



Life-Cycle Robustness: Prospects and Challenges

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What is Life Cycle Robustness?

Life-Cycle Robustness

Society demands

- **Safety**

- accepted failure probability $1E-6$ / year

- **Serviceability / Functionality**

- accepted failure probability $1E-3$ / year

- **Durability / Sustainability**

- required life time of 50 to > 100 years

How to ensure?

Life-Cycle Robustness

Challenges arise from

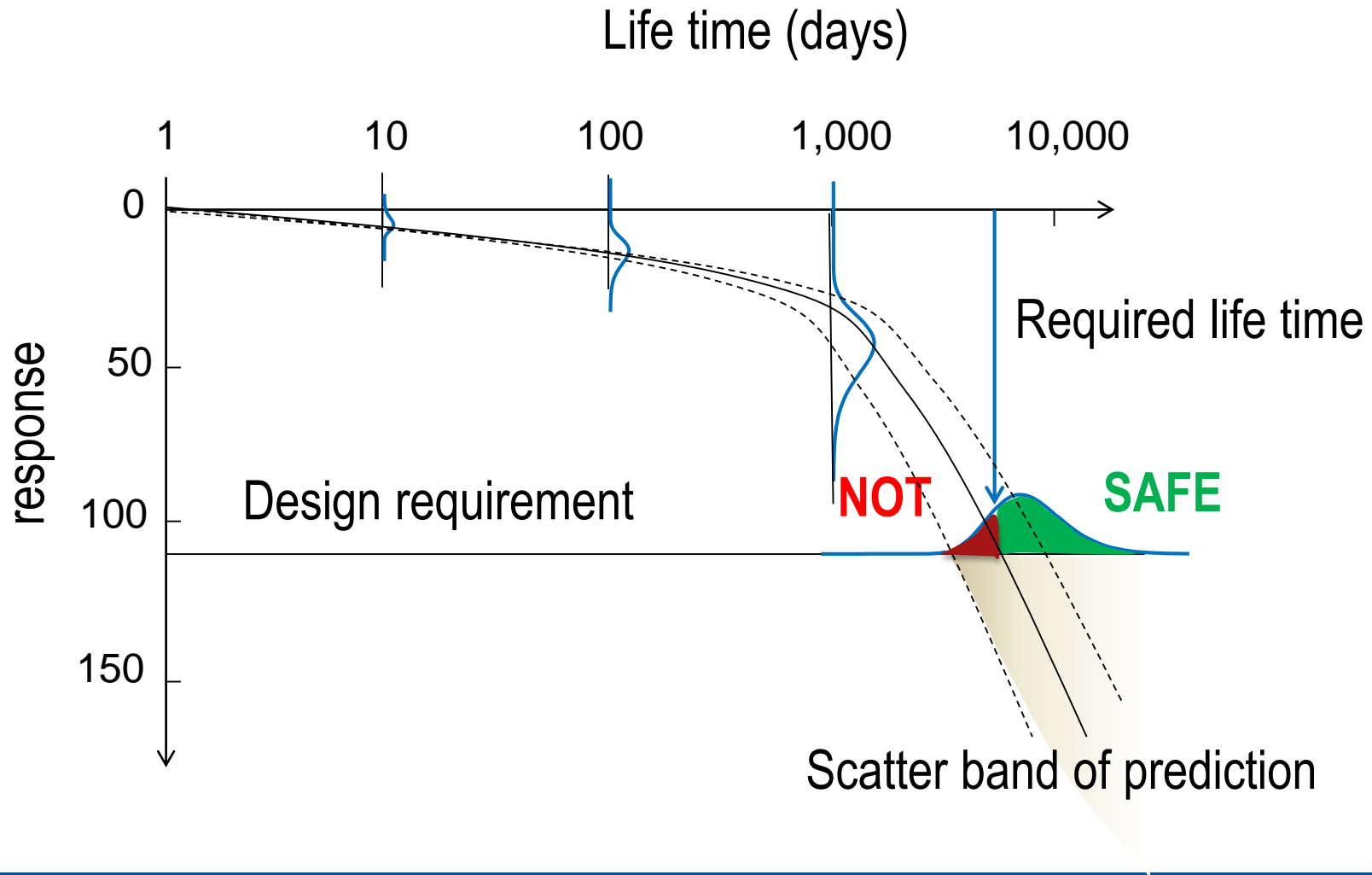
- Ageing of materials
- Deterioration processes
corrosion, cracking, fire, freeze-thaw
- Number of potential loads/scenarios
permutations of: dead load, traffic, wind, snow,
impact, earth quake
- Uncertainty in values, assumptions

Life-Cycle Robustness

Solution: concept of **Life-Cycle Robustness** in the **Evaluation and Design** of systems:

Life Cycle Robustness = Ability of a system to **maintain it's intended function** and required safety level throughout the full design life-time, **in spite of ageing, deterioration,** and even rare events.

Life-Cycle Robustness



Life-Cycle Robustness

Consequence:

Need to develop **theoretically based** and **experimentally validated** models and simulation techniques that allow the

- (a) **prediction** of the **future condition** of the system, and it's
- (b) **uncertainty quantification** in order to
- (c) Determine it's reliability level



Application?

