RELAZIONE GENERALE
TEMI C e D

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STRUCTURAL ROBUSTNESS

Quality in a structure of insensitivity to local failure, in which modest damage (originated by accidental or malicious action) causes only a similar modest change in the structural behavior

A robust structure has the ability to redistribute the load in event that a load-bearing member suffers a loss of strength or stiffness and then intrinsically exhibits a ductile, rather than brittle, global failure mode

RONAN POINT APARTMENT TOWER

RISK

HAZARDS

A potentially harmful event, action or state of nature (explosion)

Quantified by its annual probability of occurrence

CONSEQUENCES

Effect of occurrence of a hazard (building damage, collapse, injury or loss of life, economic loss, damage to environment)

To be measured in terms of a value system involving some metric

CONTEXT

Provides a frame of reference for the risk analysis and assessment and resulting decisions

Only government and large corporations (self insured) tend to be risk – neutral, additionally society views incidents involving large number of people differently from incidents involving individuals

ANNUAL INDIVIDUAL FATALITY RISKS (2001)

Source	Fatality/yr
Cardiovascular disease	3.5×10^{-3}
Cancer (all)	2.0×10^{-3}
All accidents	3.4×10^{-4}
Motor vehicle	
Per vehicle-km	6.4×10^{-9}
Per year (25,000 km)	1.6×10^{-4}
Accidents in the home	1.1×10^{-4}
Fires[1]	1.2×10^{-5}
Homicide and legal intervention	6.4×10^{-5}
Electrocution	5.3×10^{-6}
Air travel	
Per round trip	1.6×10^{-7}
Per year (25 trips)	4.0×10^{-6}
Hurricanes, tornados and floods	7.2×10^{-7}
Lightening strike	3.3×10^{-7}

<u>BUT!!</u>

Acceptable risk, measured by annual frequency, MAY BE approximately 3 order of magnitude higher for activities that are undertaken voluntarily (mountain climbing, private aviation) respect to those that are involuntary

Paté-Cornell, 1994 ---> **DE MINIMIS RISK** (Risk below which society normally do not impose any regulatory guidance) is of the order of 10^{-7}/year (target value)

BASIC MATHEMATICAL FRAMEWORK FOR RISK ASSESSMENT INVOLVING A HAZARD

$$P(LOSS) = \sum_{H} \sum_{LS} \sum_{D} P(LOSS/D) \cdot P(D/LS) \cdot P(LS/H) \cdot P(H)$$

Where:

P(LOSS) = Probability of event (Severe injury or death, direct/indirect damage cost,…);

P(H) = Measure of intensity of hazard;

P(LS/H) = Conditional probability of a structural limit state;

P(D/LS) = Conditional probability of a damage state (minor/moderate/severe);

P(LOSS/D) = Conditional probability of loss.

ALTERNATIVELY, IF THE RISK IS BASED ON A STIPULATED SCENARIO EVENT:

$$P(LOSS/SCENARIO) = \sum_{LS} \sum_{D} P(LOSS/D) \cdot P(D/LS) \cdot P(LS/SCENARIO)$$

Both expressions split the risk analysis into the major constituents and along disciplinary lines

- The likelihood of the hazard is measured by P(H) or by its mean occurrence rate λ_H

- The probabilities P(LS/H) or P(LS/SCENARIO) are determined by structural analysis (generally a non linear dynamic FEM analysis is required)

- P(D/LS) describes the damage in terms of structural response evaluated with the FEM analysis

- P(LOSS/D) describes the probability of loss given by a specific damage state (insurance records)

HAZARDS

PRESSURE LOADS

Explosions, detonations, tornados

IMPACT

Vehicular collisions, aircraft or missile impacts, debrises, swinging objects during construction or demolition

DEFORMATION RELATED

Softening of steel in fire, foundation subsidence

FAULTY PRACTICE

Usually act over a relatively short period of time, are generally time-varying and MAY BE static or dynamic

Poisson model can be used to model the occurrence of events assumed to occur "randomly"

A terrorist attack is a deliberate malevolent event directed to maximize sociopolitical impact

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POISSON MODEL CANNOT BE APPLIED TO TERRORIST EVENTS

DESIGN TO REDUCE PROGRESSIVE COLLAPSE RISK

- IDENTIFICATION OF PERFORMANCE REQUIREMENTS
- IDENTIFICATION OF SPECIFIC HAZARD SCENARIOS
- EVALUATION OF PROBABILITY OF NOT FULFIL THE PERFORMANCE REQUIREMENTS
- ASSESSMENTS OF CONSEQUENCES OF NOT FULFIL THE REQUIREMENTS

PRIMARY PERFORMANCE REQUIREMENTS

- LIFE SAFETY
- RAPID EXIT OF BUILDING OCCUPANTS
- LIFE SAFETY FOR FIRE-FIGHTERS
- POST-FIRE BUILDING BEHAVIOUR

HOW LONG THE BUILDING MUST REMAIN STANDING FOLLOWING LOCAL DAMAGE TO ALLOW THESE ESSENTIAL ACTIONS ?

OTHER PERFORMANCE REQUIREMENTS

- PROTECTION OF PROPERTY
- MINIMIZATION OF FUNCTIONALITY
- MINIMIZATION OF INTERRUPTION OF BUSINESS OPERATION
- ENVIRONMENTAL PROTECTION

SPECIFIC DESIGN STRATEGIES

PREVENT THE OCCURRENCE OF INTENTIONAL ABNORMAL ACTIONS THROUGH SOCIAL AND POLITICAL MEANS

PREVENT THE OCCURRENCE OF LOCAL IMPORTANT STRUCTURAL DAMAGE LIKELY TO INITIATE A PROGRESSIVE COLLAPSE

PREVENT STRUCTURAL SYSTEM COLLAPSE AND LOSS OF LIFE THROUGH STRUCTURAL DESIGN, COMPARTIMENTALIZATION, DEVELOPMENT OF ALTERNATIVE LOAD PATH AND OTHER ACTIVE AND PASSIVE MEASURES

PROBABILITY OF STRUCTURAL COLLAPSE

$$P(C) = P(C/LD) \cdot P(LD/H) \cdot \lambda_H$$

Assuming :

$$P(H) \approx \lambda_H$$

The overall probability of collapse is decomposed into 3 components that address the appropriate strategies for hazard prevention

COLLAPSE RESISTANCE

ROBUSTNESS

LOCAL ELEMENT BEHAVIOUR

EVENT CONTROL

→ TO BE MAXIMIZED

$$P(C) = P(C/LD) \times P(LD/H) \times \lambda_H$$

VULNERABILITY

HAZARD

→ TO BE MINIMIZED

EVENT CONTROL

PREVENTION OF THE OCCURRENCE OF THE HAZARD

LIMITATION OF λ_H BELOW THE DE MINIMIS THRESHOLD

THE CONTROL OF PROBABILITY OF OCCURRENCE OF HAZARD IS THE MOST EFFECTIVE ROUTE TO RISK REDUCTION

STRUCTURAL DESIGN

ENSURE AN ACCEPTABLE LOW PROBABILITY OF

- CATASTROPHE INVOLVING LOSS OF HUMAN LIFE
- UNACCEPTABLE ECONOMIC OR SOCIAL LOSSES
- DAMAGE TO ENVIRONMENT

STRUCTURAL ENGINEERING IS FOCUSED ON THE TERMS

P(C/LD)

P(LD/H)

ALTERNATIVE LOAD PATH STRATEGY

SPECIFIC LOCAL RESISTANCE STRATEGY

- Limitation of P(LD/H) → Minimization of likelihood of initiation of damage that may lead to progressive collapse

- Limitation of P(C/LD) → Identify a specific threat or envisage certain damage scenarios, not regarding specific causes, requiring the system to support as a whole the damage without progressive collapse

RELIABILITY CONCEPT TO DESIGN FOR CONDITIONAL L.S.

In order to limit P(C) at de minimis threshold, this conditional probability should be limited to:

$$P(C/LD) \approx 10^{-7}/\lambda_H$$

To reach such a goal, sources of load-carrying capacity usually not considered in the design should be included in G(x)

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Membrane effects, catenary action, substantial inelastic behavior of members and connections, other load-resisting mechanisms accompanied by large deformations…

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Structural analysis performed in the field of geometrical and mechanical non linearities, with accurate modelling of connections at extreme conditions

APPROACHES TO DESIGN FOR ROBUSTNESS

FOUR BASIC APPROACHES

- **TIE-FORCE DESIGN METHODS**
- **ALTERNATIVE LOAD PATH METHODS**
- **KEY ELEMENT DESIGN**
- **RISK-BASED METHODS**

TIE-FORCE BASED DESIGN METHODS

Rule based (prescriptive) approaches by which application the structure is usually considered to fulfil the robustness requirements through a minimum level of ductility/continuity/tying

Proportionate design method for low-risk structures

MEMBERS ARE MECHANICALLY TIED TOGETHER ACCORDINGLY TO SPECIFIED REQUIREMENTS

IN HORIZONTAL MEMBERS ONLY

IN BOTH HORIZONTAL AND VERTICAL MEMBERS

- INITIALLY CONCEIVED FOR LARGE-PANEL STRUCTURES;
- HELPFUL IN FRAMED STRUCTURES TO DEVELOP VERTICAL CONTINUITY IN COLUMNS.

REMARK:

Tying capacity of connection is determined in absence of beam rotation, but when rotations intervene due to catenary action, connections can develop a prying action that leads to rapid failure

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Tie-force methods provide a minimum level of robustness that cannot be quantified

SUITABLE **QUALITATIVE** METHOD FOR **LOW-RISK** STRUCTURES, BUT **QUANTITATIVE** METHODS ARE NECESSARY FOR BUILDINGS BEING **HIGHER-RISK**

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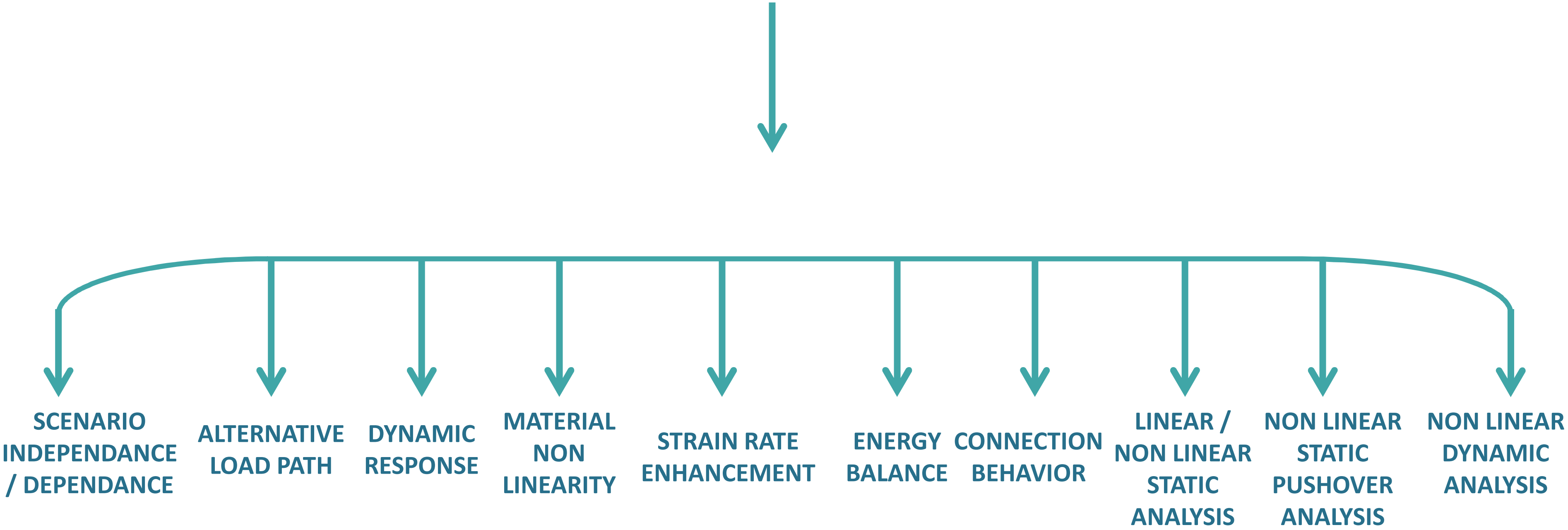
ALTERNATIVE LOAD PATH METHODS

