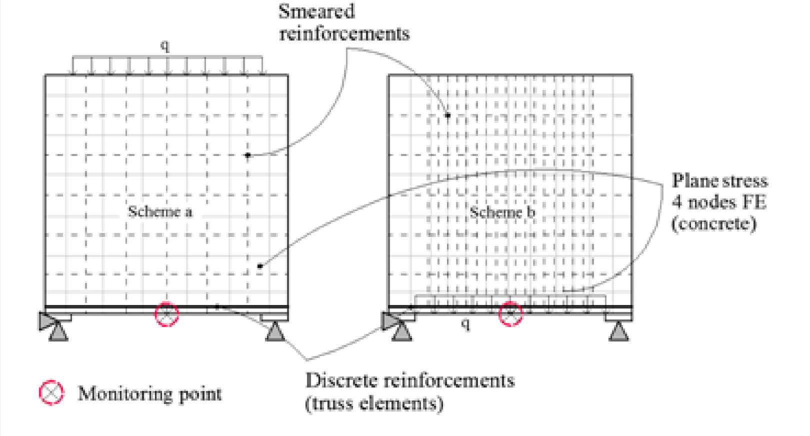


EXPERIMENTAL TESTS

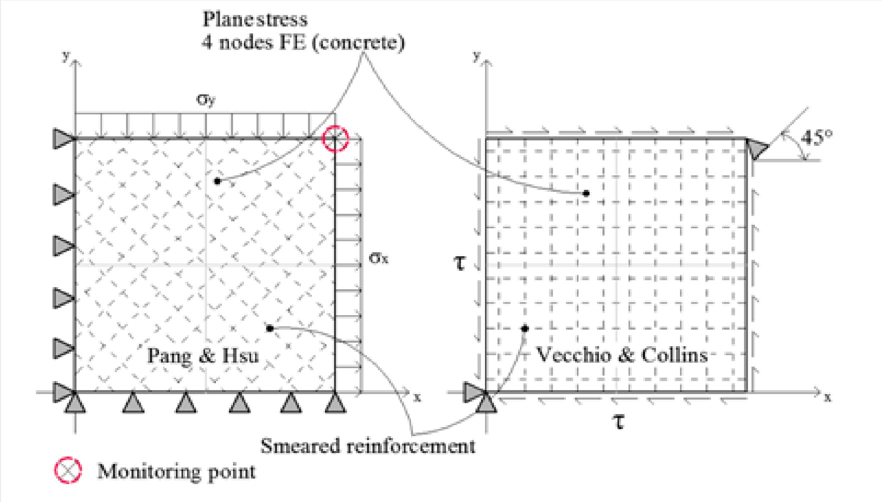


Lefas and Kotsovos 1990

Leonhardt and Walther 1966

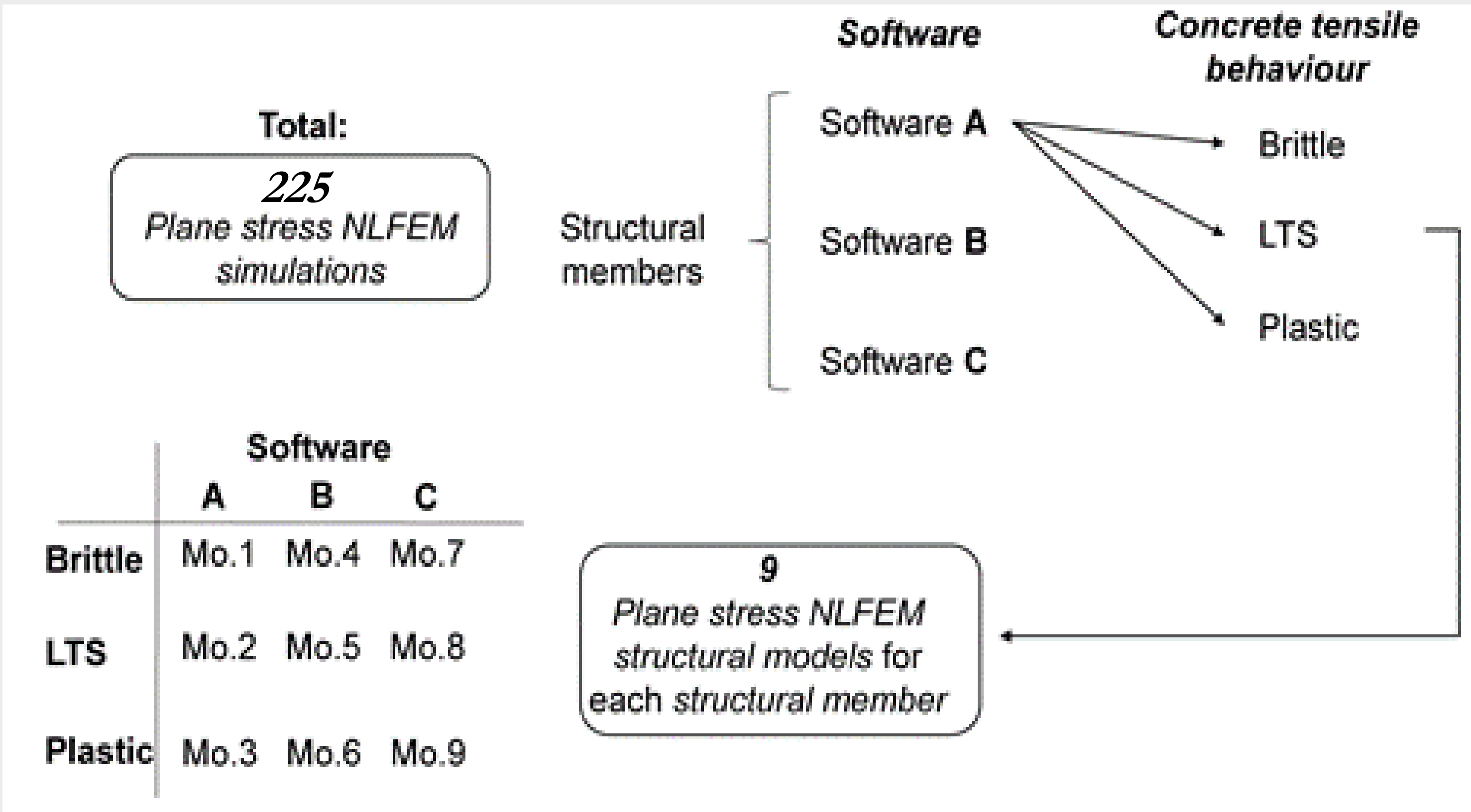


Vecchio and Collins 1982



DEFINITION OF THE NLN MODELS – MODEL UNCERTAINTIES

225 NLNAs = 25 r.c. structures x 3 Software codes x 3 Constitutve laws in tension for concrete



DEFINITION OF THE NLN MODELS – MODEL UNCERTAINTIES

Table 1
Summary of the basic hypotheses assumed in the definition of non-linear FE numerical models.