Fastenings



Fastening system = post-installed elements that connect structural members with each other or to equipment



Fastening systems

Fastenings systems can be differentiated by

- Material (metal, plastics,...)
- Shape (screw, bolt, sleeve,...)
- Mechanism (friction, bond, shape)
- Exposition (indoor, outdoor)
- Anchor ground (brick, stone, concrete,...)



questions

open questions by themselves or in combination:

- Behavior under sustained loads
- Influence of corrosion
- and/or of aggressive agents
- Influence of freeze/thaw

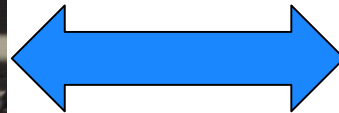


questions

– Remaining capacity after fire



– Capacity of ageing concrete



questions

- Capacity after **earth quake**



- Influence of **unexpected events**

CHALLENGE 1:

permutations and occurrence of loads/events



- Direct Loads

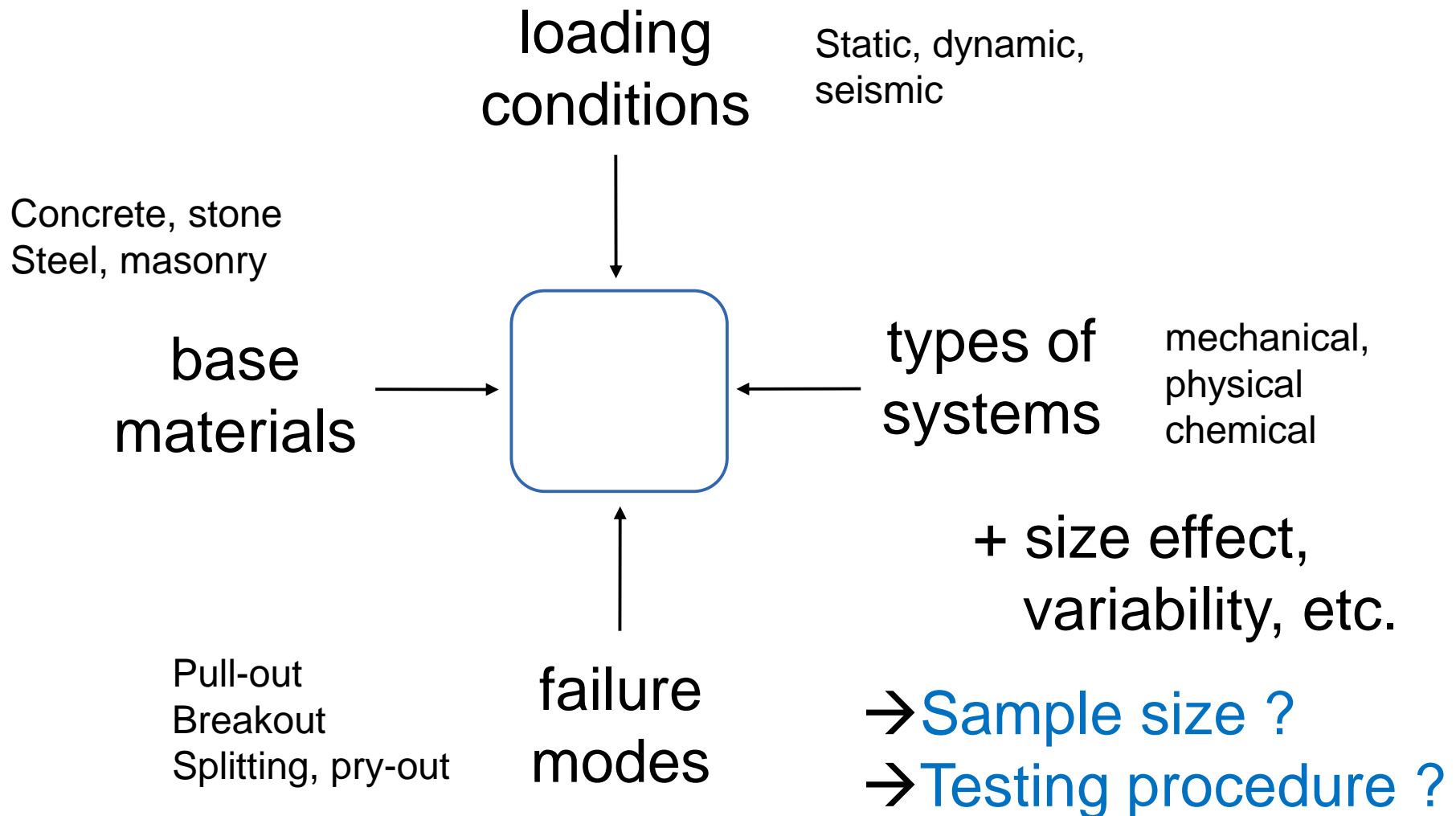
- Sustained loads
- Quasi-static
- Dynamic

- Indirekt Loads (incompatible strains) due to

- Temperature (temperature gradient, fire, freeze/thaw)
- Expansive reactions (ASR, corrosion)
- Relaxation
- Shrinkage
- Creep

CHALLENGE 2:

Large number of tests

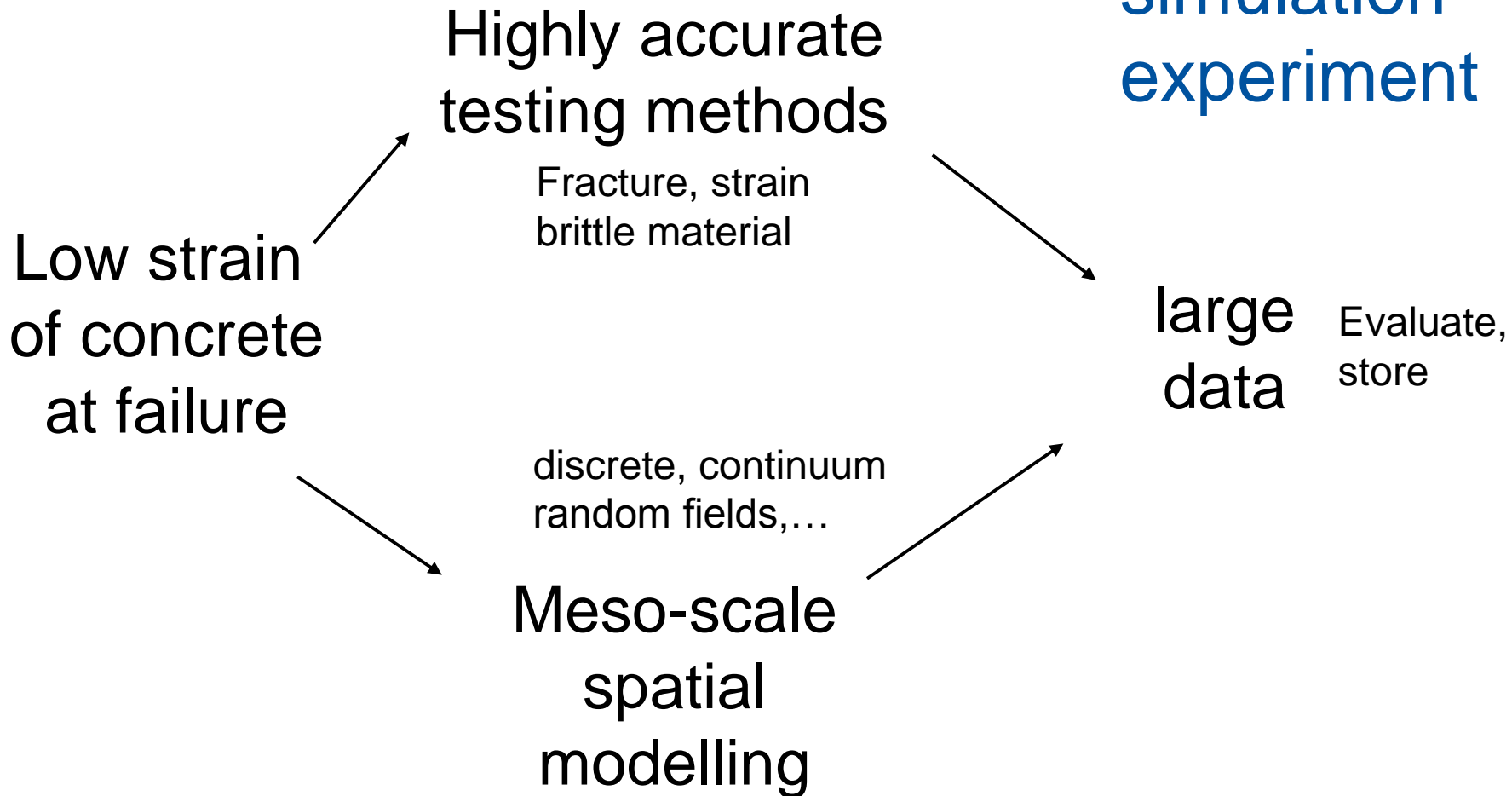


CHALLENGE 3:

Large volume of data



simulation
experiment



CHALLENGE 3:

Large volume of data



Low strain
of concrete
at failure

Noise
Spurious correlations
Dimensionality
Overfitting
Model robustness
Lack of physical
understanding
Uncertainty importance

large
data

modelling

CHALLENGE 4:

Low failure probabilities

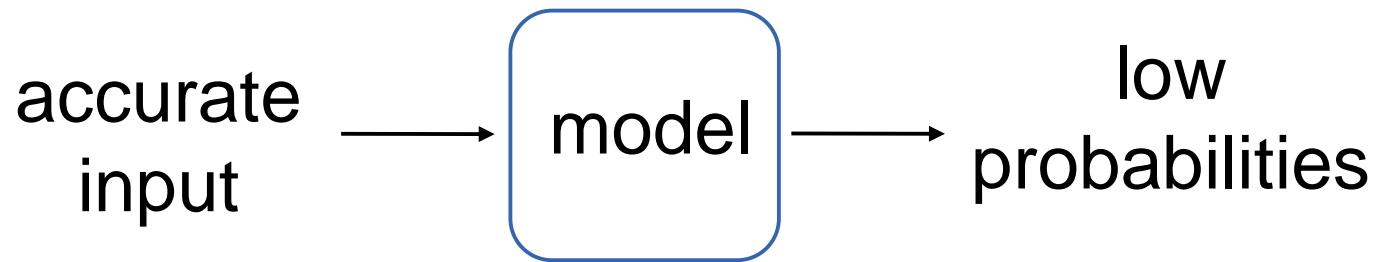


- They do not imply accurate frequencies
- Sensitive to uncertainties/non-linearities
- Depend on tails of distributions
- Require large samples
- Limitations in cost, resolution, etc.
- Computationally intensive

Model uncertainties: dominant

CHALLENGE 4:

Low failure probabilities



variability

model uncertainty

assumptions, simplifications

physical limitations (resolution etc.)

CHALLENGE 6: Temporal effects



Different effects on the load side and properties on the resistance side develop differently in time.

$$F(\tilde{x}, t) \quad \text{or} \quad F_t(\tilde{x}) \quad ?$$

Time as a
variable

Time as part
of the model

CHALLENGE 6: Temporal effects



Long-term behaviour: highly uncertain

Monotonic, periodical, point processes: combination?

Predictability of random events: possible?

Response: non-linearities

CHALLENGE 7:

Extrapolation based on limited data



multi-decade predictions required in design

e.g. creep, shrinkage, corrosion, ...