Deterministic/quantitative method by which robustness is demonstrated

Analytical assessment of the strcuture under damaged conditions, like partial or total loss of bearing capacity of a beam or a column, by investigation whether alternative load path are able to redistribute the additional actions on the remaining structural elements deriving by the occurrence of damage

MAIN ASPECTS OF ALTERNATIVE LOAD PATH METHODS



SCENARIO DEPENDANCE / INDEPENDANCE

SCENARIO INDEPENDANCE

HAZARD THAT CAUSES THE INITIAL STRUCTURAL DAMAGE IS NOT CONSIDERED

GENERALLY BASED ON THE ASSUMPTION OF A SINGLE COLUMN LOSS IN ANY POSITION

ANALYSIS ABSTRACTED FROM HAZARD THEN ROBUSTNESS IN THE STRUCTURE IS IRRESPECTIVE OF CAUSE AND EVENT OF DAMAGE

SCENARIO DEPENDANCE

SPECIFIC HAZARDS ARE CONSIDERED IN THE ANALYSIS AND THE STRUCTURAL BEHAVIOR DUE TO THE CONSEQUENT DAMAGE IS SPECIFICALLY CALCULATED

DEMONSTRATE THE ACHIEVEMENT OF AN ADEQUATE LEVEL OF ROBUSTNESS AGAINST SPECIFIC EVENTS

ALTERNATIVE LOAD PATHS

↓

LOSS OF A COLUMN IMPLIES THE TRANSFER OF ITS LOAD BY MEANS OF BEAMS TO ADJACENT COLUMNS

↓

IF THE INVOLVED ELEMENTS ARE ABLE TO WITHSTAND THE ADDIOTIONAL LOAD THE COLLAPSE IS ARRESTED (STRUCTURE STABLE IN DAMAGED STATE), OTHERWISE THEY ALSO FALL AND THE COLLAPSE PROPAGATES

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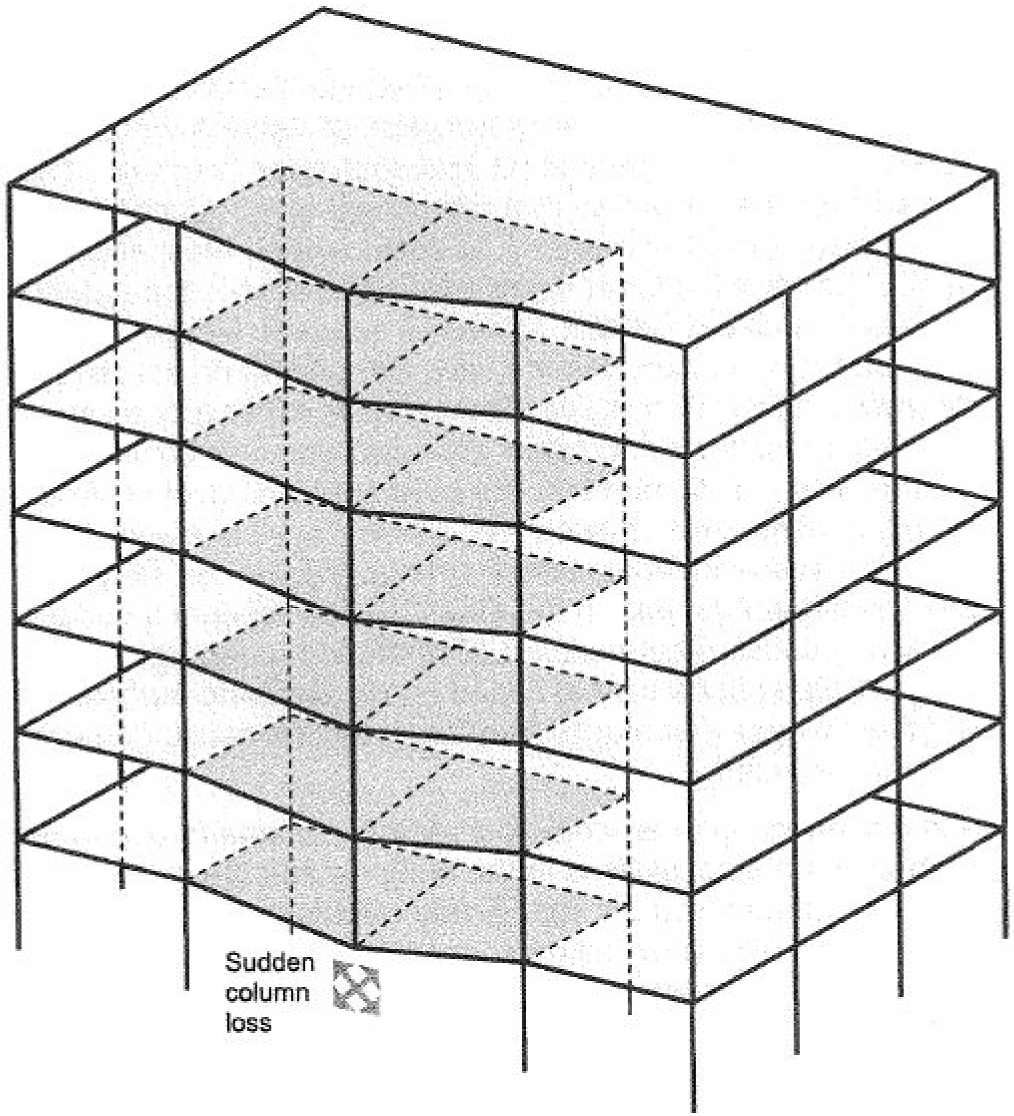
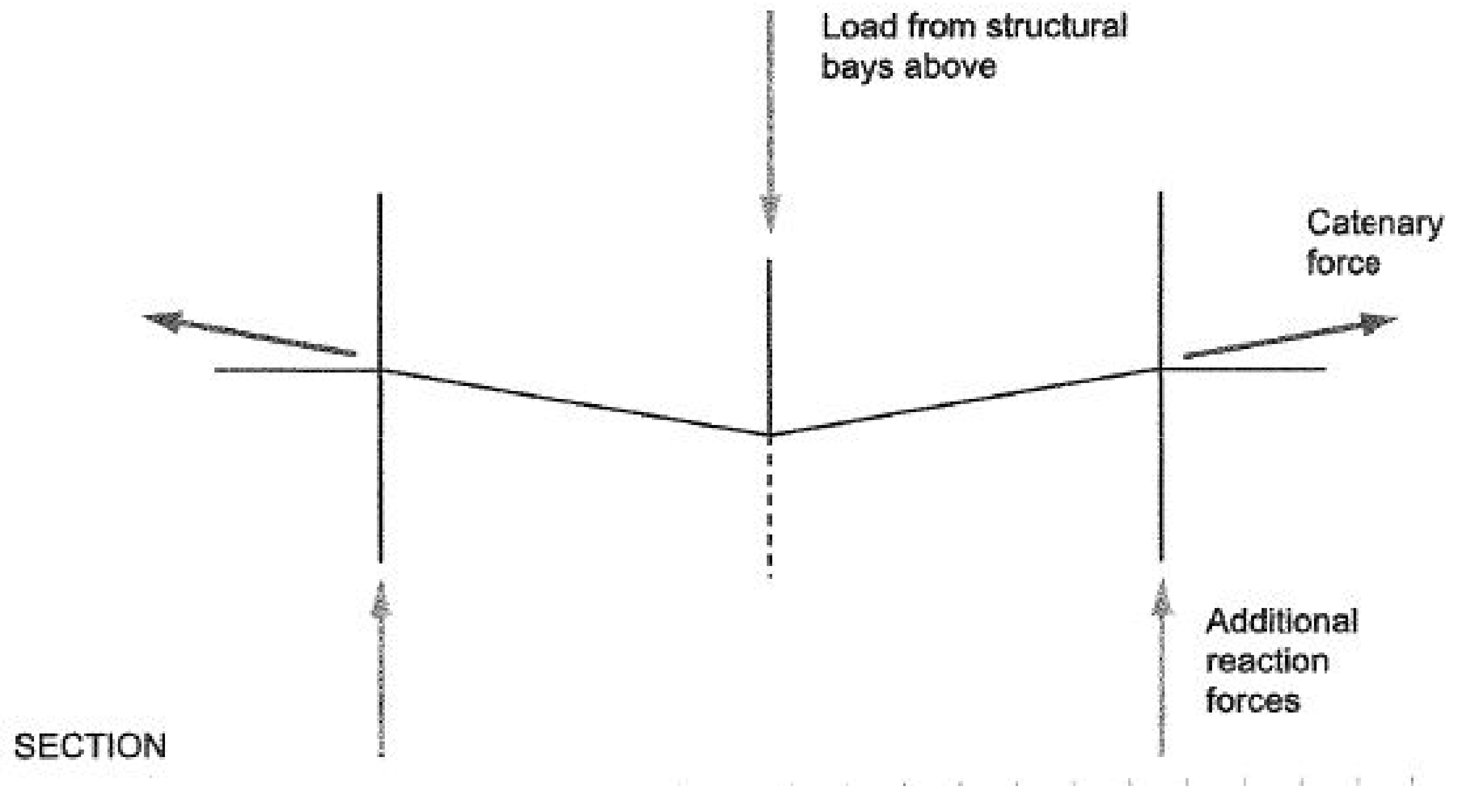
THE CYCLE FOLLOWS UP TO THE INDIVIDUATION OF A STEP IN WHICH THE STRUCTURE OFFERS SUFFICIENT RESIDUAL CAPACITY TO ARREST THE COLLAPSE OR THE COMPLETE FAILURE STATE IS REACHED