	Software A	Software B	Software C
Equilibrium	– *Standard Newton-Raphson based on the hypothesis of linear approximation* [1] – *Convergence criteria based on strain energy* – *Load step sizes defined in compliance with the experimental procedure*		
Compatibility	*Finite elements* – Isoparametric plane stress 4 nodes (2 × 2 Gauss points integration scheme with linear interpolation) – Discrete reinforcements – Element size defined by means of an iterative process of numerical accuracy	*Finite elements* – Isoparametric plane stress 4 nodes (2 × 2 Gauss points integration scheme with linear interpolation) – Smeared reinforcements/ discrete reinforcements – Element size defined following an iterative process of numerical accuracy	
Constitutive laws	*Concrete* – Fixed crack model, smeared cracking, constant shear retention factor = 0.2 – Mono-dimensional model extended to biaxial stress state – Compression: non-linear with post peak linear softening branch – Tension (differentiating between 3 modelling hypotheses): (1) Elastic - Brittle (BRITTLE) (2) Elastic with post peak linear tension softening (LTS) (3) Elastic - perfectly plastic (PLASTIC) *Reinforcements steel* – Tri-linear elastic–plastic		

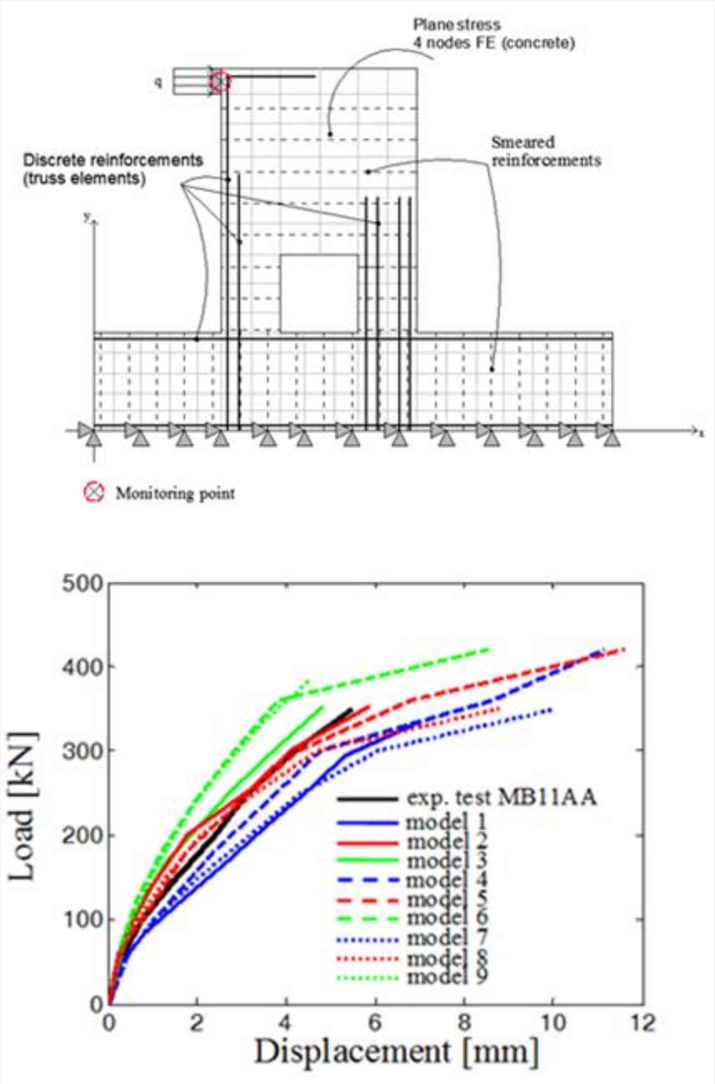
(between

and

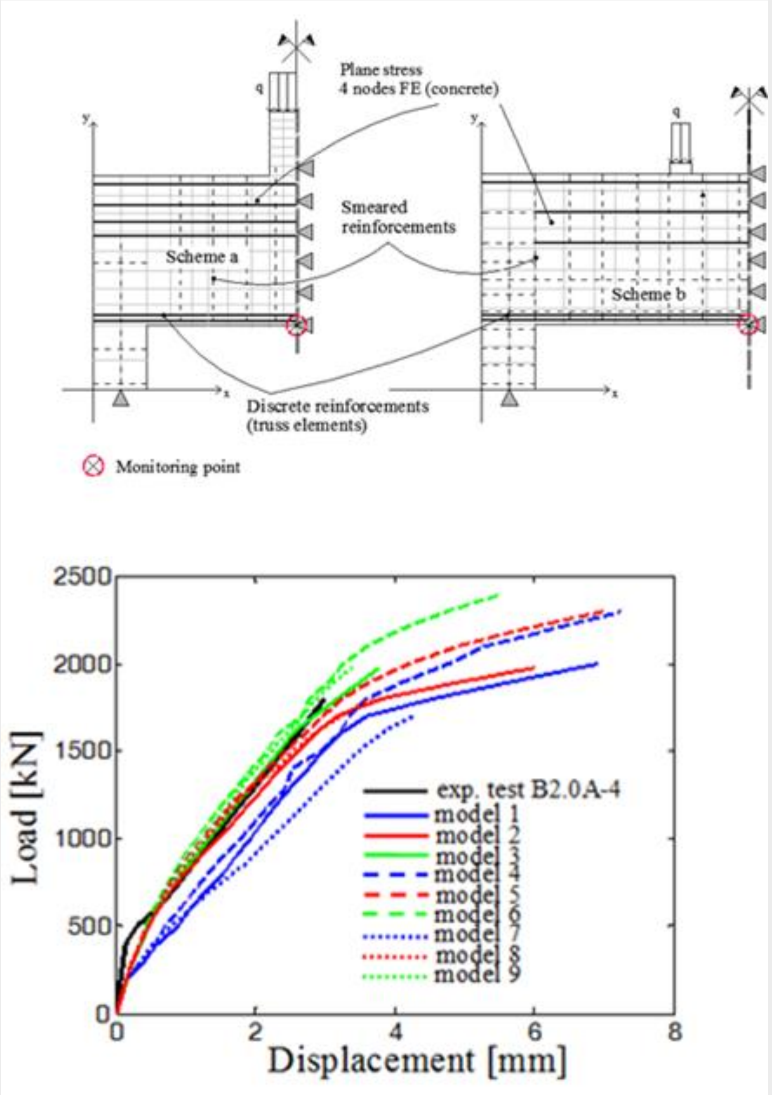
within)

NLNAs RESULTS

Filho 1995



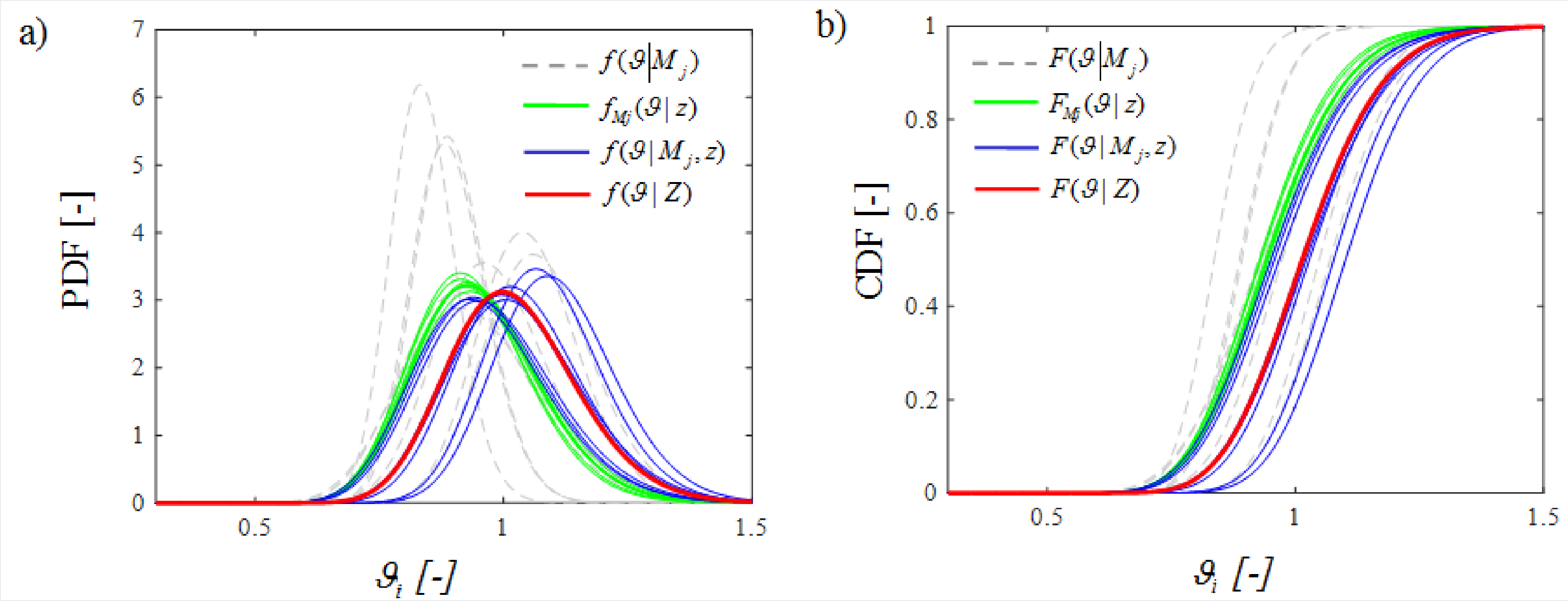
Foster and Gilbert 1998



PROBABILISTIC MODEL AND BAYESIAN UPDATING

From NLNAs results, resisting model uncertainties have been computed:

$$\vartheta_i = \frac{R_{EXP,i}}{R_{NLNA,i}}$$



PARTIAL SAFETY FACTOR FOR THE RESISTING MODEL UNCERTAINTIES

	Service life	Consequences of failure	Reliability index β	FORM factor α_R	Partial safety factor γ_{Rd}
New structures	[Years]	[-]	[-]	[-]	[-]
	50	Low	3.1	Non-dominant 0.32	*1.12*
	50	Moderate	3.8		*1.15*
	50	High	4.3		*1.17*
Existing structures	**Residual service life**		**Reliability index β**	**FORM factor α_R**	**Partial safety factor γ_{Rd}**
	[Years]		[-]	[-]	[-]
	50		3.1 - 3.8	Non-dominant 0.32	*1.12-1.15*
	15		3.4 - 4.1		*1.13-1.16*
	1		4.1 - 4.7		*1.16 - 1.19*

$$\gamma_{Rd} = 1.15$$

Model uncertainties for cyclic loads

Experimental tests

16 different r.c. walls:

Kypros Pilakoutas and Amr Einashai. Cyclic Behaviour of Reinforced Concrete Canti-lever Walls, Part I : Experimental Results. ACI structural journal no.92-S25, 1995.

Ioannis D. Lefas and Micheal D. Kotsovos. Strength and deformation characteristics of reinforced concrete walls under load reversals. ACI structural journal no.87-S74, 1990.

Yunfeng Zhang and Zhihao Wang. Seismic behaviour of reinforced concrete shear walls subjected to high axial loading. ACI structural journal no.97-S75, 2000.

Model hypotheses

	Software A	Software B
Equilibrium	*- Standard Newton-Raphson based on the hypothesis of linear approximation [1]* *- Convergence criteria based on strain energy* *- Load step sizes defined in compliance with the experimental procedure*	
Compatibility	*Finite Elements* - Isoparametric plane stress 4 nodes (2x2 Gauss points integration scheme with linear interpolation) - Discrete reinforcements - Element size defined by means of an iterative process of numerical accuracy	*Finite Elements* - Isoparametric plane stress 4 nodes (2x2 Gauss points integration scheme with linear interpola-tion) - Smeared reinforcements/discrete reinforce-ments - Element size defined following an iterative process of numerical accuracy
Constitutive laws	*CONCRETE* - Fixed crack model, smeared cracking, constant shear retention factor equal to: 1) 0.1 2) Variable 3) 0.3 - Mono-dimensional model extended to biaxial stress state - Compression: Non-linear with post peak linear softening branch - Tension (differentiating between 3 modelling hypotheses): 1) Elastic - Brittle (BRITTLE) 2) Elastic with post peak linear tension softening (LTS) 3) Elastic - perfectly plastic (PLASTIC) *REINFORCEMENTS STEEL* - Tri-linear elastic – plastic	

NLNAs

17 structural RC members

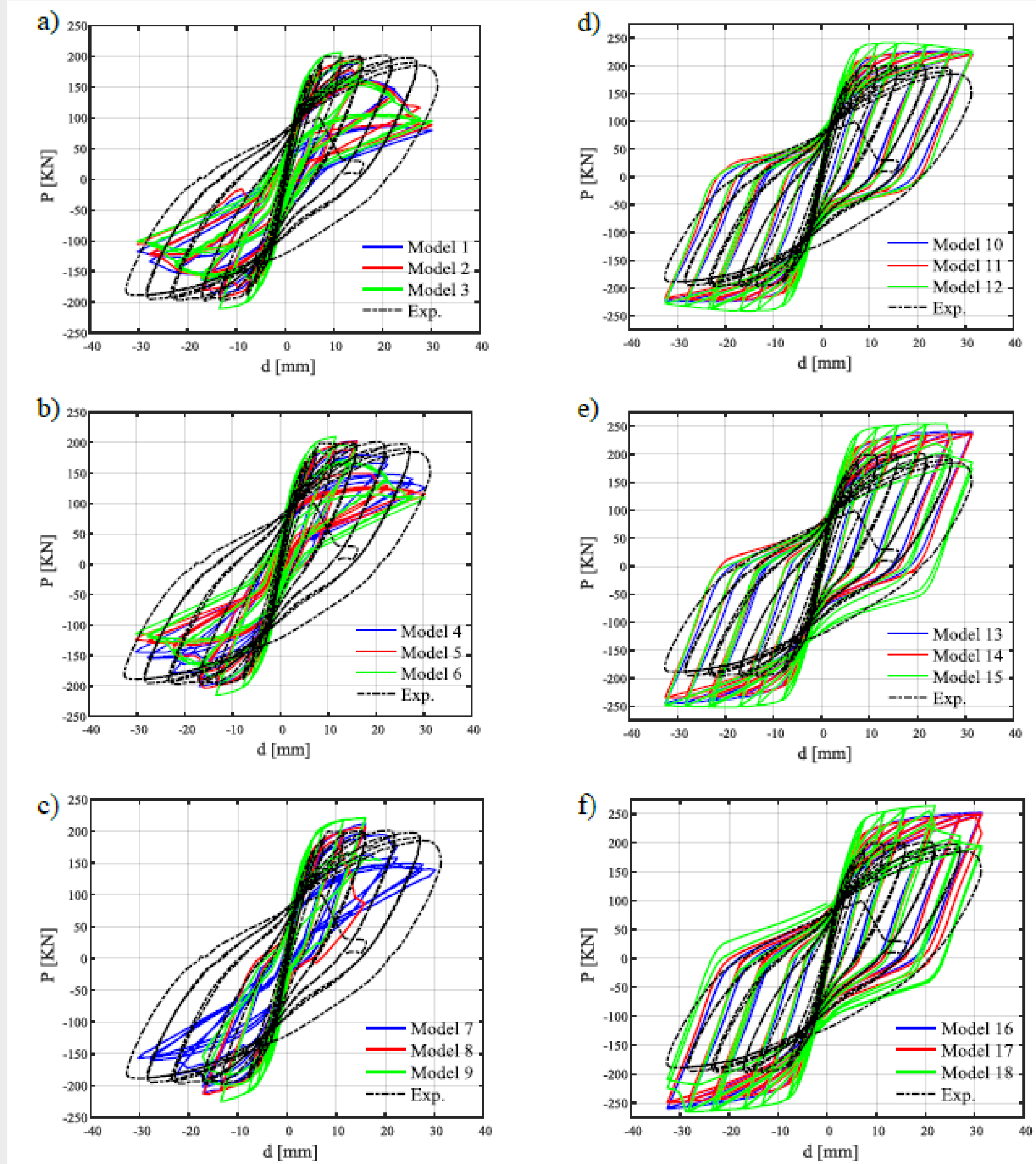
Concrete tensile behavior	Numerical code A			Numerical code B		
	Shear retention factor β			*Shear retention factor* β		
	0.1	*variable: 0.1-0.3*	*0.3*	*0.1*	*variable: 0.1-0.3*	*0.3*
Brittle	Model 1: M_1	Model 4: M_4	Model 7: M_4	Model 10: M_{10}	Model 13: M_{13}	Model 16: M_{16}
LTS	Model 2: M_2	Model 5: M_5	Model 8: M_8	Model 11: M_{11}	Model 14: M_{14}	Model 17: M_{17}
Plastic	Model 3: M_3	Model 6: M_6	Model 9: M_9	Model 12: M_{12}	Model 15: M_{15}	Model 18: M_{18}

