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Advances in Robustness Assessment of Multi-storey Buildings

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Overview

Introduction

Robustness limit state for sudden column loss

Multi-level robustness assessment framework

- Nonlinear static response
- Simplified dynamic assessment
- Ductility limit

Significance of modelling assumptions

- Realistic modelling of composite floor
- Contribution of infill panels
- Influence of steel rate-sensitivity

Conclusions

Introduction

Disproportionate collapse

WTC (2001)

Disproportionate: No

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Introduction

Disproportionate collapse

Ronan Point (1968)

Disproportionate: Yes

Introduction

Disproportionate collapse

- Structures cannot be designed to withstand unpredictable extreme events
- But they should be designed for structural robustness:

  the ability of the structure to withstand the action of extreme events without being damaged to an extent disproportionate to the original cause

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Introduction

Disproportionate collapse

Setúbal, Portugal (2007)

Robust structure

Introduction

Robustness design

Prescriptive approach after Ronan Point (1968)

- Tying provisions irrational with neglect of ductility, and largely inadequate even if beneficial
- Not permitted for Class 3 (high-rise) buildings

Need for a performance-based design approach

- Large deformations under rare extreme events
- Design envelope stretched beyond strength limit to ductility limit
- Quantification of safety margin

Emergence of robustness assessment for sudden column loss

- USA codes: GSA (2003), UFC 4-023-03 (2009)
- Multi-level framework developed at Imperial College

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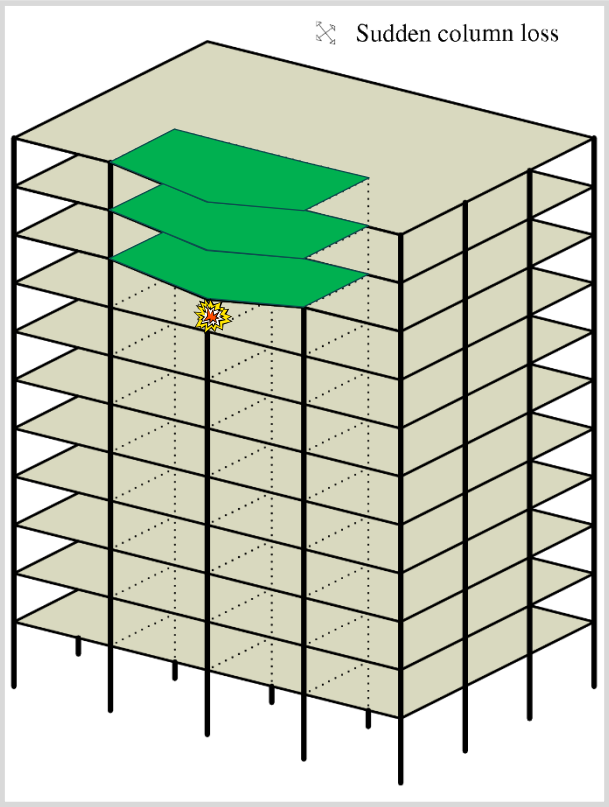
Robustness limit state for sudden column loss

Sudden column loss (SCL)

- Event-independent scenario

Robustness limit state

- Prevention of upper floor collapse
- Allow large deformations
- Within ductility limit



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Robustness limit state for sudden column loss

Sudden column loss (SCL)

- Event-independent scenario

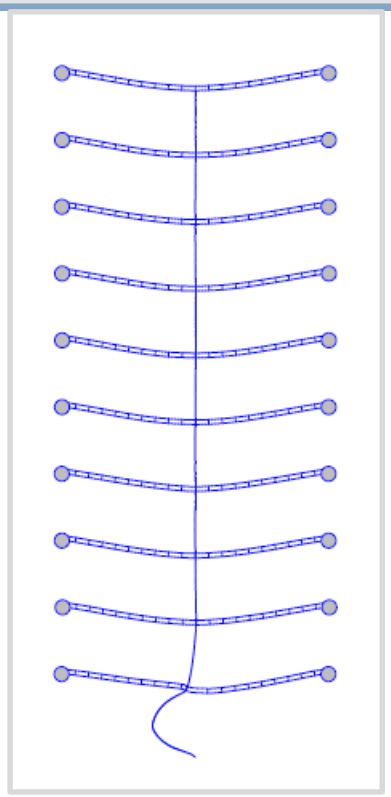
Robustness limit state

- Prevention of upper floor collapse
- Allow large deformations
- Within ductility limit

More than just a standard test of robustness

- SCL vs column damage by blast
- Comparison of deformation demands in upper floors
- SCL presents an upper bound on floor deformations