BUT

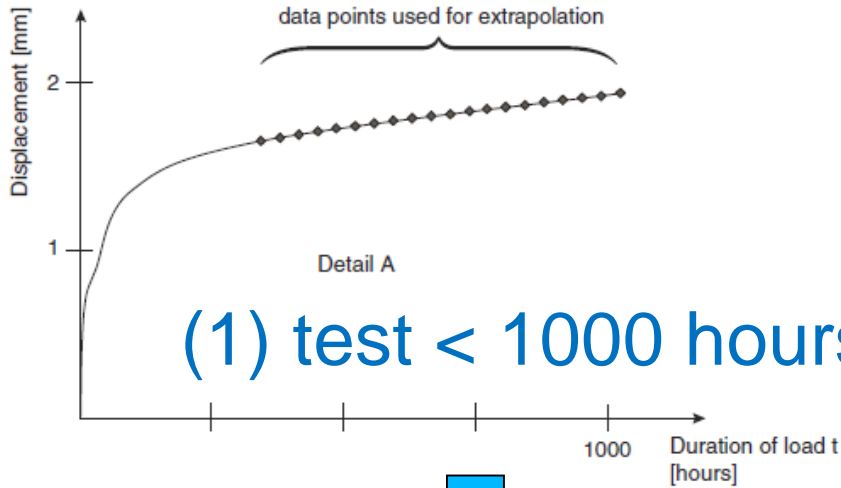
Typically only relatively short exp. data available

→ How quantify uncertainty?

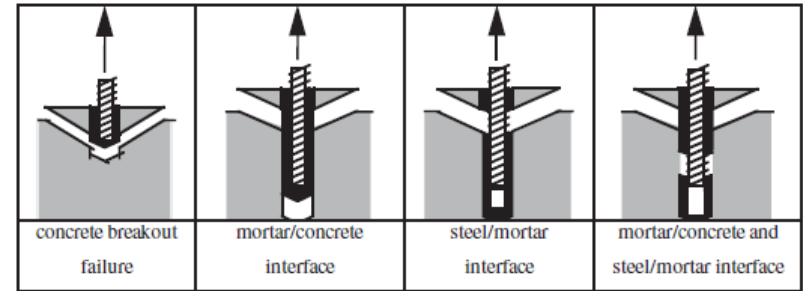
→ How improve calibration of prediction?

Example

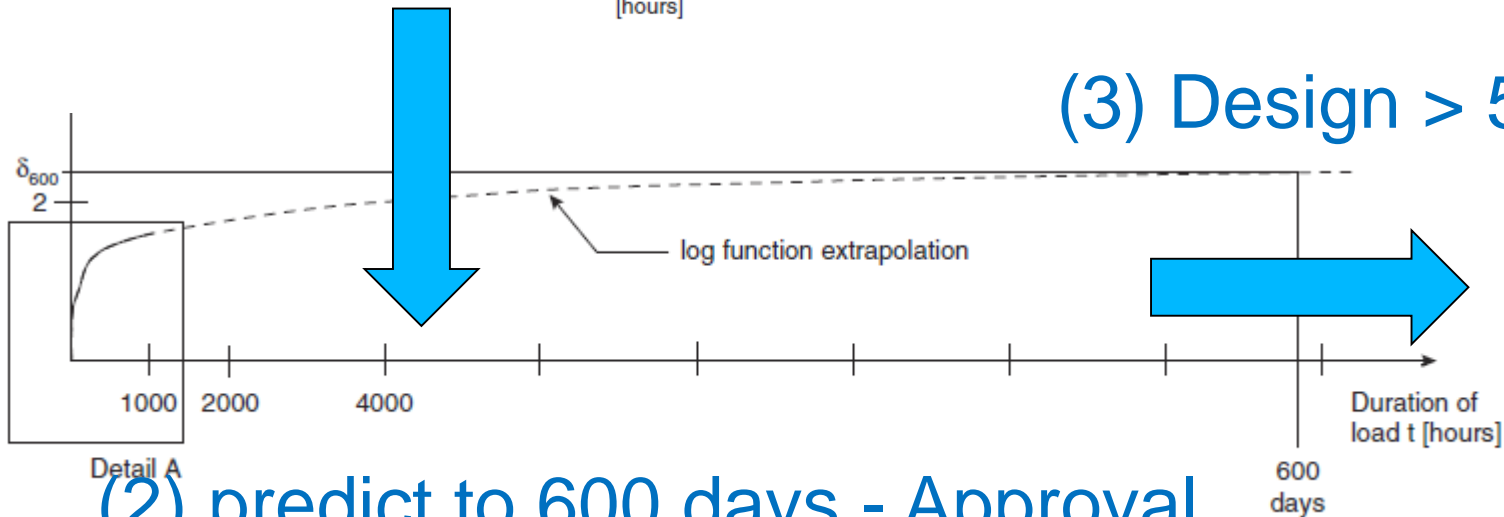
Adhesive Anchors & Sustained loads



(1) test < 1000 hours



Reprinted with permission from Cook et al. (4).



(3) Design > 50 years

(2) predict to 600 days - Approval

Extrapolation of sustained load displacements per ASTM E1512-01.

Example

Concrete Creep and Shrinkage



HETEROGENEOUS DATA

creep strain

shrinkage strain

structural response

EXPERIMENTAL BIAS

For certain composition and testing conditions

Due to sampling rate

UNCERTAIN/INCOMPLETE MEASUREMENTS

Reported concrete age

Reported start of measurement

INTERDEPENDENCE OF DATA

Measured strains **ALWAYS** include **autogenous shrinkage**

Creep data **ALWAYS** includes **elastic deformation** and **basic creep**

OTHER INACCURACIES in SOURCE DATA

Creep and Shrinkage in Concrete



Concrete undergoes deformations while in service due to:

- applied stress (mechanical and environmental) and
- changes of internal structure and composition (from hydration and degradation).

⇒ **CREEP**

⇒ **SHRINKAGE**

CAUSES:

coupled mechanisms of **basic creep, drying creep, drying shrinkage, autogenous shrinkage**, cracking, swelling, and hydration product buildup.

Creep and shrinkage must be predicted for safe multi-decade design of concrete structures.