306 NLFE simulations

(between and within)

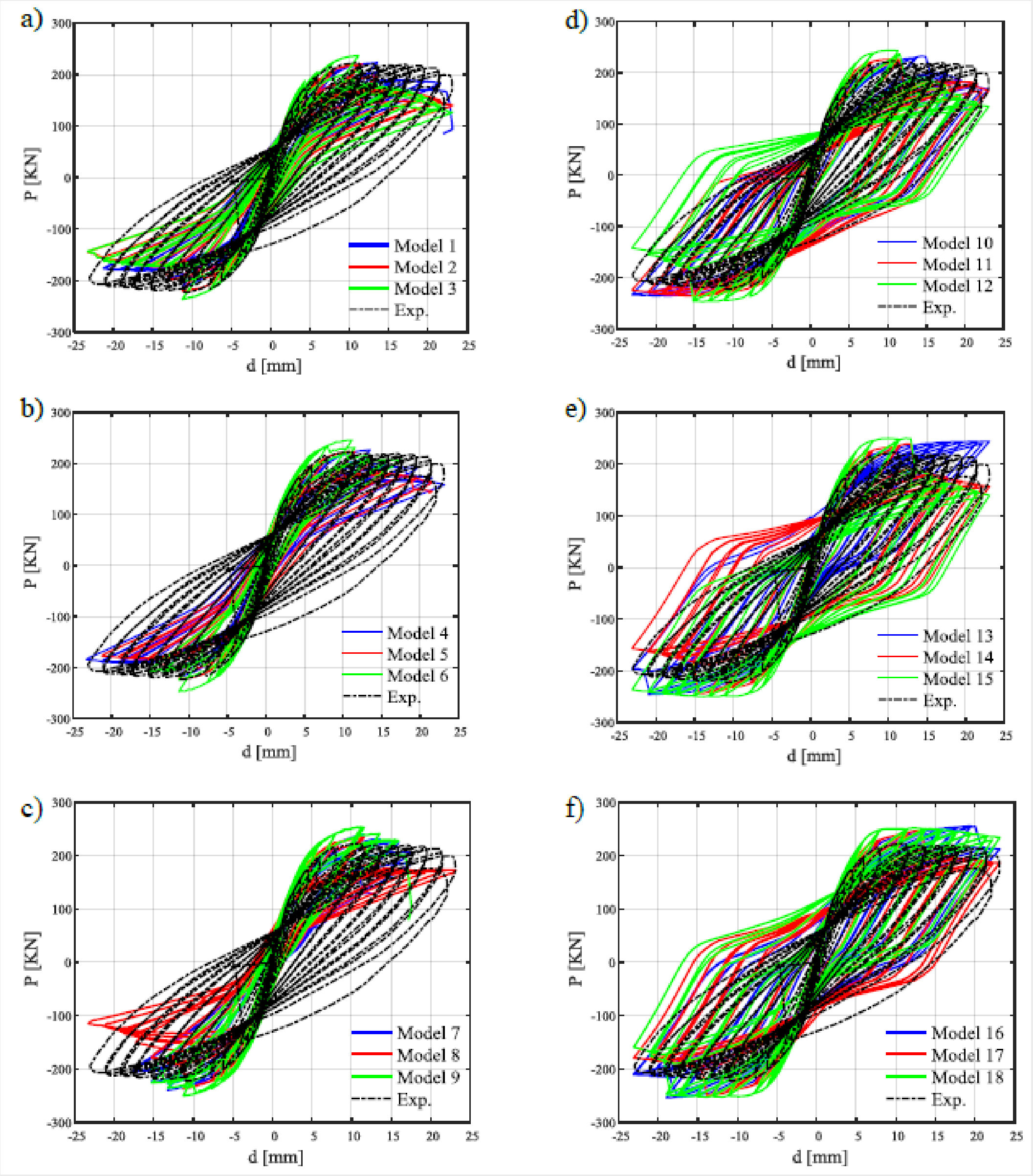
Results:

Load vs displacement diagrams from experimental tests SW7 of Zhang and Wang and NLFEA results:
(a-c) Software A,
(d-f) Software B



Results

Load vs displacement diagrams from experimental tests SW8 of Zhang and Wang [22] and NLFEA results: (a-c) Software A, (d-f) Software B.



Results

$\vartheta_i = R_{EXP,i}/R_{NLFA,i}$

Ref [*]	Exp. tests	Structural model																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
[34]	SW4	0.83	1.00	0.76	0.82	0.81	0.75	0.81	0.82	0.85	0.82	0.77	0.68	0.82	0.77	0.67	0.81	0.74	0.67
	SW6	1.08	0.90	0.89	0.92	0.90	0.81	0.88	0.87	0.80	0.98	0.90	0.76	0.98	0.87	0.76	0.97	0.88	0.76
	SW8	0.74	0.75	0.67	0.72	0.73	0.64	0.69	0.70	0.62	0.74	0.68	0.60	0.74	0.69	0.59	0.72	0.68	0.59
[35]	SW31	1.04	0.96	0.72	0.96	0.87	0.69	0.91	0.83	0.66	1.32	0.99	0.83	1.18	0.91	0.79	1.17	0.88	0.77
	SW32	1.01	0.97	0.78	0.97	0.94	0.78	0.93	0.85	0.77	1.18	1.09	0.86	1.18	1.09	0.86	1.12	1.09	0.86
	SW33	1.04	1.00	0.86	1.01	0.98	0.80	0.98	0.95	0.78	1.18	1.16	0.94	1.17	1.10	0.91	1.16	1.13	0.88
[36]	SW7	1.06	1.03	0.97	0.99	0.99	0.96	0.95	0.98	0.89	0.89	0.90	0.83	0.84	0.85	0.79	0.80	0.81	0.76
	SW8	1.00	1.02	0.95	0.99	1.00	0.93	0.93	0.95	0.88	0.96	0.99	0.92	0.92	0.93	0.89	0.88	0.90	0.89
	SW9	0.94	0.93	0.88	0.88	0.90	0.84	0.84	0.88	0.83	0.94	0.95	0.88	0.91	0.92	0.86	0.88	0.90	0.85
[37]	B6	0.96	1.01	0.87	0.92	1.01	0.88	0.91	0.97	0.88	0.94	0.93	0.82	0.94	0.92	0.82	0.91	0.91	0.82
	B7	0.96	1.00	0.79	0.91	0.96	0.78	0.90	0.95	0.76	0.78	0.81	0.69	0.77	0.79	0.69	0.75	0.79	0.68
	B8	0.95	0.97	0.85	0.89	0.91	0.81	0.86	0.91	0.79	0.80	0.82	0.72	0.77	0.82	0.73	0.76	0.82	0.73
	F2	1.07	1.00	0.80	1.01	1.01	0.77	0.97	0.93	0.76	0.80	0.82	0.67	0.80	0.82	0.67	0.76	0.82	0.66
[38]	WSH2	0.95	0.99	0.70	0.93	0.97	0.69	0.82	0.88	0.64	0.95	0.88	0.73	0.98	0.87	0.73	0.92	0.87	0.73
	WSH3	1.03	1.02	0.75	1.00	1.01	0.69	0.83	0.96	0.67	0.94	0.85	0.75	0.91	0.84	0.74	0.94	0.85	0.75
	WSH6	0.94	0.96	0.81	0.90	0.91	0.80	0.87	0.88	0.75	0.97	0.90	0.81	0.96	0.90	0.79	0.93	0.89	0.78