SCL can be assessed without full nonlinear dynamic analysis



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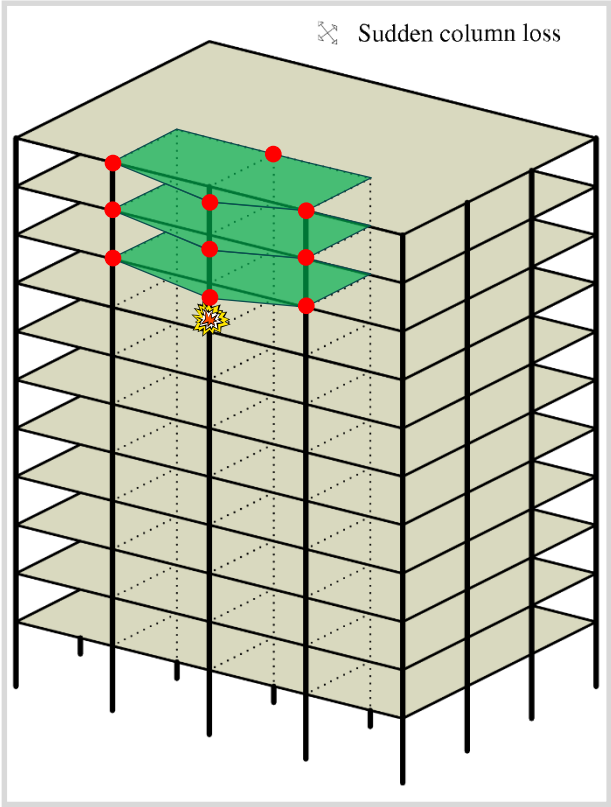
Multi-level robustness assessment framework

Robustness limit state

- Prevention of collapse of upper floors
- Ductility: demand ≤ supply

Two stages of assessment

- Nonlinear static response accounting for ductility limit
- Simplified dynamic assessment



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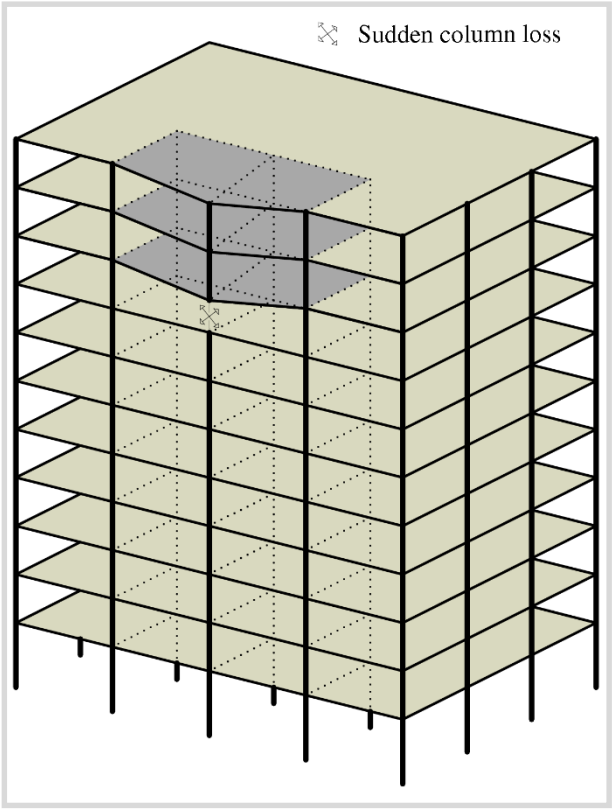
Multi-level robustness assessment framework

Maximum gravity load sustained under sudden column loss

Applicable at various levels of structural idealisation



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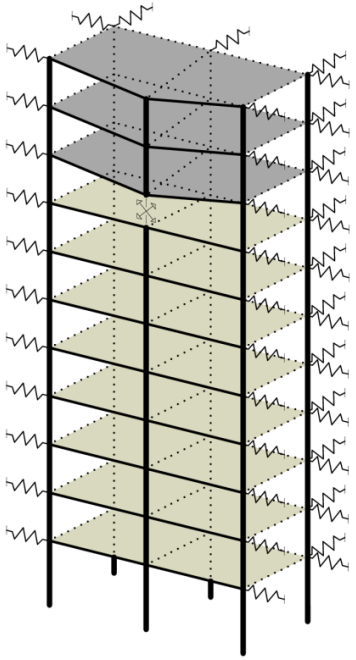
Multi-level robustness assessment framework