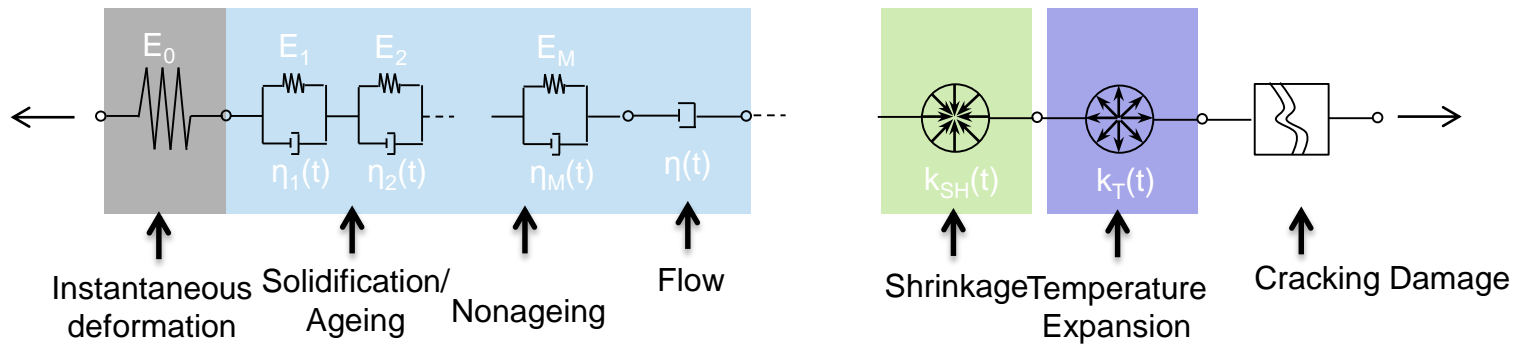
Model Formulation



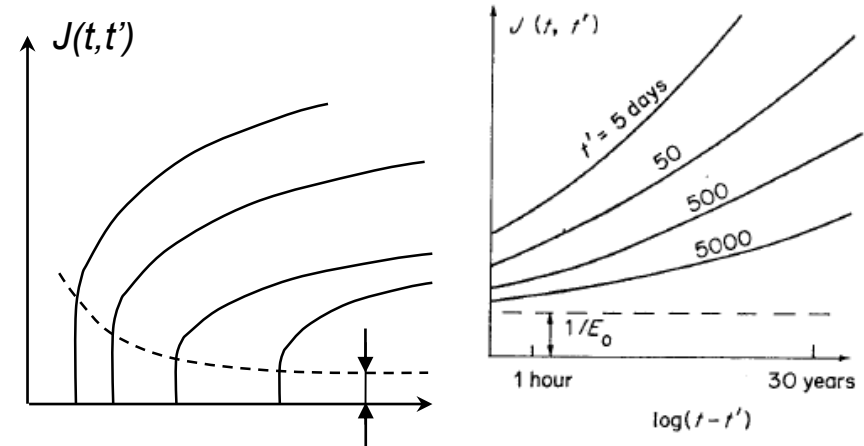
Only mechanism based formulations

- provide true predictive capabilities
- can be calibrated in spite of biased and incomplete data

Mechanisms based on the micro-prestress solidification (MPS) theory:



- **Many parameters** to be calibrated
- Superposition of **similarly shaped time** functions leads to non-uniqueness



Database for Development of Creep models



Extensive collection of **short-term laboratory** tests provide insight into influence of **intrinsic concrete properties**, and **environmental** influence factors (relative humidity, temperature)

BUT

- 95% of tests are shorter than 6 years
- only few long-term laboratory tests exist:

Brooks (30 year), Russell and Burg (18 year),
Browne and Buro of Recl. (12 year),

Troxell (23 year)