Probabilistic analysis

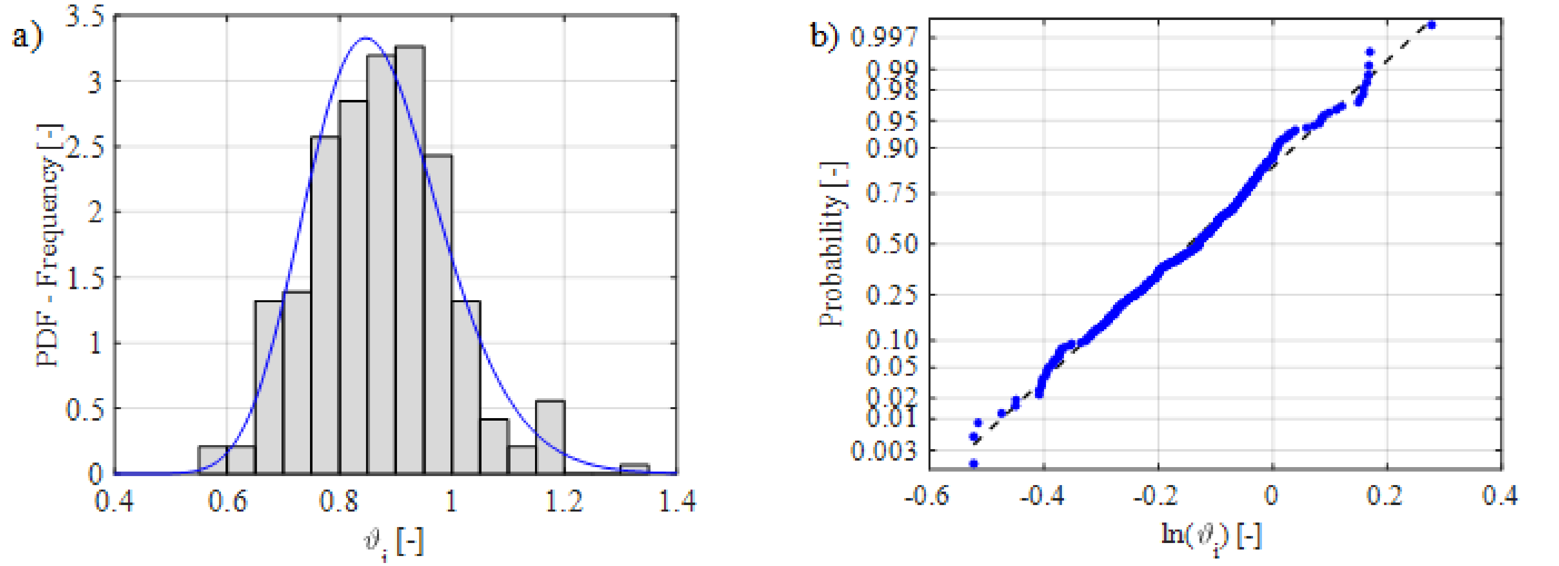


Fig. 20. Histogram and lognormal probability density function of the ratio ϑ_i for all the models (a); Probability plot of ln(ϑ_i) for all the models (b).

Results

New structures	Reference life [Years]	Consequences of failure [-]	Reliability index β [-]	FORM factor α_R [-]	Partial safety factor γ_{Rd} [-]
	50	Low	3.1	Non-dominant 0.32	*1.31*
	50	Moderate	3.8		***1.35***
	50	High	4.3		*1.38*

Existing structures	Reference life [Years]	Reliability index β [-]	FORM factor α_R [-]	Partial safety factor γ_{Rd} [-]
	50	3.1 - 3.8	Non-dominant 0.32	*1.31-1.35*
	15	3.4 - 4.1		*1.33-1.37*
	1	4.1 - 4.7		*1.37-1.41*

PARTIAL SAFETY FACTOR FOR THE RESISTING MODEL UNCERTAINTIES – STATIC ANALYSES

	Service life	Consequences of failure	Reliability index β	FORM factor α_R	Partial safety factor γ_{Rd}
New structures	[Years]	[-]	[-]	[-]	[-]
	50	Low	3.1	Non-dominant 0.32	*1.12*
	50	Moderate	3.8		*1.15*
	50	High	4.3		*1.17*
Existing structures	Residual service life		Reliability index β	FORM factor α_R	Partial safety factor γ_{Rd}
	[Years]		[-]	[-]	[-]
	50		3.1 - 3.8	Non-dominant 0.32	*1.12-1.15*
	15		3.4 - 4.1		*1.13-1.16*
	1		4.1 - 4.7		*1.16 - 1.19*

$$\gamma_{Rd} = 1.15$$

PARTIAL SAFETY FACTOR FOR THE RESISTING MODEL UNCERTAINTIES – SEISMIC ANALYSES

	Service life	Consequences of failure	Reliability index β	FORM factor α_R	Partial safety factor γ_{Rd}
New structures	[Years]	[-]	[-]	[-]	[-]
	50	Low	3.1	Non-dominant 0.32	*1.30*
	50	Moderate	3.8		*1.33*
	50	High	4.3		*1.36*

	Residual service life	Reliability index β	FORM factor α_R	Partial safety factor γ_{Rd}
Existing structures	[Years]	[-]	[-]	[-]
	50	3.1 - 3.8	Non-dominant 0.32	*1.30-1.33*
	15	3.4 - 4.1		*1.31-1.35*
	1	4.1 - 4.7		*1.35-1.38*

$$\gamma_{Rd} = 1.35$$

PARTIAL SAFETY FACTOR FOR THE RESISTING MODEL UNCERTAINTIES – SLENDER MEMBERS

	Reference life	Consequences of failure	Reliability index β	FORM factor α_R	Partial safety factor γ_{Rd}	
					Experimental uncertainty	
					Limited	*Significant*
New structures	[Years]	[-]	[-]	[-]	[-]	[-]
	50	Low	3.1	Non-dominant 0.32	*1.14*	*1.11*
		Moderate	3.8		*1.19*	*1.15*
		High	4.3		*1.22*	*1.17*
		Low	3.1	Dominant 0.8	*1.49*	*1.38*
		Moderate	3.8		*1.65*	*1.50*
		High	4.3		*1.77*	*1.59*

	Reference life	Reliability index β	FORM factor α_R	Partial safety factor γ_{Rd}	
				Experimental uncertainty	
				Limited	*Significant*
Existing structures	[Years]	[-]	[-]	[-]	[-]
	50	3.1 - 3.8	Non-dominant 0.32	*1.14-1.19*	*1.11-1.15*
	15	3.4 - 4.1		*1.16-1.21*	*1.13-1.16*
	1	4.1 - 4.7		*1.21-1.25*	*1.16-1.20*
	50	3.1 - 3.8	Dominant 0.8	*1.49-1.65*	*1.38-1.50*
	15	3.4 - 4.1		*1.56-1.72*	*1.43-1.56*
	1	4.1 - 4.7		*1.72-1.87*	*1.56-1.67*

PARTIAL FACTOR METHOD (PFM)
GLOBAL FACTOR METHOD (GFM)

fib MODEL CODE 2010 and 2020

EUROCODICE 2 - Annex F

Comparison neglecting the modelling uncertainties:

PARTIAL FACTOR METHOD (PFM)

$$R_d = \frac{R_{NLNA}(X_d ; a_d)}{\cancel{\gamma_{Rd}}}$$

GLOBAL FACTOR METHOD (GFM) - ECoV

$$R_d = \frac{R_{NLNA}\left(X_m ; a_{nom}\right)}{\gamma_R \cancel{\gamma_{Rd}}}$$

RC structures - beams

- 4 Beams with web openings:

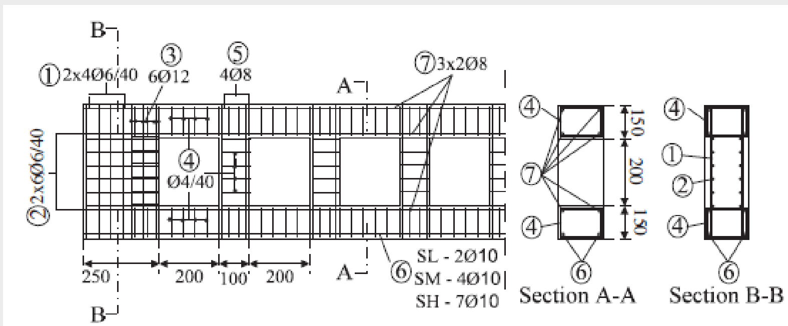
**Aykac, B., Kalkan, I., Aykac, S., Egriboz, E.M. : Flexural behaviour of RC beams with regular square or circular web openings, Engineering Structures, 56, pp. 2165-2174, 2013.*