Sudden
column
loss

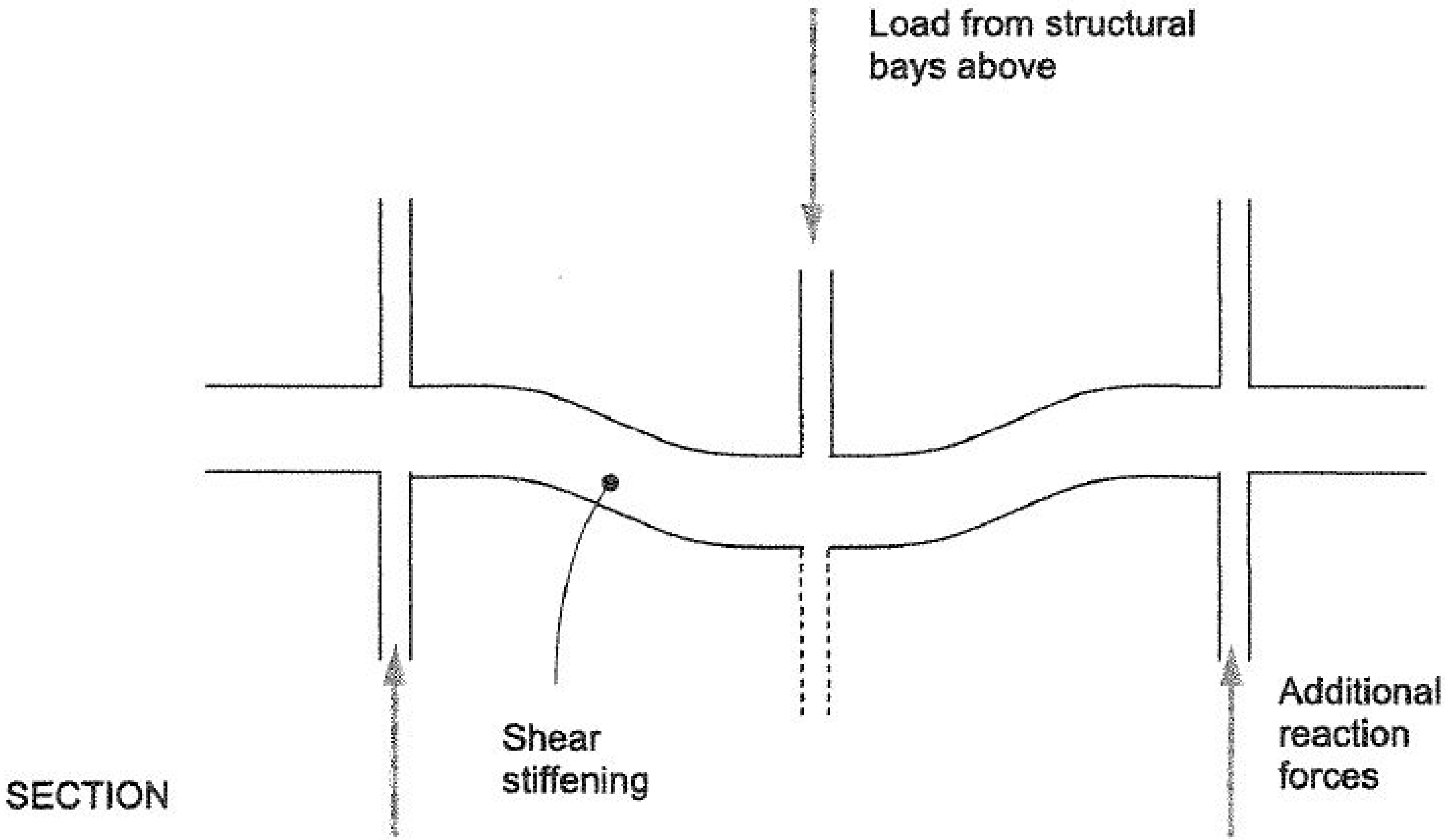
FOUNDAMENTAL MECHANISMS FOR ROBUSTNESS

- CATENARY ACTION IN THE STRUCTURAL FRAME
- SHEAR DEFORMATION OF TRANSFER STRUCTURES
- MEMBRANE ACTION IN STRUCTURAL SLABS
- VIERENDEEL ACTION
- COMPRESSIVE ARCHING IN FLOOR BEAMS / SLABS
- COMPRESSIVE STRENGHT ACTION IN MASONRY PANELS