COMPARED TO REQUIRED PREDICTION TIME

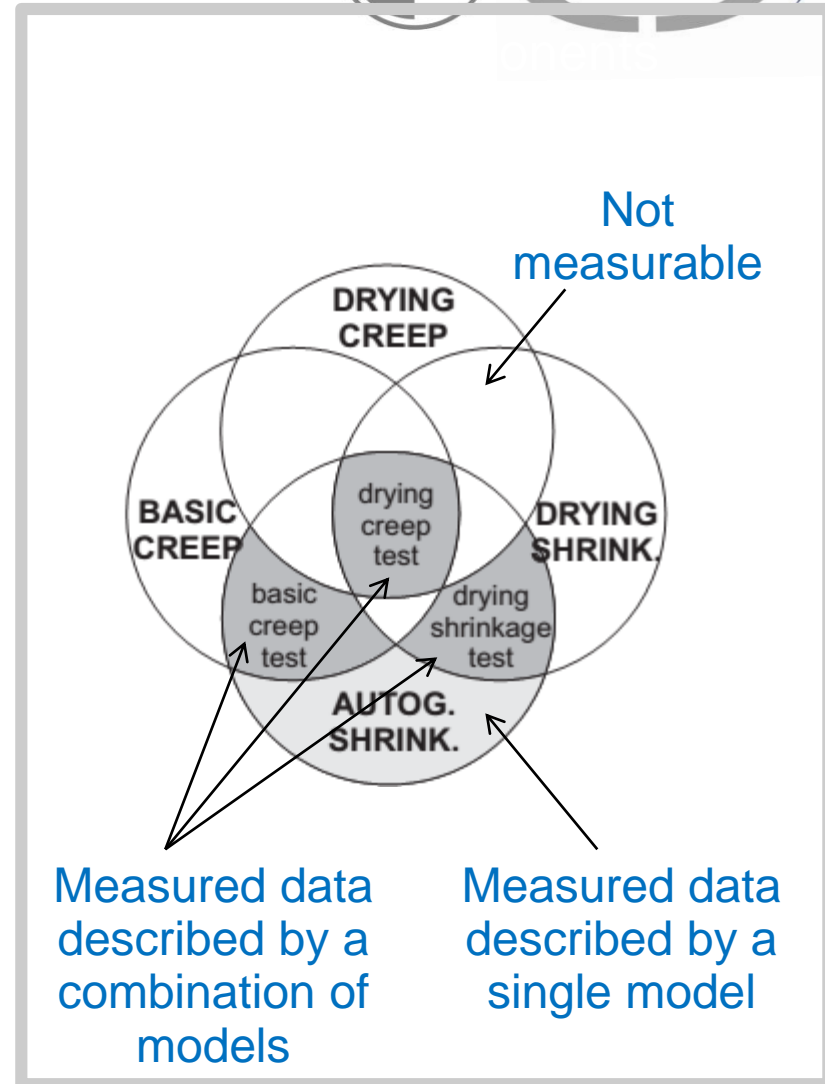
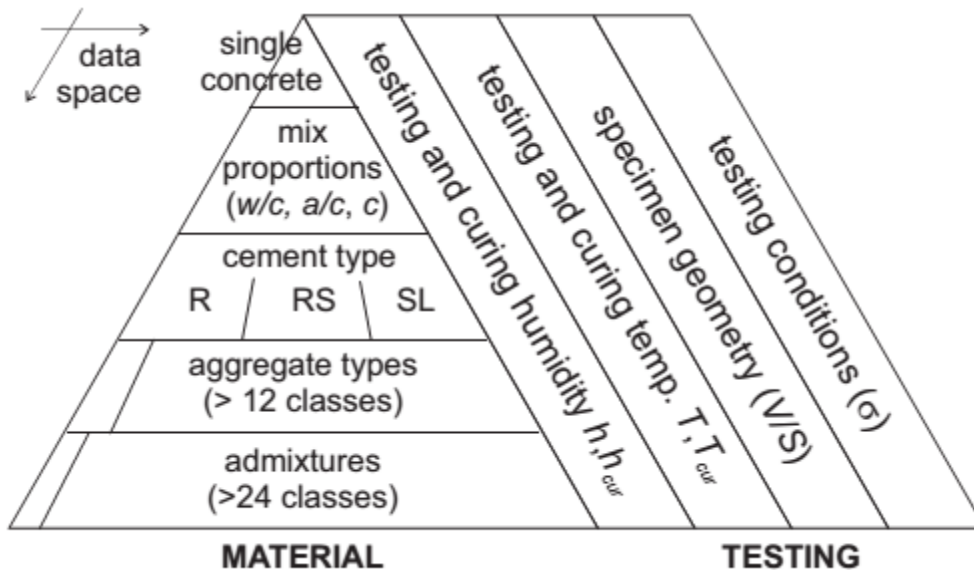
- Silica Fume
- Air-Entraining-Agents
- Water-Reducer