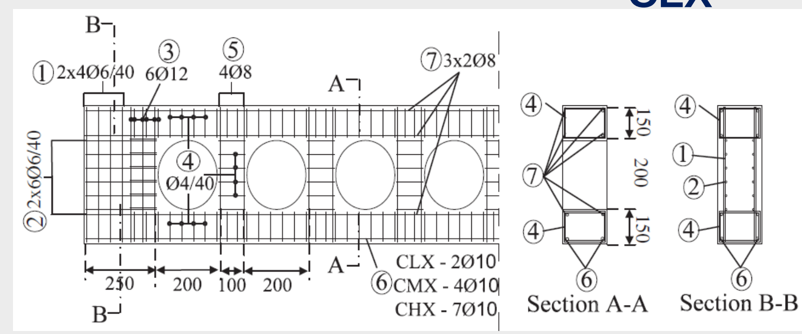
CLX

SL

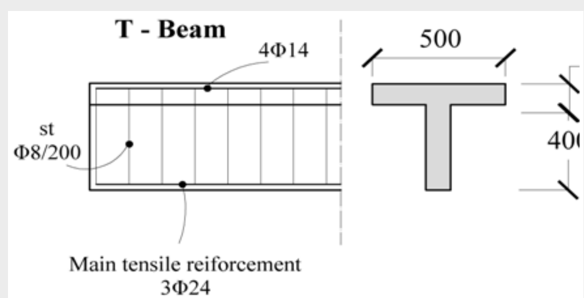
SM

SH





- 1 Beam with a T-shaped cross section designed according to *fib* Model Code 2010 and to EC 2.



RC beams

The *failure mode* identifies a specific resisting mechanism developed with the crisis of a specific material in a certain region of the structural member.

FAILURE MODES

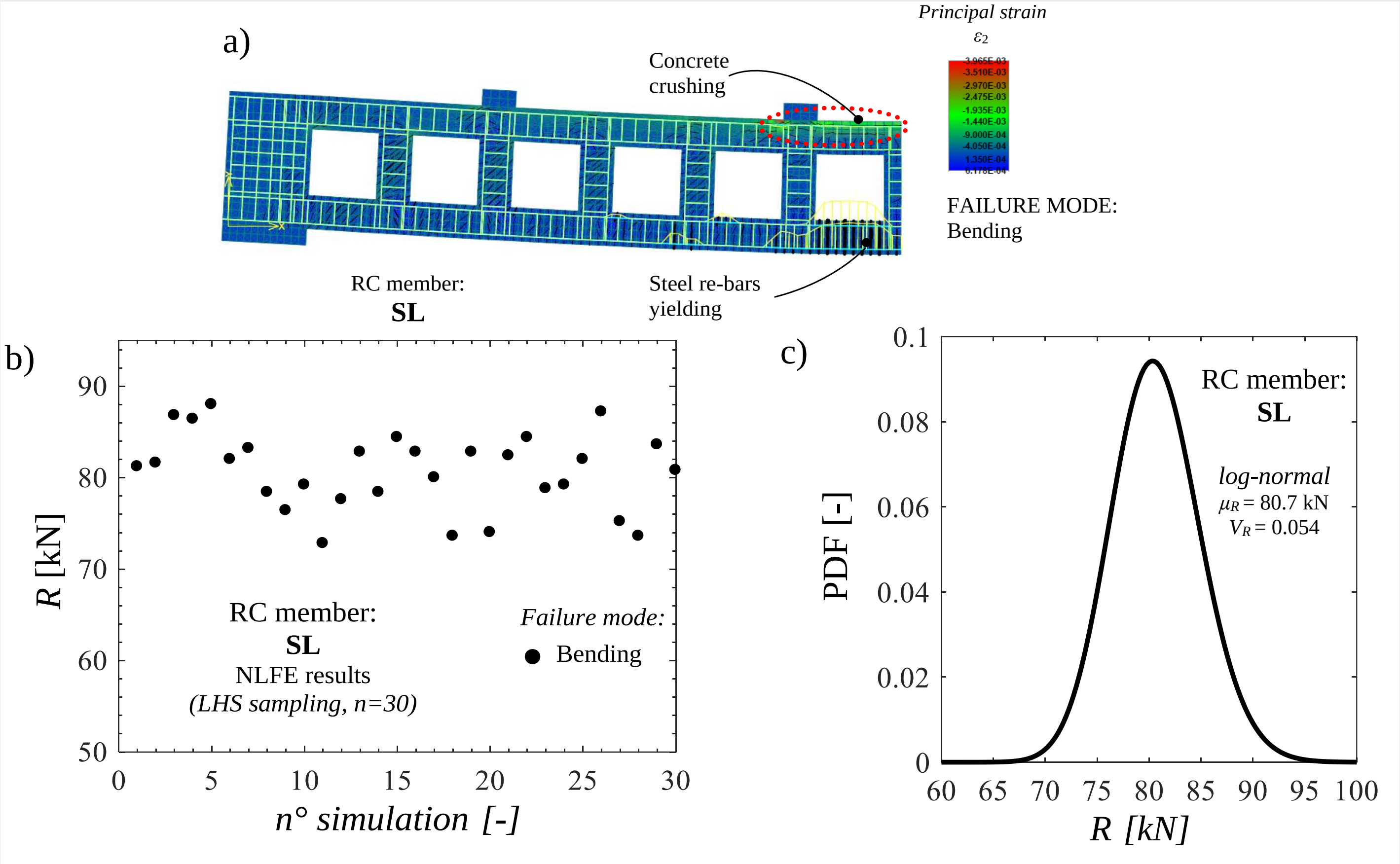
NLFEA Results: PFM, GRF, ECOV and GSF

- **SL:** *Beam type (Bending)*
- **SM:** *Vierendeel type*
- **SH:** *Vierendeel type*
- **CLX:** *Beam type (Bending)*
- **T-Beam:** *Beam type (Bending)*

In line with the experimental outcomes!