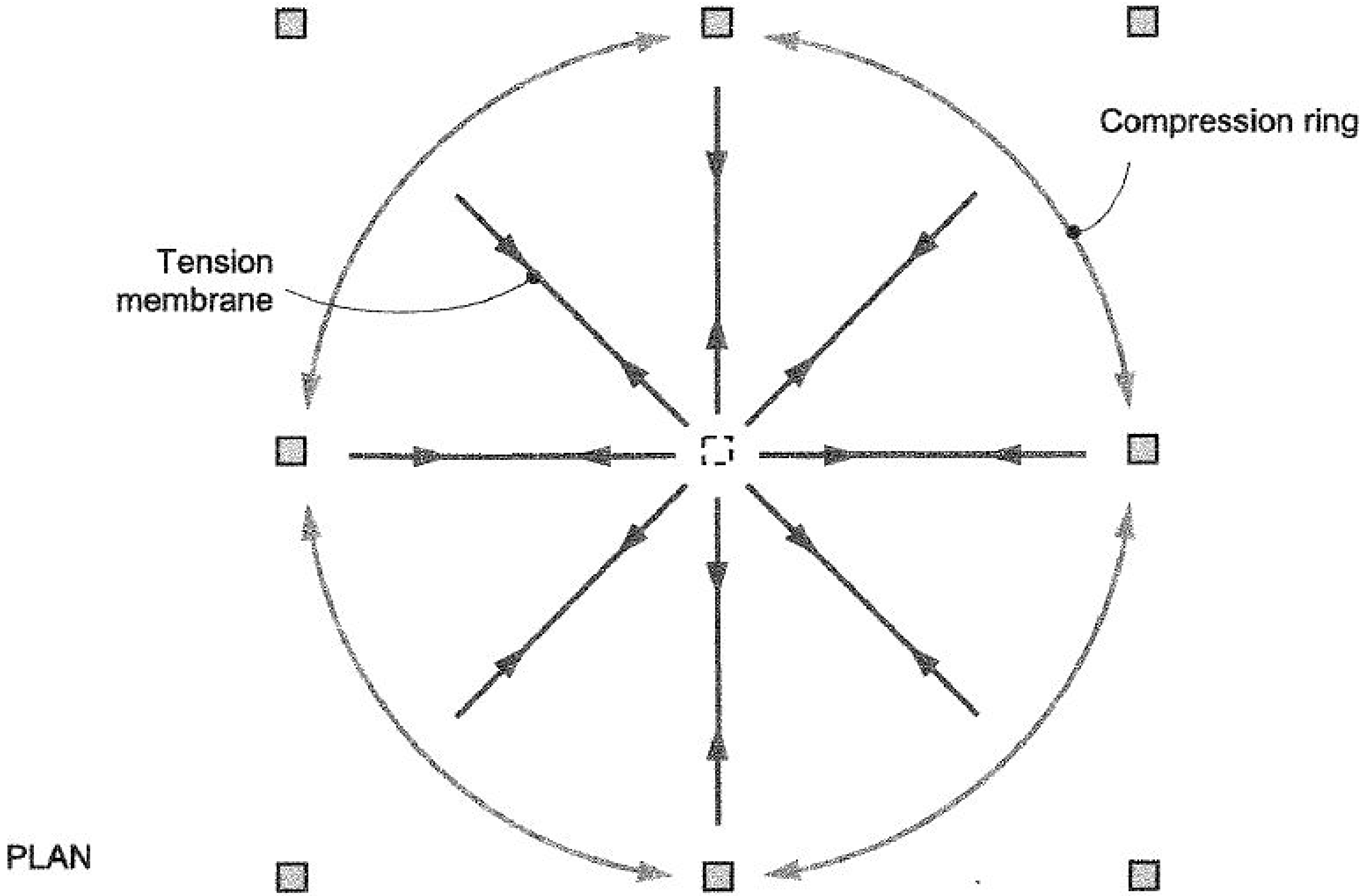
CATENARY ACTION



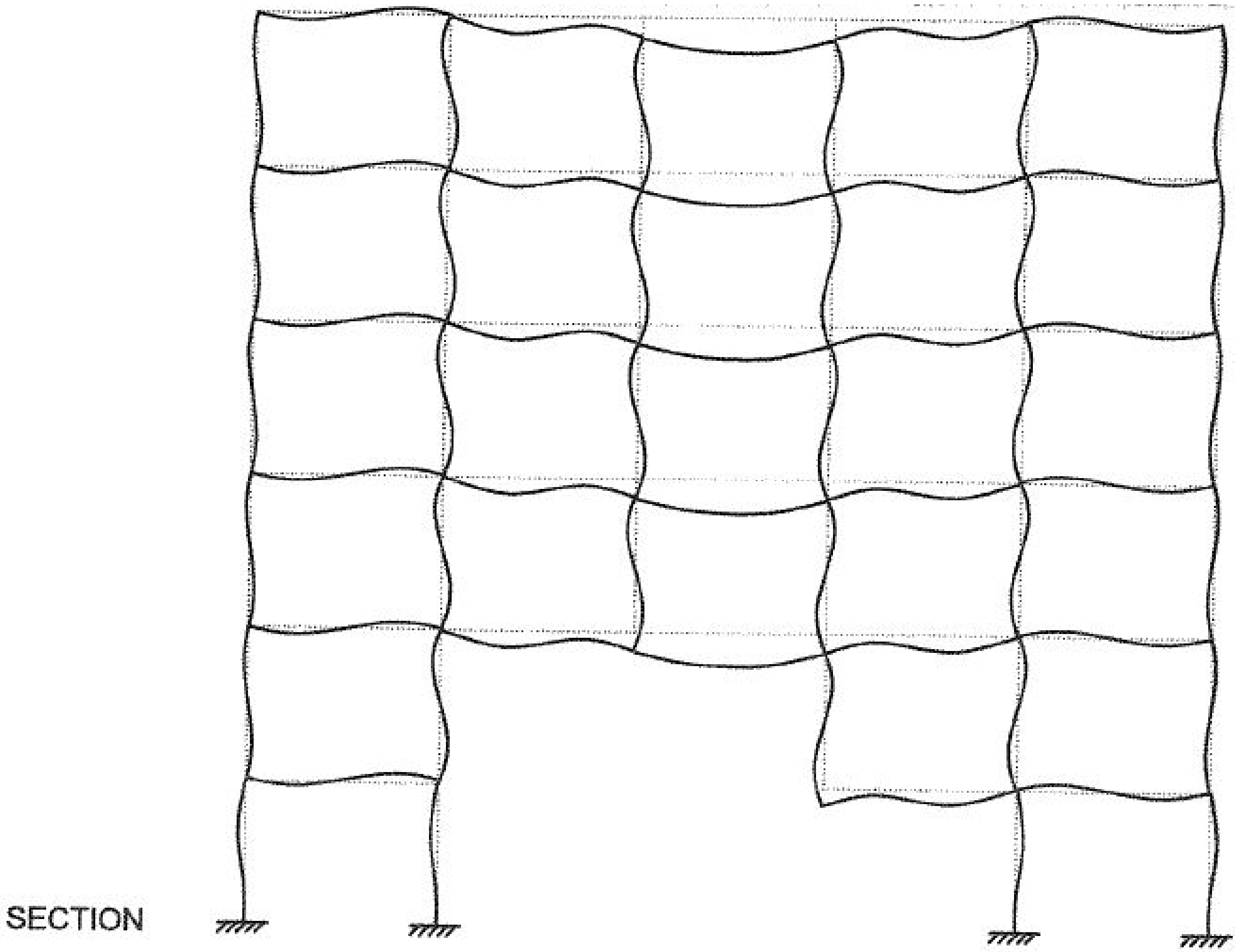
SHEAR DEFORMATION OF DEEP TRANSFER / SPANDREL BEAMS



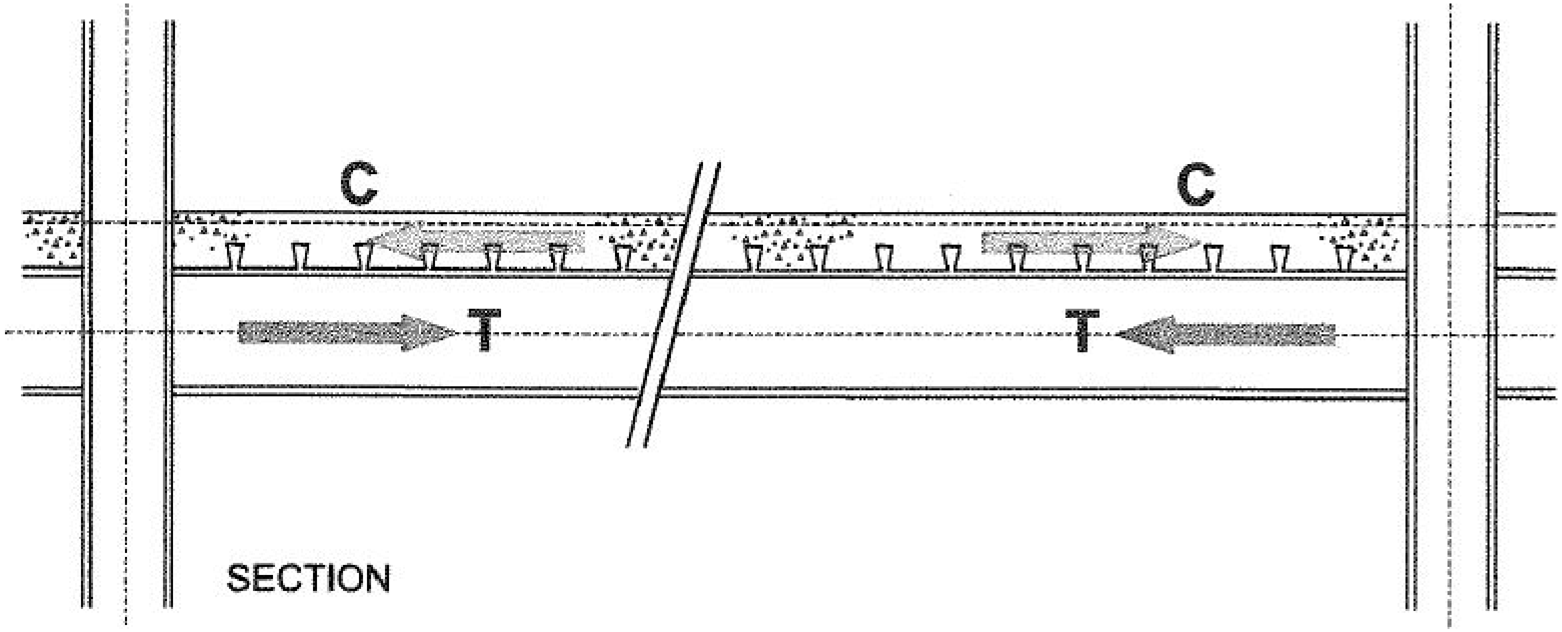
MEMBRANE ACTION IN STRUCTURAL SLABS



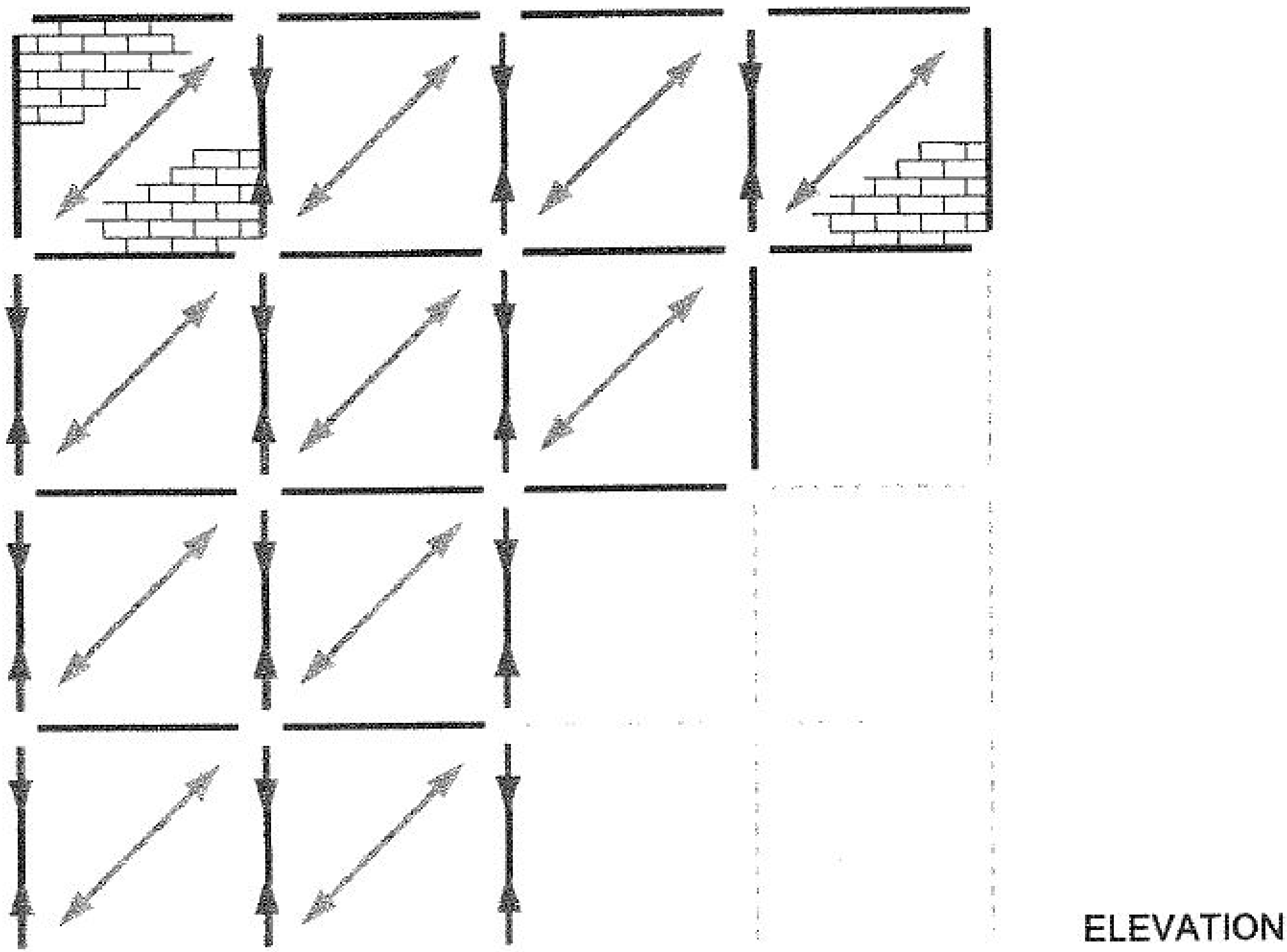
VIERENDEEL ACTION DUE TO BENDING CAPACITY IN BEAM / COLUMN CONNECTIONS



COMPRESSIVE ARCHING ACTION IN COMPOSITE DECK WITH STEEL BEAMS



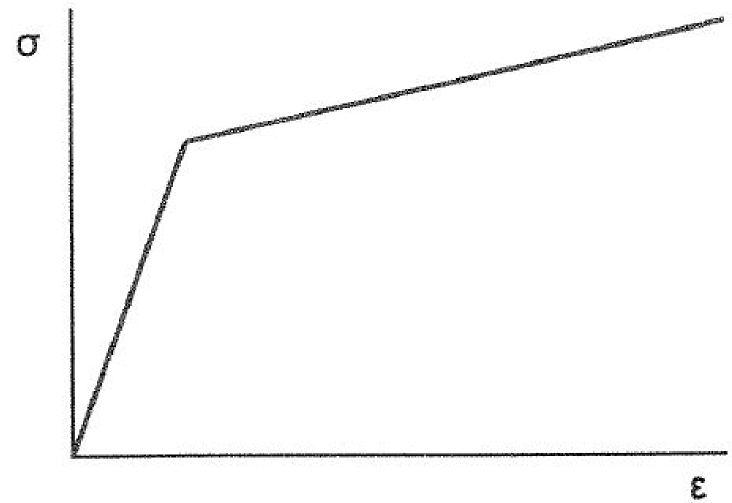
COMPRESSIVE STRUCT ACTION IN MASONRY PANELS



MATERIAL NON LINEARITY

ROBUSTNESS REQUIRES DUCTILITY (TO BE MODELED!)

IN SOME CIRCUMSTANCES MODELING OF STRAIN HARDENING IS NECESSARY



DYNAMIC RESPONSE

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SUDDEN REMOVAL OF LOAD-BEARING ELEMENT FROM THE STRUCTURE IMPLIES INERTIAL FORCES AMPLIFICATING THE EFFECTS OF THE CHANGE IN STRUCTURAL GEOMETRY IN TERMS OF LOAD EFFECTS ON THE ALTERNATIVE LOAD PATH

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REMOVING STATICALLY A COLUMN FROM A RESISTING MODEL IS SEVERELY UNCONSERVATIVE!!!

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DYNAMIC LOAD FACTOR (DLF) SHOULD BE CONSIDERED, CONVERTING THE STATIC IN DYNAMIC LOAD IN TERMS OF CORRESPONDING DYNAMIC DISPLACEMENT