Granite, Sandstone,
Graywacke, Limestone,
Diabase, Diorite, Quartzite,
Schist

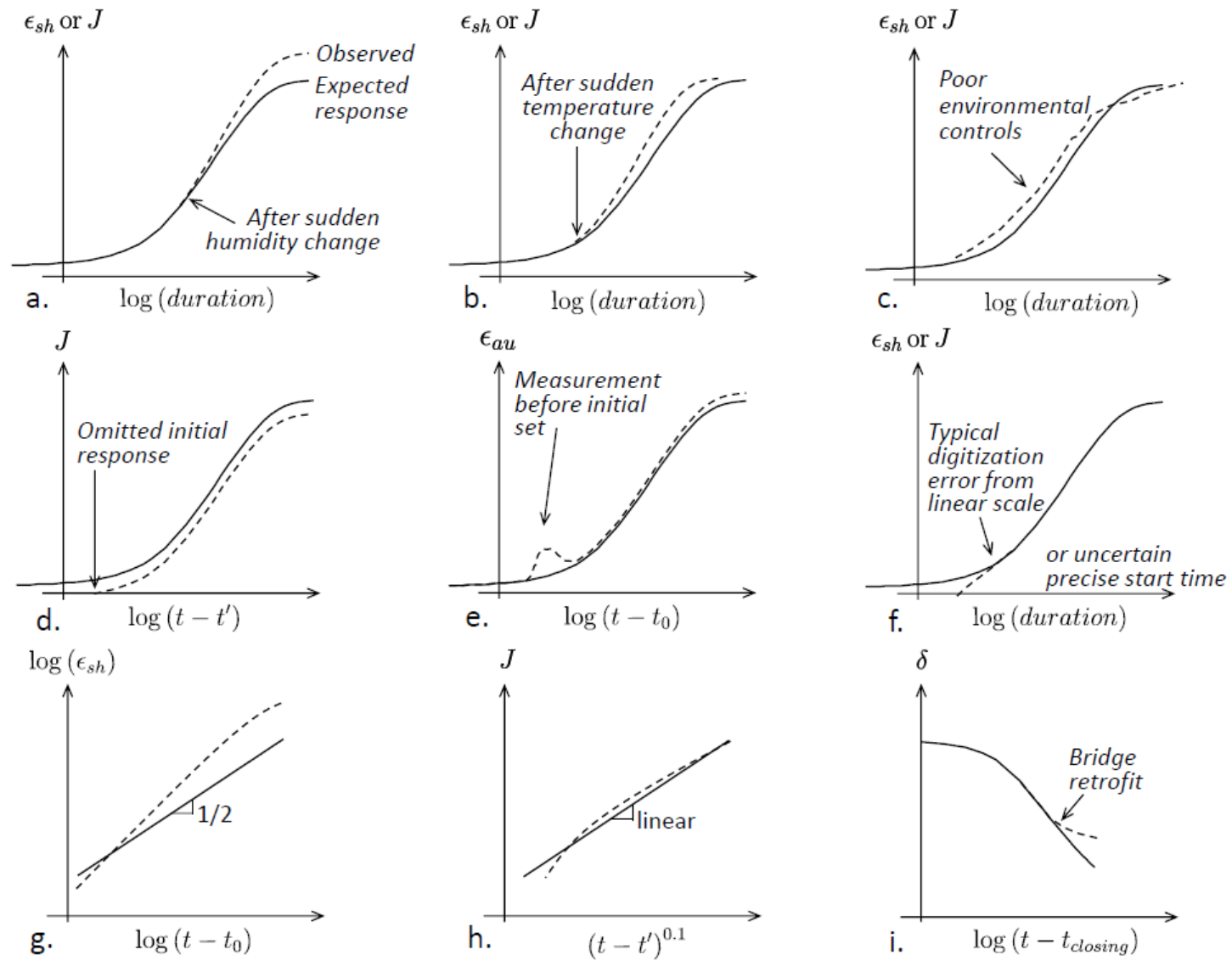
Complexity of the optimization problem



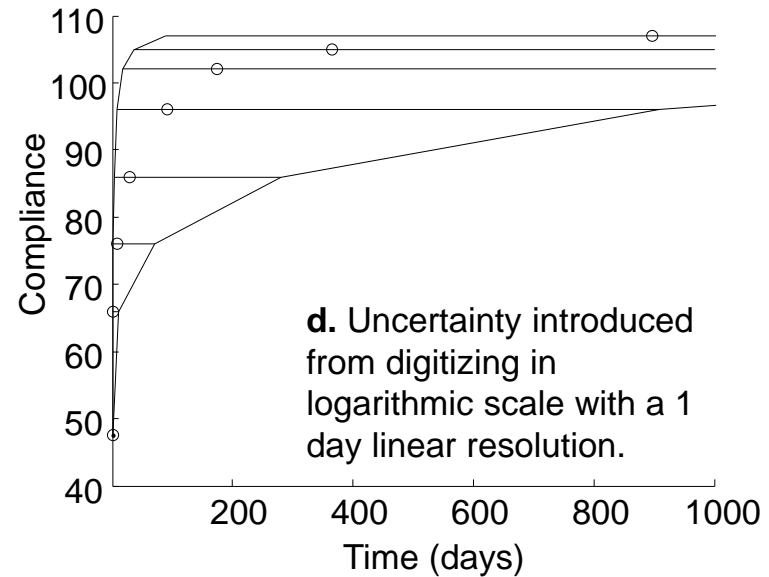
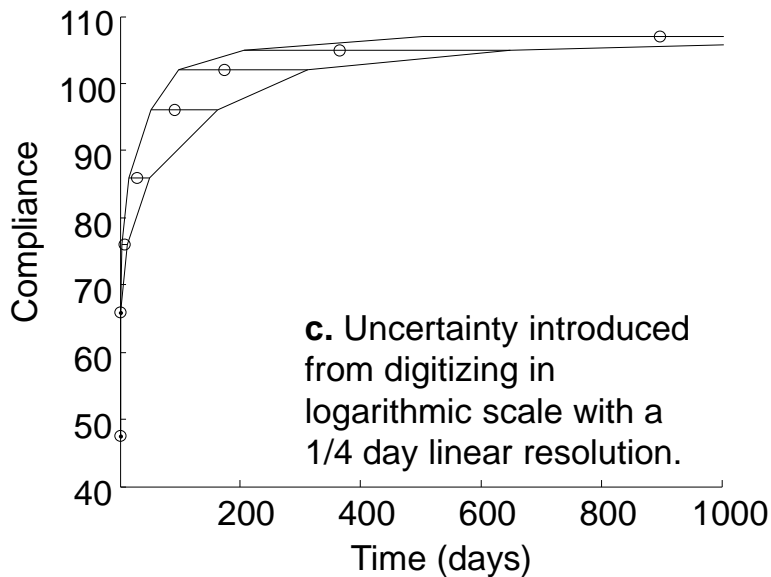
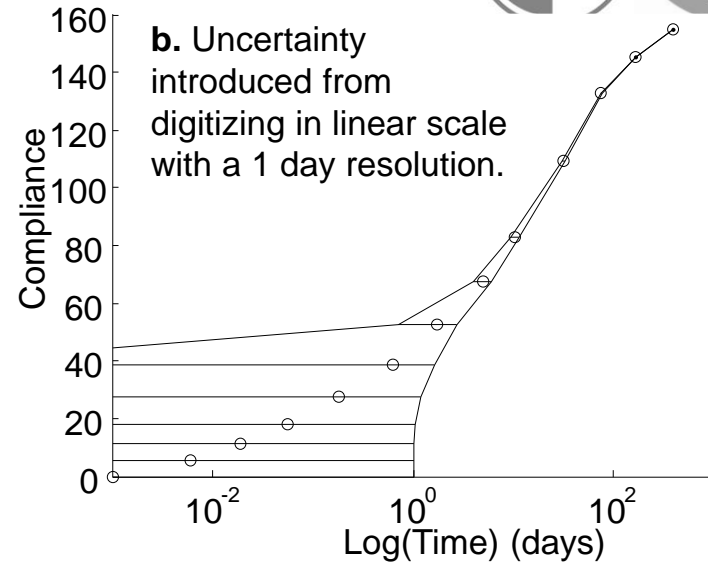
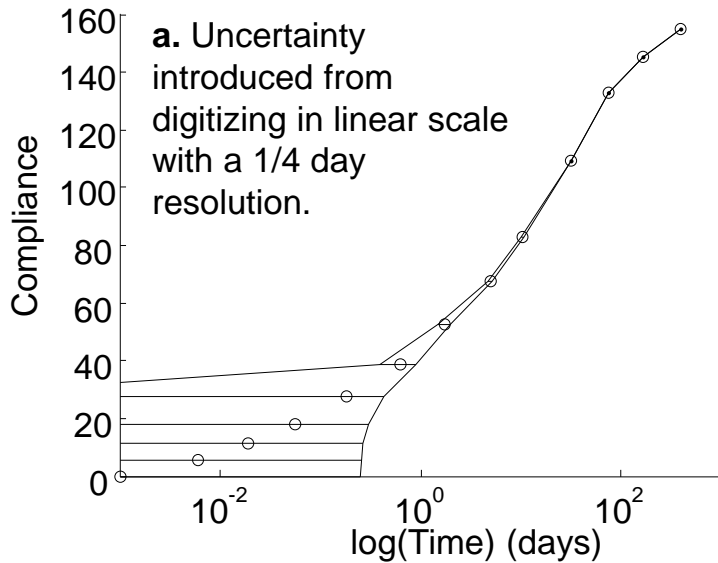
The number of test parameters depending on intrinsic and extrinsic factors:



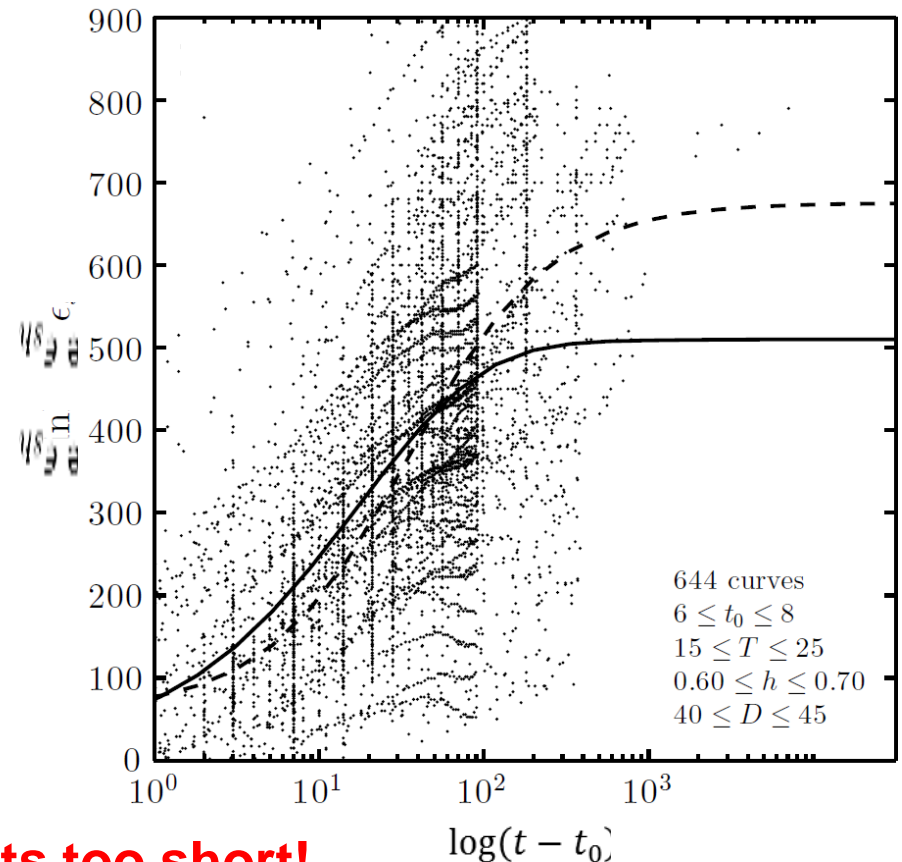
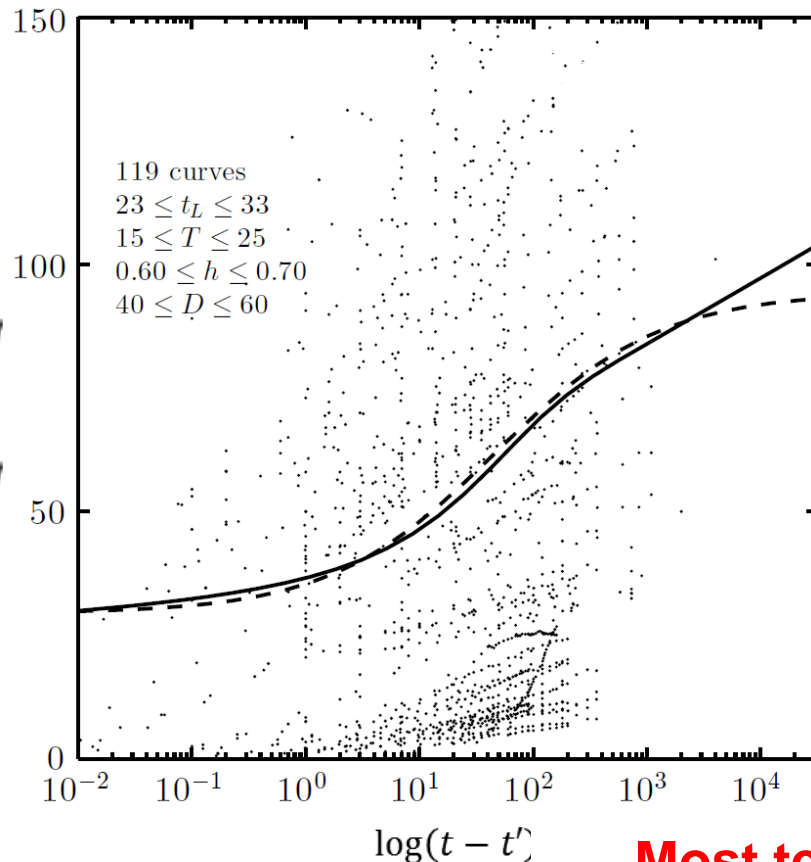
Data uncertainty – measurement accuracy



Data uncertainty – digitization accuracy



Inherent intrinsic scatter
 >>>
 variability in the functional form



Most tests too short!

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