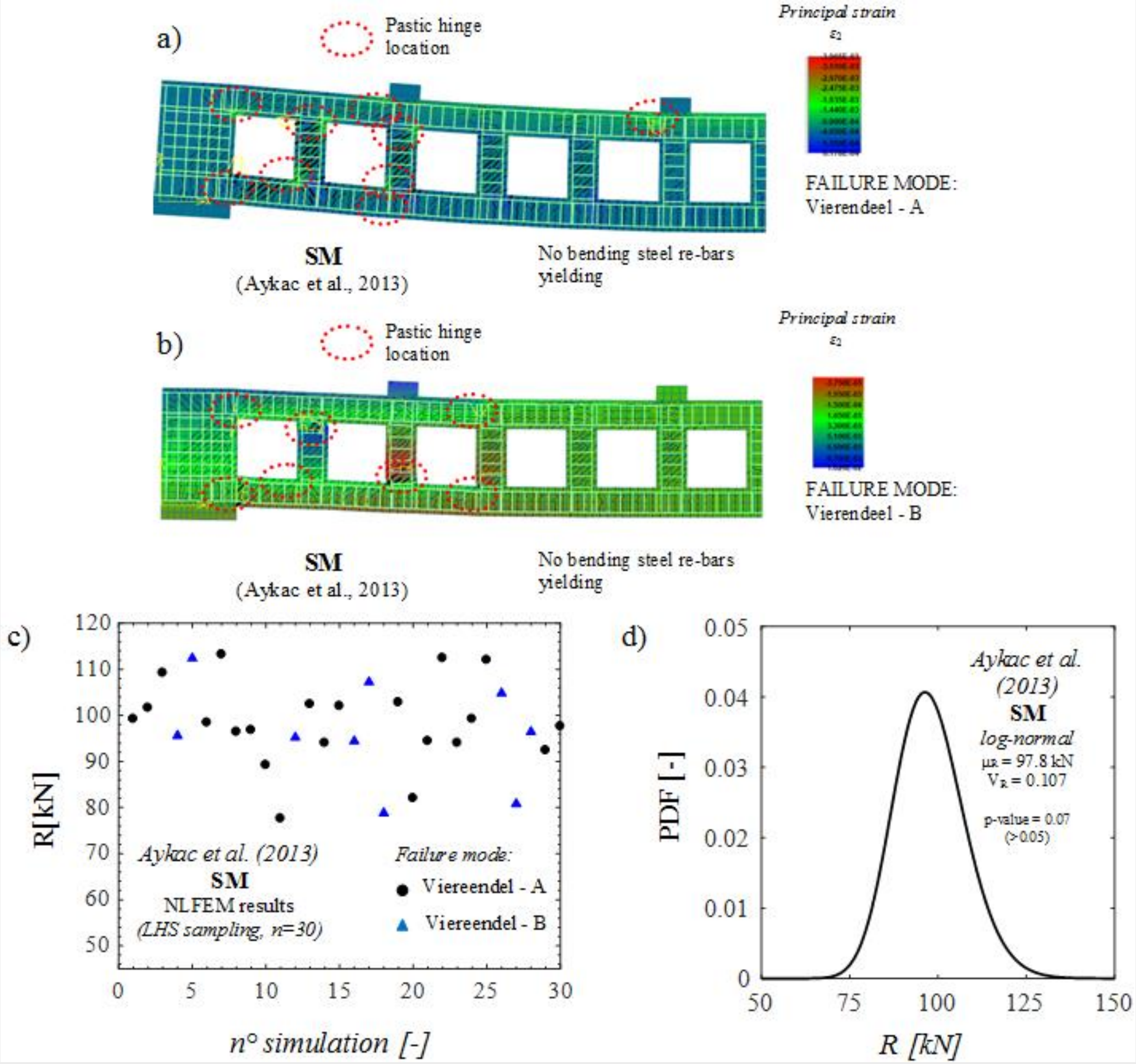
NLNA Results: PM

Beam SL



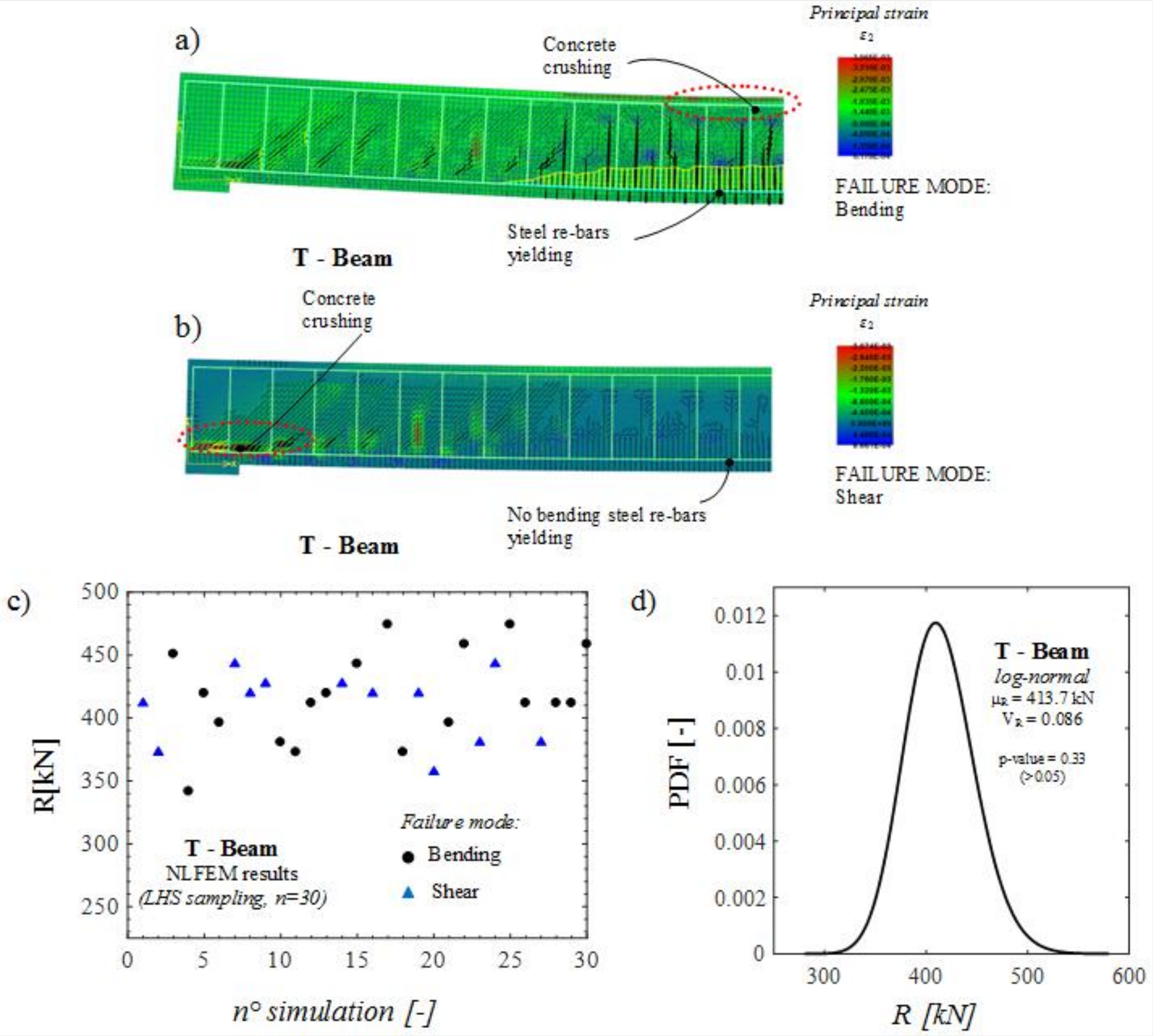
NLNA Results: PM

Beam SM

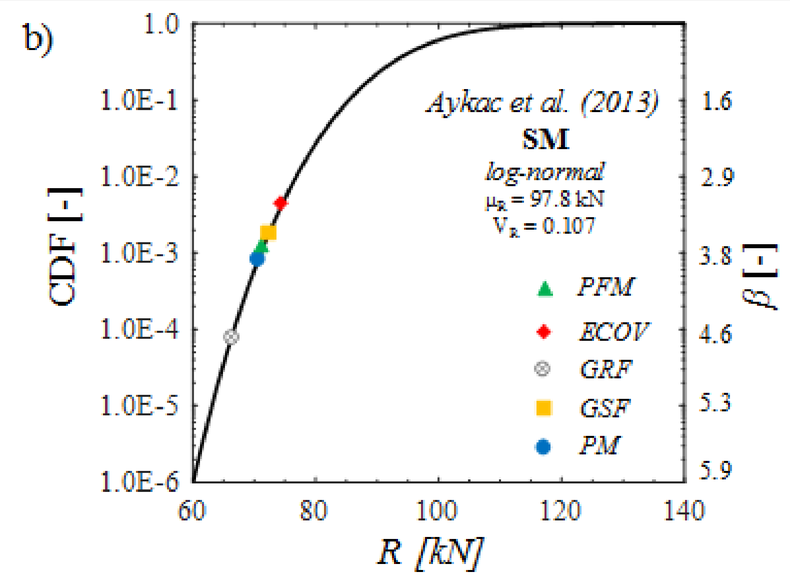


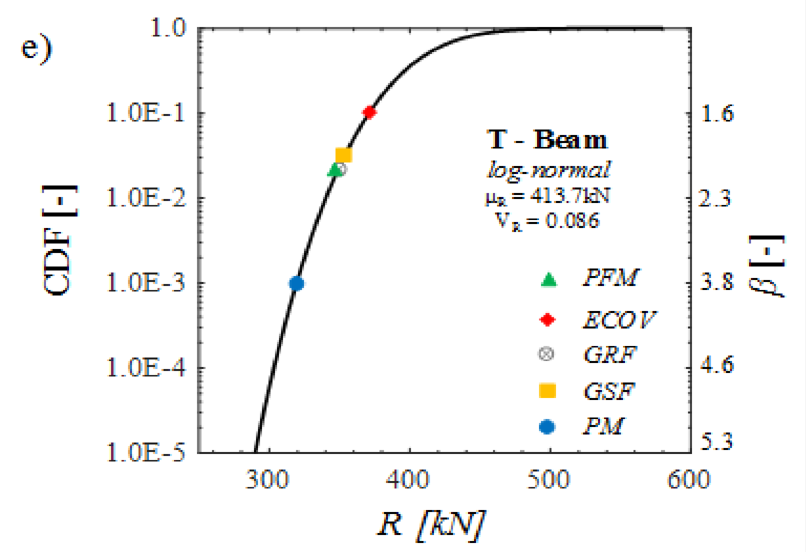
NLNA Results: PM

T-Beam



Comparison between GLOBAL SAFETY FORMATS





The model uncertainties are not considered in these evaluations!

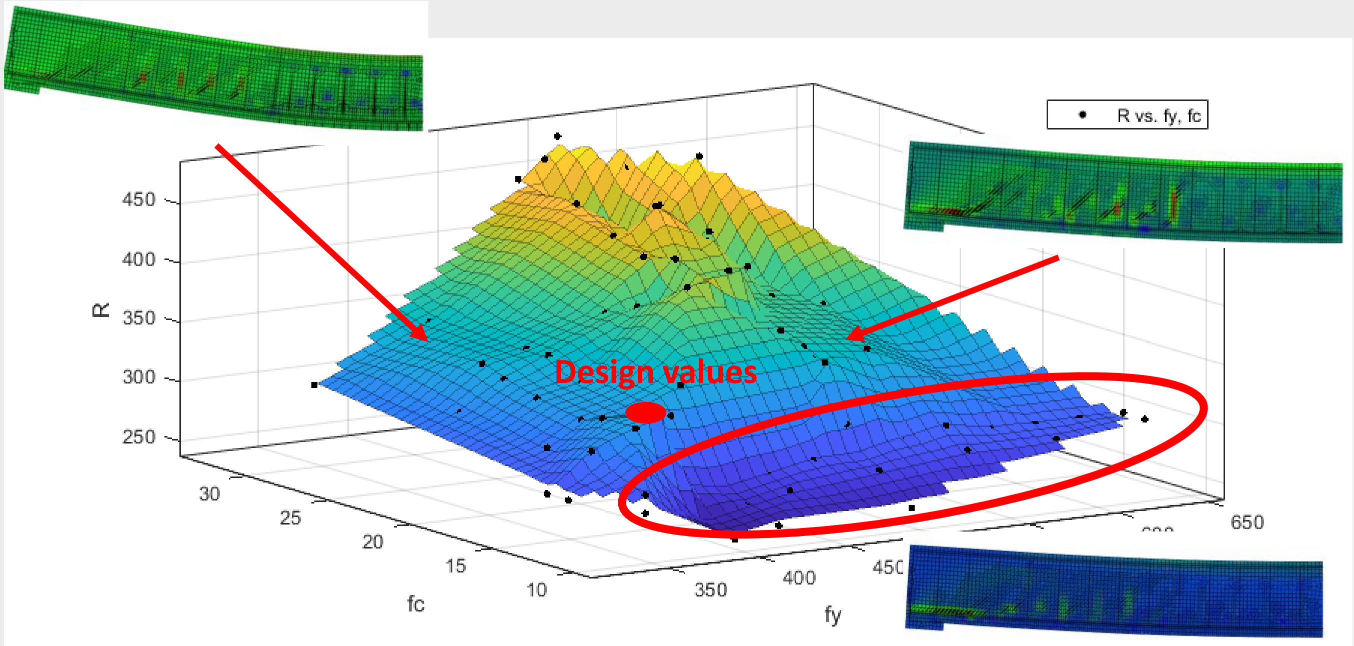
GLOBAL SAFETY FORMATS AND SAFETY FACTORS

fib MODEL CODE 2010 and 2020

EUROCODICE 2 - Annex F

…different failure modes: the RESPONSE SURFACE IS NOT CONVEX!!!

T-Beam



- The uncertainty related to sensitivity of the model to modify the prediction of failure mode depending on material uncertainties is not accounted for in γ_{Rd}, that should be always applied

fib MODEL CODE 2010 and 2020

EUROCODICE 2 - Annex F

PRELIMINARY ANALYSES (*3*)

- ***Mean*** **concrete** strength **–** ***Design*** **reinforcements** strength
- ***Design*** **concrete** strength **–** ***Mean*** **reinforcements** strength
- ***Design*** **concrete** strength **–** ***Design*** **reinforcements** strength

$$R\{f_{cd}, f_{yd}; a_{nom}\} \leq R\{f_{cd}, f_{ym}; a_{nom}\} \quad and \quad R\{f_{cd}, f_{yd}; a_{nom}\} \leq R\{f_{cm}, f_{yd}; a_{nom}\}$$

(The **FAILURE MODES** are the ***same***?)

YES

NO

$$R_d = \frac{R_{rep}}{\gamma_R \cdot \gamma_{FM} \cdot \gamma_{Rd}}$$

Failure mode-based safety factor γ_{FM}: 1.15

PARTIAL FACTOR METHOD (PFM)
GLOBAL FACTOR METHOD (GFM)

fib MODEL CODE 2010 and 2020

EUROCODICE 2 - Annex F

PARTIAL FACTOR METHOD (PFM)

$$R_d = \frac{R_{NLNA}(X_d; a_d)}{\gamma_{Rd}}$$

$$R_d = \frac{R_{NLNA}(X_d; a_d)}{\gamma_{Rd} \cdot 1.15}$$