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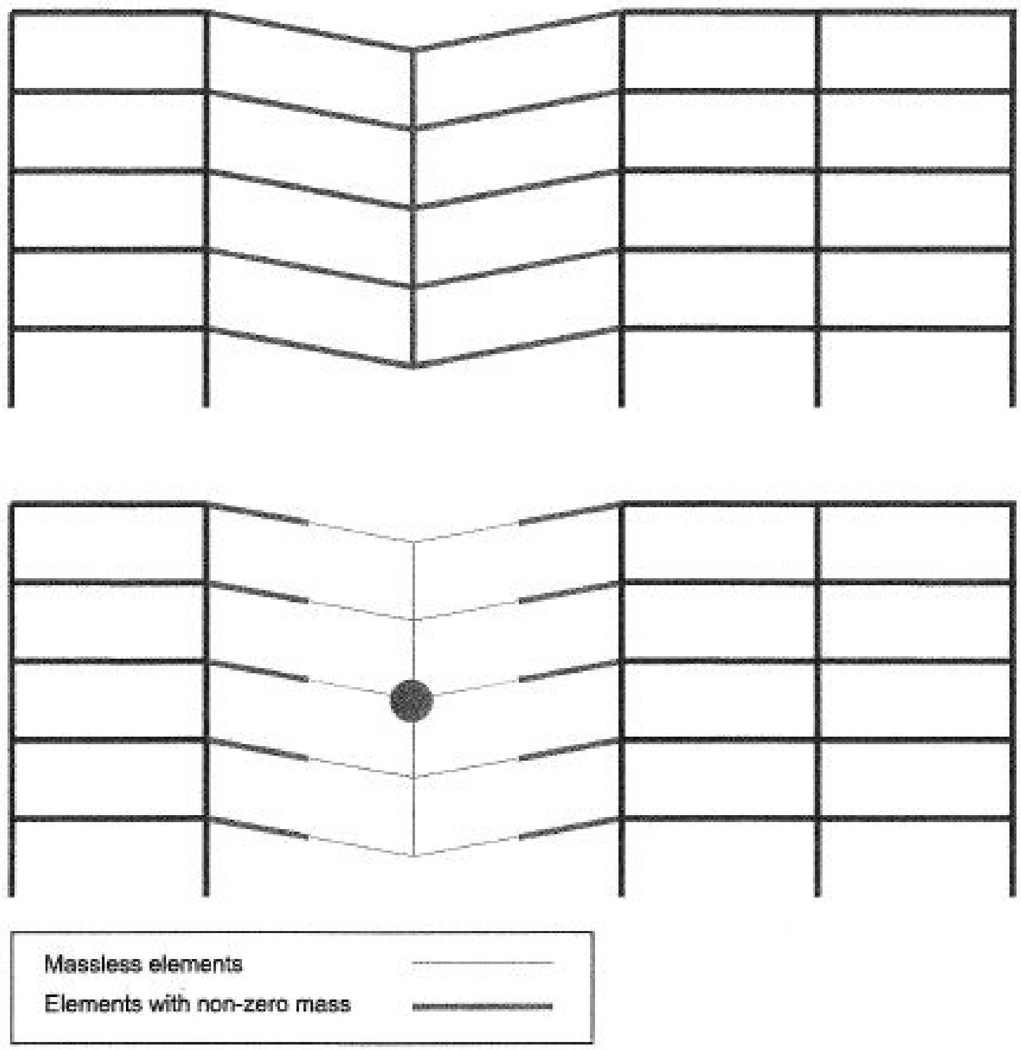
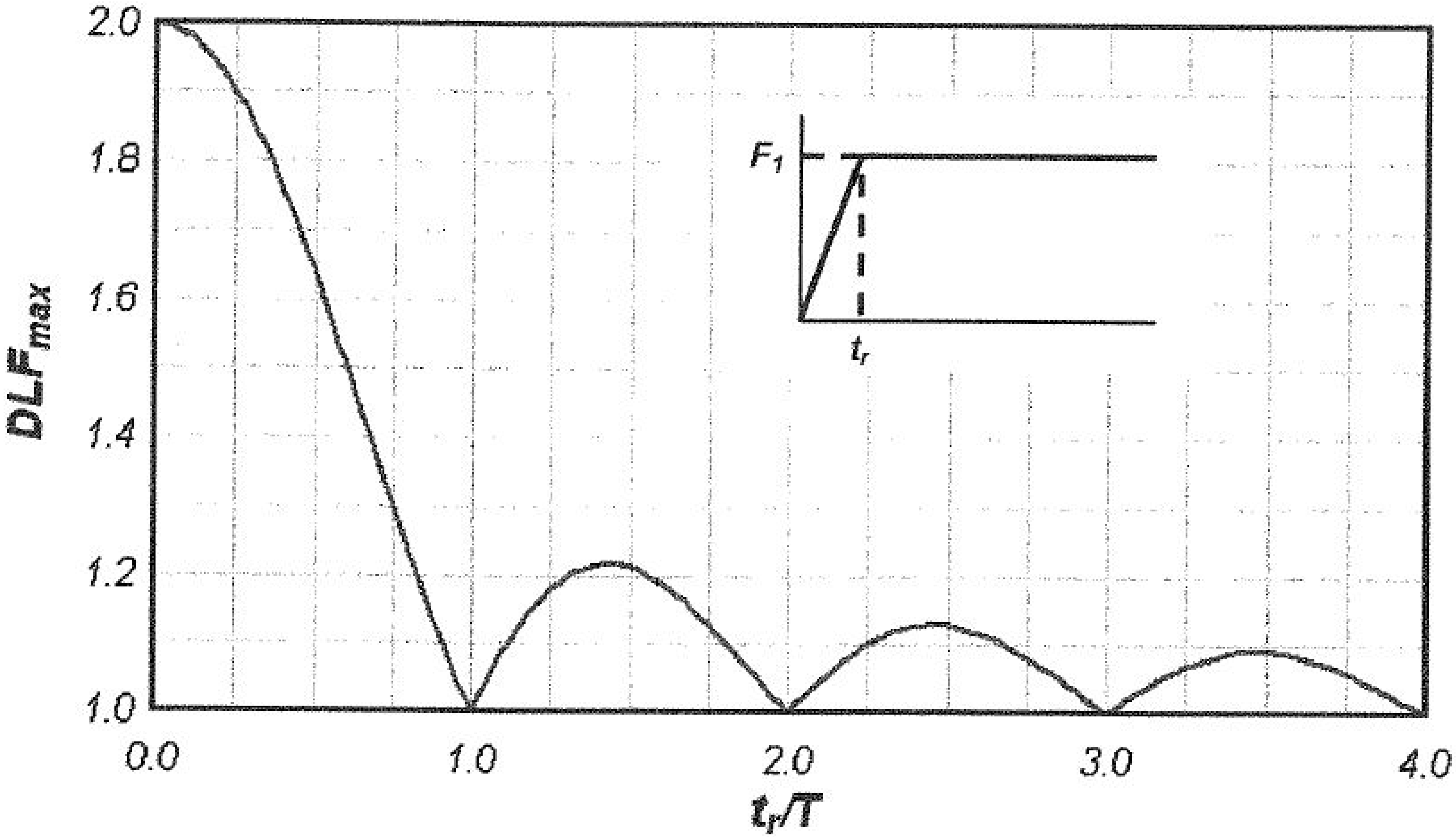
DLF IS THE RATIO BETWEEN THE MAGNITUDE OF DYNAMIC AND STATIC LOAD REQUIRED TO PRODUCE THE SAME DISPLACEMENT

IDEALIZATION OF STRUCTURAL PORTION AS A SINGLE DEGREE OF FREEDOM



MAXIMUM RESPONSE OF ONE-DEGREE ELASTIC SYSTEM SUBJECTS TO CONSTANT FORCE WITH FINITE RISE TIME



- Assuming a linear behavior DLF = 2.0

- Assumption of response in a single mode is not universally valid: if floor slabs respond in a separate mode due to uplift and re-seating of slabs on bearings DLF can well exceed 2.0

- Introduction of plasticity reduces the DLF value due to energy dissipation from the system. The solution becomes an iterative process because the DLF depends on the level of plasticity reached, not known until the system is solved

↓

As design tool DLF can be evaluated for a linear system, with some adjustment to account for modest levels of plasticity

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- RISK-BASED METHODS

KEY ELEMENT DESIGN

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If a structure cannot be designed to ensure that the effects of the loss of a column are not disproportionate, the elements must be designed to withstand the applied actions, ensuring that it is not allowed to fall

- KEY ELEMENT DESIGN IS BY DEFINITON A SCENARIO-SPECIFIC APPROACH

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USUALLY REPRESENTS A CLIFF EDGE IN THE STRUCTURAL CAPACITY, BEYOND WHICH A SUDDEN DECREASE IN STIFFNESS OR STRENGHT INTERVENE

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KEY ELEMENT DESIGN (OR SPECIFIC LOAD RESISTANCE) SHOULD BE CONSIDERED AS A METHOD OF LAST RESORT

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SHALL ONLY BE USED IF THE ALTERNATIVE LOAD PATH METHOD IS NOT FEASIBLE

APPROACHES TO DESIGN FOR ROBUSTNESS

FOUR BASIC APPROACHES

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RISK BASED METHODS

Probabilistic (risk and/or consequence-based) approaches as alternative to deterministic ones

Recognize uncertainties in basic variables and perform uncertainty analysis on a range of values with an assumed statistical distribution

Particularly difficult to apply (lack of data) in events terrorism-related

QUANTIFICATION OF ROBUSTNESS

A SIGNIFICANT CHALLENGE!!!

PRACTICAL EVALUATION METHODS, WHERE THE STRUCTURAL BEHAVIOR UNDER AN ACTION SCENARIO IS MODELED

RELIABILITY OR RISK-BASED APPROACHES, STUDYING RELIABILITY OR ATTENDANT RISK OF A SYSTEM IN PRESENCE OF A GENERAL DESCRIPTION OF POTENTIAL LOADING SCENARIOS

- **A PARTICULAR ATTENTION SHOULD BE APPLIED IN DEFINITON OF "SYSTEM" FOR WHICH THE ROBUSTNESS EVALUATION IS REQUIRED**

CONSEQUENCES AND ALTERNATIVE DECISIONS SHOULD BE ASSESSED AND OPTIMIZED BY CARE!!!

RELIABILITY CONCEPTS SHALL BE EXTENDED AND UPDATED TO COVER AT THE SAME TIME NEW AND EXISTING STRUCTURES

A CLEAR DIFFERENTIATION IS NECESSARY BETWEEN THE TWO STRUCTURAL FAMILIES

MAIN DIFFERENCES BETWEEN NEW AND EXISTING STRUCTURES

→ INCREASE OF TARGET RELIABILITY LEVELS IMPLIES A LARGER COST INCREMENT IN EXISTING STRUCTURES COMPARED TO THE NEW ONES

→ REMAINING SERVICE LIFE IS SMALLER FOR EXISTING STRUCTURES COMPARED TO DESIGN WORKING LIFE OF NEW STRUCTURES

→ UPDATED INFORMATION ON ACTUAL RESISTANCE OF AN EXISTING STRUCTURE CAN BE AVAILABLE

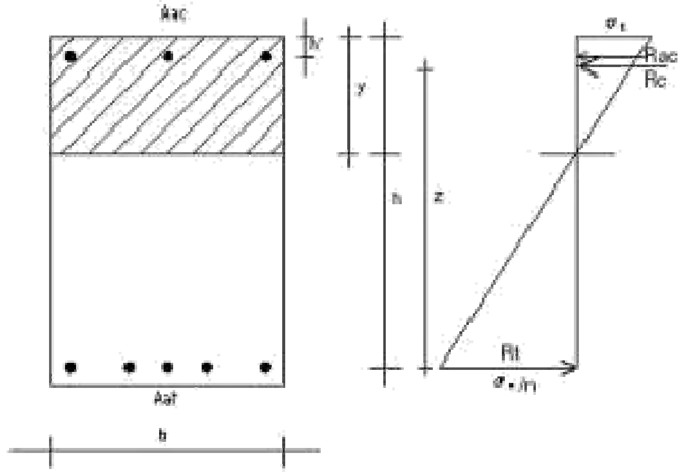
A FURTHER DIFFERENTIATION
ARISES ABOUT THE MODEL UNCERTAINTIES

IN THE EXISTING STRUCTURES NEW EPISTEMIC UNCERTAINTIES SHOULD BE ADDED

LACK OF KNOWLEDGE OF ACTUAL STRUCTURAL SYSTEM

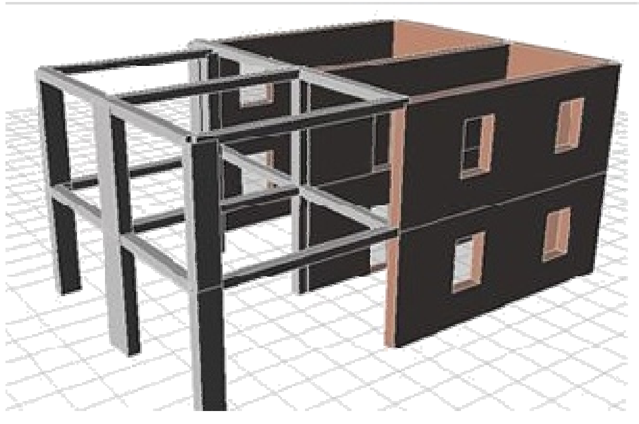


THE GENERAL AND LOCAL LAYOUT OF REINFORCEMENT MAY BE UNKNOWN



MANUALS OF CONSTRUCTION AGE MAY BE USED AS REFERENCE (BETON KALENDER…)

AN EVENT TREE SIMULATION IS SUGGESTED FOR THE TREATMENT OF SUCH TYPE OF UNCERTAINTIES



ALL THOSE DIFFERENCES IMPLY IMPORTANT CONSEQUENCES ON

CONSTRUCTION | REPAIR | UPGRADE…**COSTS**

IF WE MAINTAIN UNCHANGED THE RISK FOR HUMAN LIFE (~10^{-5}/YEAR)

THE TARGET RELIABILITY VALUES (β) MAY BE REDUCED IN EXISTING STRUCTURES COMPARED TO THE NEW ONES

SEVERAL REFERENCES AND SCIENTIFIC PAPERS HAVE BEEN PUBLISHED IN THE LAST TWO DECADES ON THIS CONCEPT (MC 2010, ISO, JCSS)