GLOBAL FACTOR METHOD (GFM)

$$R_d = \frac{R_{NLNA}(X_m; a_{nom})}{\gamma_R \gamma_{Rd}}$$

$$R_d = \frac{R_{NLNA}(X_m; a_{nom})}{\gamma_R \gamma_{Rd} \cdot 1.15}$$

Failure mode-based partial safety factor γ_{FM}

fib MODEL CODE 2010 and 2020

EUROCODICE 2 - Annex F

PARTIAL FACTOR METHOD (PFM)

- ***Mean* – *Design*** properties
- ***Design* – *Mean*** properties
- ***Design* – *Design*** properties

β fixed

GLOBAL FACTOR METHOD (GFM)

- ***Mean* – *Design*** properties
- ***Design* – *Mean*** properties
- ***Design* – *Design*** properties

- ***Mean*** – ***Mean*** properties

Future developments …

- ***Mean* – *Design*** properties
- ***Design* – *Mean*** properties
- ***Design* – *Design*** properties

Repeated as a function of *β* for both **actions** and **materials**

β variable

- ***Mean* – *Design*** properties
- ***Design* – *Mean*** properties
- ***Design* – *Design*** properties

- ***Mean*** – ***Mean*** properties

- Repeated as a function of *β* only for **actions**

References:

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- Gino D., Castaldo P., Giordano L., Mancini G. (2021) “Model uncertainty in non-linear numerical analyses of slender reinforced concrete members”, Structural Concrete, 22(2), 845-870, DOI: 10.1002/suco.202000600.

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- G. Gino, E. Miceli, P. Castaldo, A. Recupero, G. Mancini, Strain-based method for assessment of global resistance safety factors for NLNAs of reinforced concrete structures, Engineering Structures, (2024), 304:117625,.

Thanks for your kind attention

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