ALL SUPPORTING A β REDUCTION

- MAXIMUM β REDUCTION BEYOND WHICH AN UPGRADE IS MANDATORY

$\Delta\beta \approx 1.5$

- MAXIMUM β REDUCTION IN CASE OF A COMPLETE UPGRADE

$\Delta\beta \approx 0.5$

CONSEQUENTLY ALSO PARTIAL FACTORS γ SHOULD BE REVISED, CONSIDERING:

- **RESIDUAL LIFE**
- **ACTUAL SCATTERING IN MATERIAL PROPERTIES**
- **$\Delta\beta$**

A COMPREHENSIVE GUIDANCE IS CONTAINED IN BULLETIN XX OF TG3.1 READY FOR PUBLICATION AFTER TC APPROVAL IN CAPE TOWN

NECESSITY OF UPDATING OF RELIABILITY VERIFICATION METHODS COMPARED TO MODERN TOOLS USED IN THE ANALYSIS (FEM)

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In such cases the **limit state equation**

$$g(R - S) = 0$$

is not available as a closed form function of input variables (implicit)

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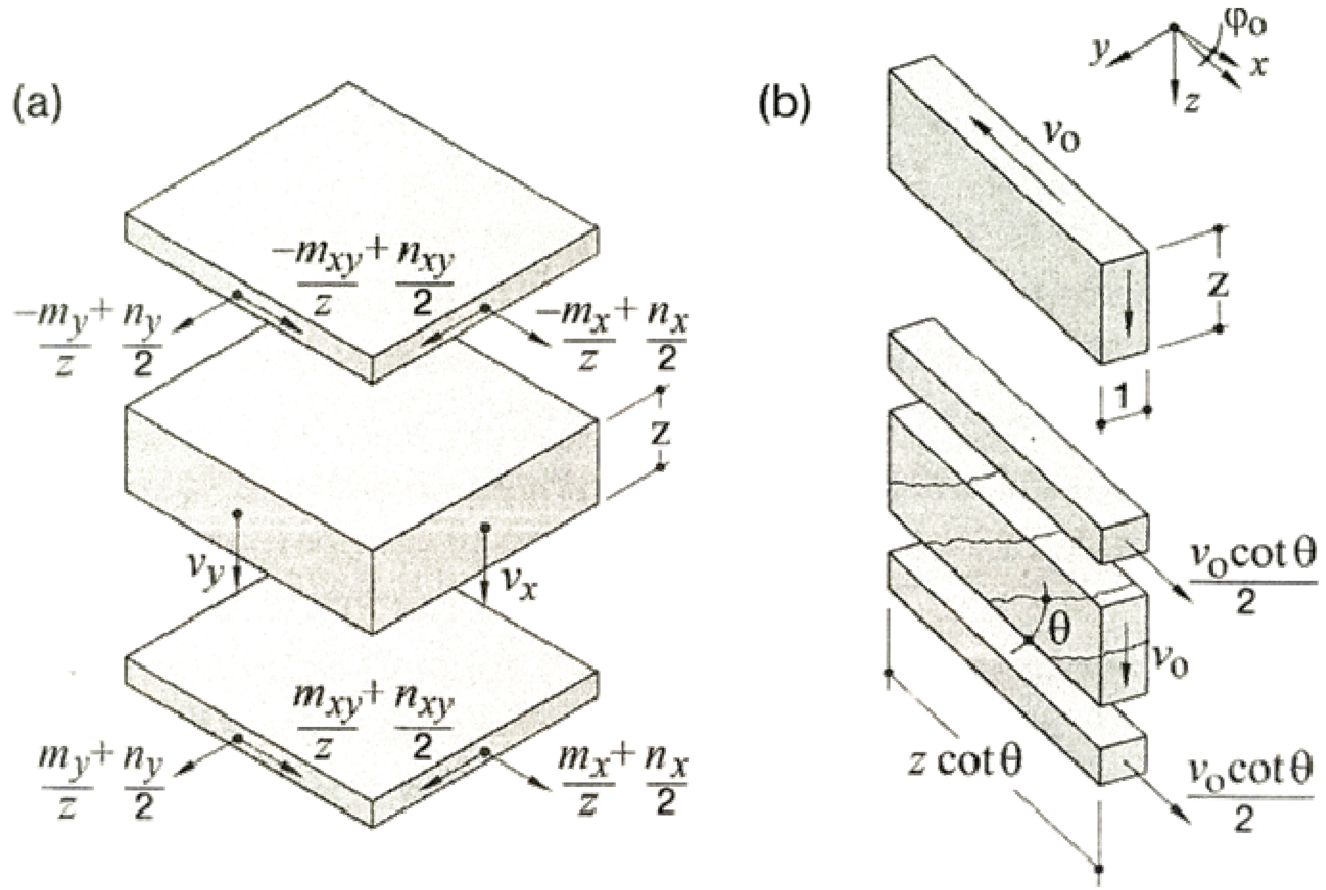
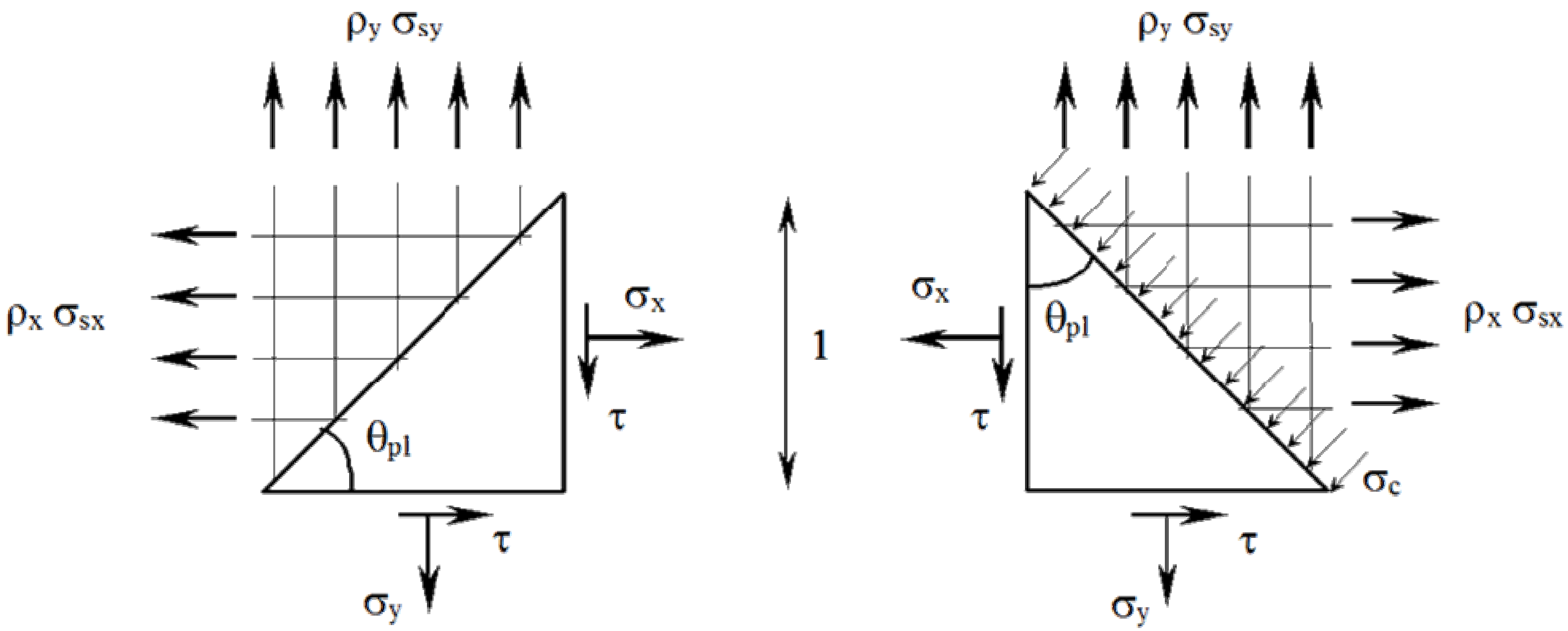
Derivatives of "g" compared to the input random variables $x = R - S$ required for evaluation of minimum distance point on the limit state are not available



For instance in shell/slab/plate elements, a system of equations combined with iterative procedures defines the limit state



Model for plate element or sub-element of slab and shell

COMPUTATION APPROACHES COULD BE PURSUED FOR THE RELIABILITY ANALYSIS OF STRUCTURES SHOWING IMPLICIT LIMIT STATE FUNCTIONS

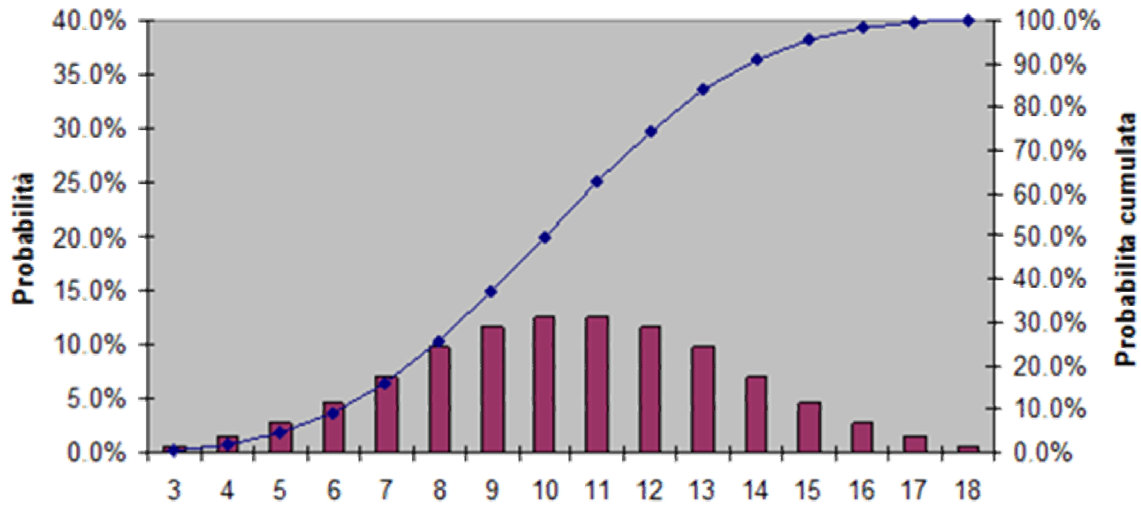
MONTECARLO SIMULATION	RESPONSE SURFACE APPROACH	SENSITIVITY BASED ANALYSIS
1	2	3

1 MONTECARLO SIMULATIONS

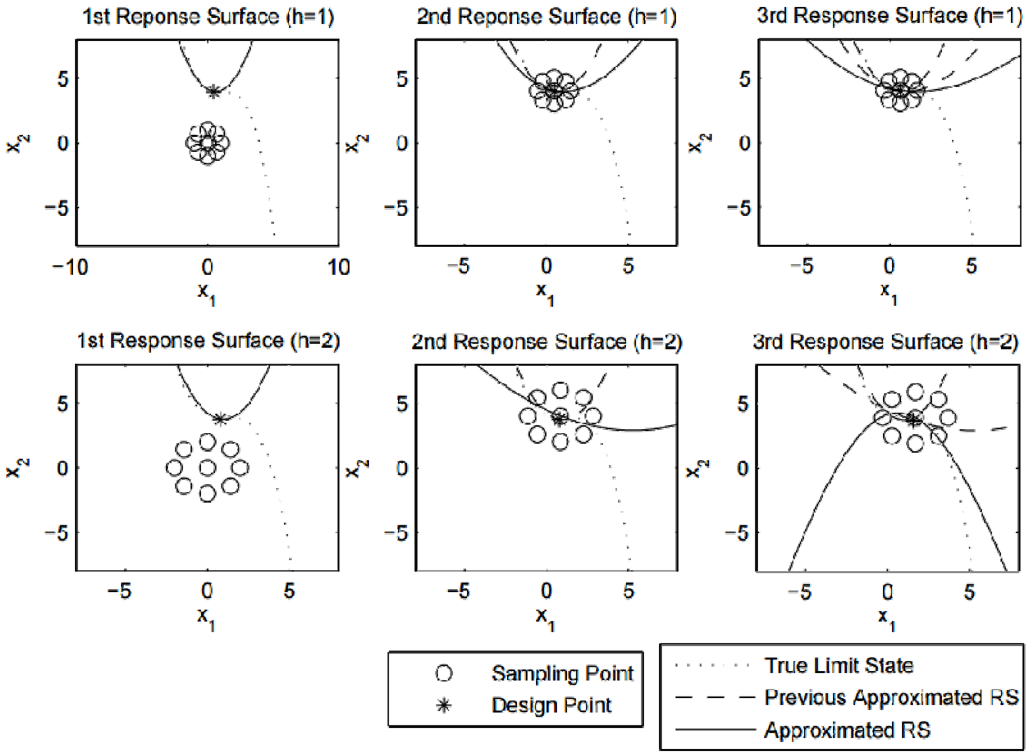
ARE TODAY MORE FEASIBLE DUE TO THE COMPUTER POWERFUL INCLUDING:

Efficient sampling methods

Variance reduction techniques



2 RESPONSE SURFACE APPROACH



A polynomial is constructed to approximate g(x) through a few selected simulations in the proximity of the most likely failure point

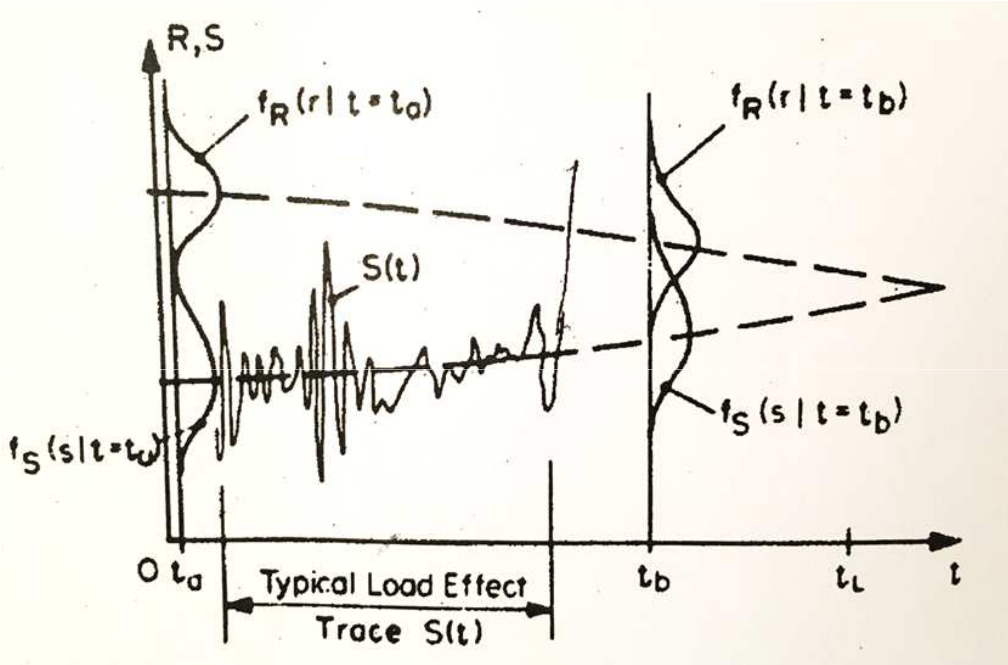
Then FORM and SORM can be used as for the explicit L.S. functions

3 SENSITIVITY BASED ANALYSIS

- FINITE DIFFERENCE APPROACH AND PERTURBATION OF EACH VARIABLE WITH FOLLOWING DETERMINISTIC ANALYSES
- CLASSICAL PERTURBATION METHODS, APPLYING THE CHAIN RULE OF DIFFERENTIATION TO FEM ANALYSIS
- ITERATIVE PERTURBATION ANALYSES TECHNIQUES

ACCOUNTING FOR PROGRESSIVE DETERIORATION PROCESS

TIME – DEPENDENT RELIABILITY ANALYSIS



$R(t)$ $R(t) and\ S(t)$ $S(t)$

$$P_f(t) = Prob\{R(t) \leq S(t)\} = Prob\,\{g(X(t)) \leq 0\}$$

$$P_f(t) = \int_{g(X(t))\leq 0} f_{x(t)}\big(x(t)\big)dx(t)$$

↑

Actual failure probability at time t assuming that

→ **THE STRUCTURE WAS SAFE AT TIME SMALLER THAN t**

NON LINEAR FEM ANALYSIS

- AT THE MOMENT NON LINEAR FEM ANALYSIS HAS NOT REACHED A FULL SATISFACTORY LEVEL

- MOST COMMON NON LINEAR FEM PROGRAMS ARE NOT ABLE TO EVALUATE IN A SATISFYING MANNER ALL THE FAILURE MODES

While waiting for a future and rapid progress in N.L. FEM, at the moment **Tailor-made programs** should be used, calibrated on certain structure typologies and failure modes

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PARTICULAR ATTENTION SHOULD BE PAID TO ANALYSE THE INTERFACE PROBLEMS BETWEEN OLD AND NEW CONCRETES WHEN EXISTING STRUCTURES ARE REPAIRED

The significant difference between experimental test results and numerical simulations, although performed by expert people using well known commercial programs with a good reputation, requires the introduction of a new coefficient covering the UNCERTAINTIES IN USING NON LINEAR FEM

$$\gamma_{Rd,FEM}$$

SAFETY FORMATS FOR NON LINEAR ANALYSIS

FULL PROBABILISTIC SAFETY FORMAT

Evaluation of **RELIABILITY INDEX β** or failure probability

In case of existing structures, actual structure condition and deterioration models should be used

GLOBAL RESISTANCE SAFETY FACTOR

Evaluation of overall structure design resistance by use of a **GLOBAL RESISTANCE FACTOR**, chosen so that reliability requirements are met for a chosen reference time

GLOBAL SAFETY FACTOR

TO BE EVALUATED IN THE DOMAIN OF GENERALIZED ACTIONS
(FORCES, IMPOSED DEFORMATIONS, ACCELERATIONS, ..)
OR IN THE ONE OF ACTION EFFECTS
(MORE SUITABLE FOR LINEAR ELEMENTS)

$$F_d \le R_d = \frac{R_m}{\gamma_R^* \ \gamma_{Rd}}$$

Where:

F_d Design value of applied actions

R_m Structural resistance predicted with a N.L. Analysis performed with mean values of material resistances

γ_R^* Global safety factor accounting for uncertainties related to material properties and geometrical data

γ_{Rd} Model uncertainty factor accounting for resisting model uncertainties

PROBABILISTIC EVALUATION OF GLOBAL RESISTANCE FACTORS

Design value R_d of resistance R is:

$$Prob\ (R \leq R_d) = \Phi(-\alpha_R \beta)$$

Where:

Φ	Cumulative distribution function of standard normal distribution
α_R	Form sensitivity factor
β	Reliability index

IN PRACTICE

Use Monte Carlo method to estimate μ_R $(mean)$ and $V_R(Coefficient\ of\ variation)$ of global resistance PDF

↑

DESCRIBING THE MATERIAL WITH LOGNORMAL PDF ALSO THE GLOBAL RESISTANCE PDF IS SENSIBLY LOGNORMAL

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Only 100÷1000 samples are necessary to evaluate μ_R and V_R

Then:

$$R_d = \mu_R \, exp(-\alpha_R \beta V_R^*) \qquad (V_R \leq 0.25)$$

$$\gamma_R^* = \frac{\mu_R}{R_d} = \frac{\mu_R}{\mu_R \, exp(-\alpha_R \beta V_R^*)} = exp(\alpha_R \beta V_R^*)$$

b) With a conservative procedure assuming the V_R^* value equal to the concrete's one (0.15)

$$\gamma_R^* = exp\,(0.8 * 3.8 * 0.15) = 1.58$$

ASSESSMENT OF MODEL UNCERTAINTIES FOR 2D R.C. STRUCTURES ANALYSED WITH N.L. FEM

25 Experimental tests performed with three commercial programs A/B/C (Adina / Diana / Athena)

THREE RELATIONSHIPS FOR CONCRETE BEHAVIOUR IN TENSION

Elastic-brittle

Elastic-plastic

By – linear with softening

Globally 25x3x3 =225 case studies

MODEL UNCERTAINTY DEFINED ACCORDING TO JCSS P.M.C.

$$X = \frac{R_{actual}}{R_{FEM}(y)}$$

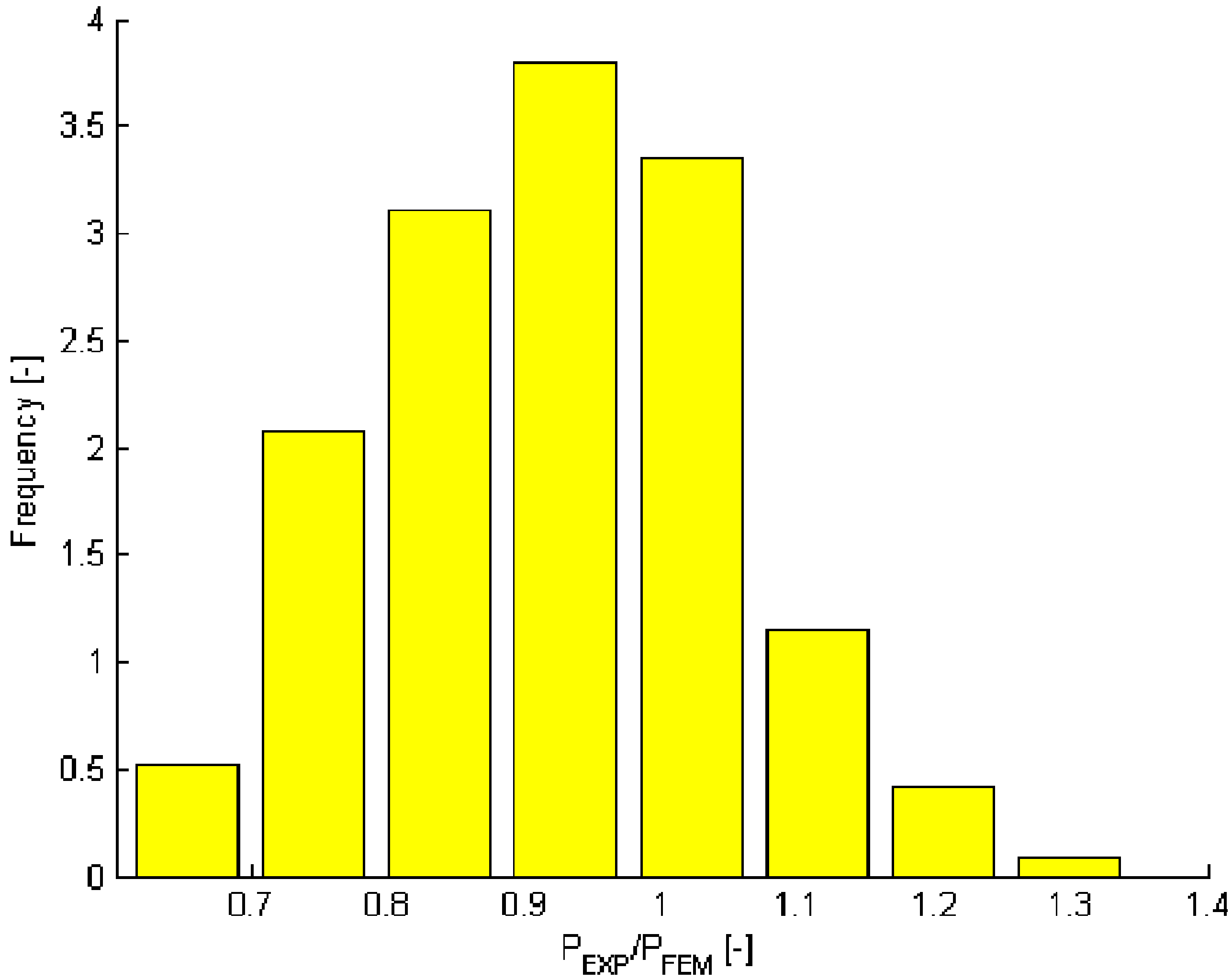
ACTUAL EXPERIMENTAL FAILURE VALUE

NUMERICALLY PREDICTED FAILURE VALUE

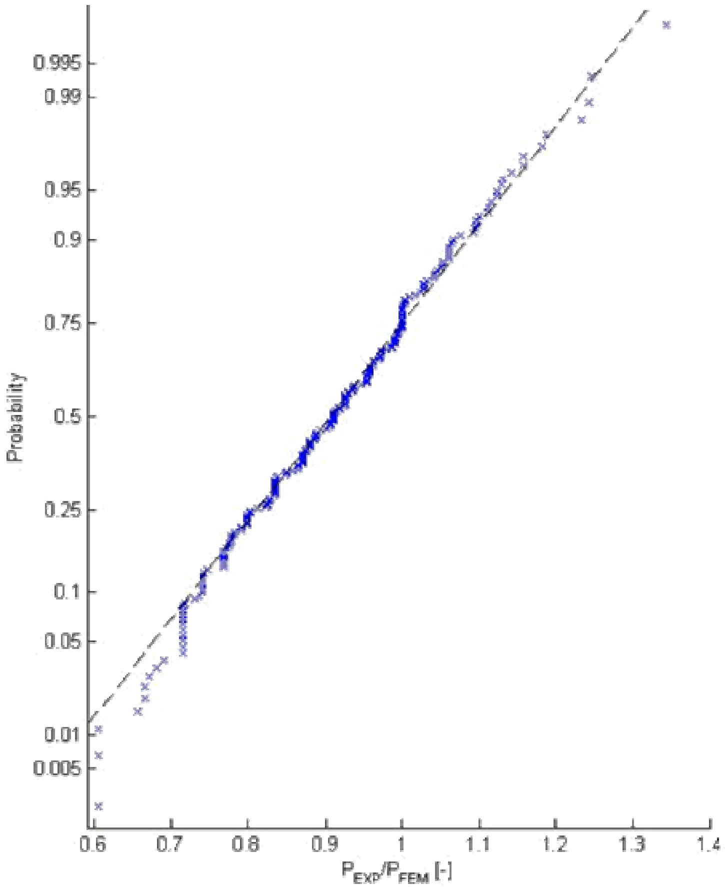
EXPERIMENTAL TESTS

- 9 shear panels
  - 4 panels of Vecchio / Collins (PV10, PV19, PV21, PV22)
  - 5 panels of Pang / Hsu (A2/ A4/ B2/ B5/ B6)
- 5 Wall of Leonhardt / Walther (WT2, WT3, WT4, WT6, WT7)
- 5 Deep-beams of Foster /Gilbert (B2.0-1, B2.0-3, B3.0-1, B2.0A-4 B3.0A-4)
- 1 Wall of Lefas / Kotsovos (SW11)
- 5 Wall of Filho (MB11AA, MB11AE, MB1EE, MB1EE1, MB4EE)

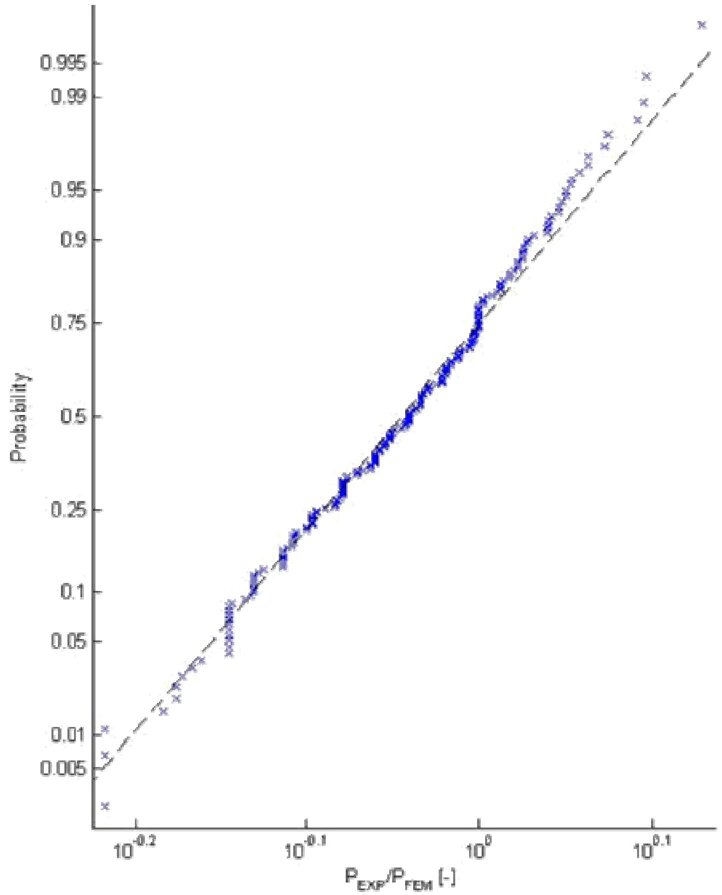
HISTOGRAM OF THE RATIO P_{exp} / P_{FEM}



PROBABILITY PLOTS OF THE RATIO P_{exp} / P_{FEM}



Probability plot for Normal distribution



Probability plot for Lognormal distribution

PROBABILISTIC MODEL

BAYESIAN APPROACH WITH COMBINATION OF PRIOR INFORMATION AND NEW DATA

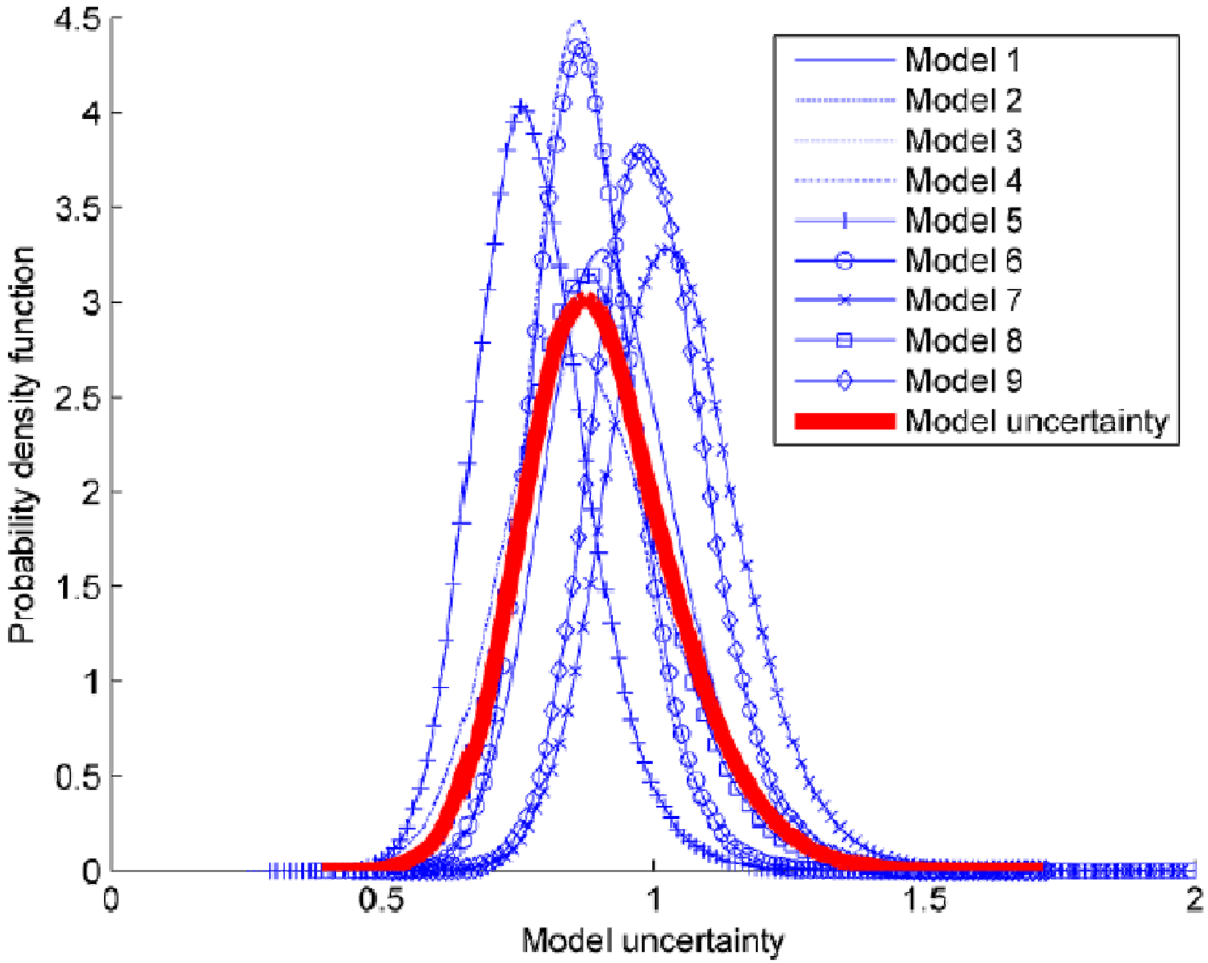
Finite element models

	Elastic-brittle	Elastic-plastic	Bi-linear with tension softening
Program A	Model 1	Model 2	Model 3
Program B	Model 4	Model 5	Model 6
Program C	Model 7	Model 8	Model 9

PARAMETERS μ , σ^2 AND COEFFICIENT OF VARIATION OF THE POSTERIOR DENSITY FUNCTION $f''_X(x|\hat{x}, M_i)$

Model	Mean value	Variance	Cov
1	0.926	0.016	0.14
2	0.882	0.023	0.17
3	0.927	0.016	0.14
4	0.869	0.009	0.11
5	0.778	0.011	0.14
6	0.874	0.009	0.11
7	1.041	0.016	0.12
8	0.893	0.018	0.15
9	0.966	0.012	0.11

PREDICTIVE DENSITY FUNCTIONS



PARTIAL FACTOR FOR MODEL UNCERTAINTY

$$\gamma_{Rd,FEM} = \frac{1}{\mu_R \, exp(-\alpha_R \beta \, V_x)}$$

α_R=0.32 (non dominating resistance variables)

BY THE PREVIOUS PROBABILISTIC MODEL

$$\gamma_{Rd,FEM} \cong 1.35$$

THEN BY USING THE PREVIOUSLY DESCRIBED CONSERVATIVE PROCEDURE:

$$\gamma_{\mathrm{global}} = \gamma^{*} * \gamma_{\mathrm{Rd,FEM}} = 1.58 * 1.35 = 2.13$$

THANK YOU FOR THE KIND ATTENTION