Maximum gravity load sustained under sudden column loss

Applicable at various levels of structural idealisation

Reduced model where deformation is concentrated



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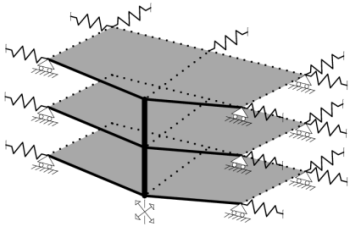
Multi-level robustness assessment framework

Maximum gravity load sustained under sudden column loss

Applicable at various levels of structural idealisation

Columns can resist re-distributed load



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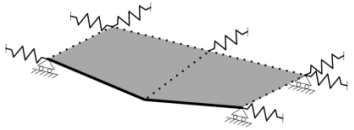
Multi-level robustness assessment framework

Maximum gravity load sustained under sudden column loss

Applicable at various levels of structural idealisation

Floors identical in components and loading



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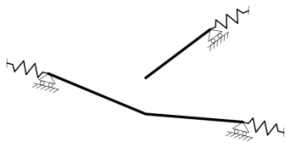
Multi-level robustness assessment framework

Maximum gravity load sustained under sudden column loss

Applicable at various levels of structural idealisation

Planar effects are neglected



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Multi-level robustness assessment framework

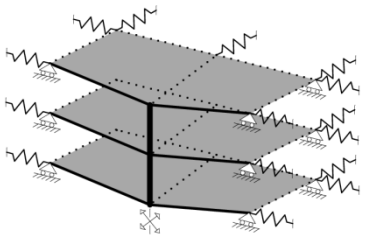
Maximum gravity load sustained under sudden column loss

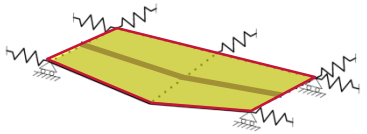
Applicable at various levels of structural idealisation

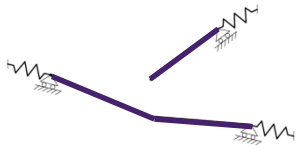
Simplified assembly of lower into higher level response

For specific level of idealisation require

- Nonlinear static response
- Simplified dynamic assessment
- Ductility limit







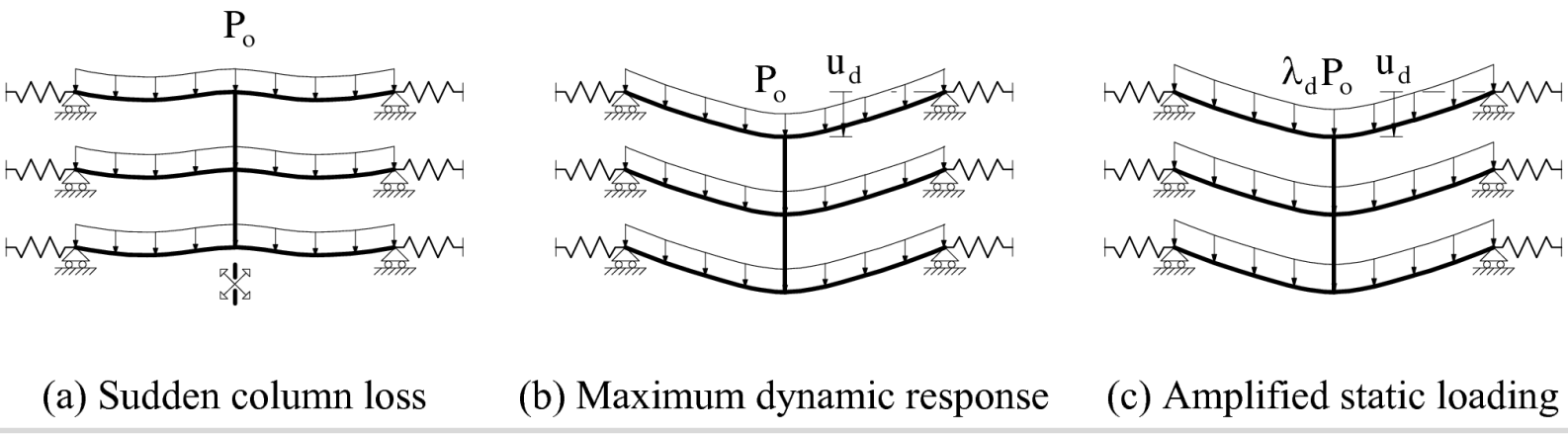
Multi-level robustness assessment framework

Nonlinear static response

Sudden column loss similar to sudden application of gravity load to structure without column

- Maximum dynamic response can be approximated using amplified static loading (λ_d P)

DIF



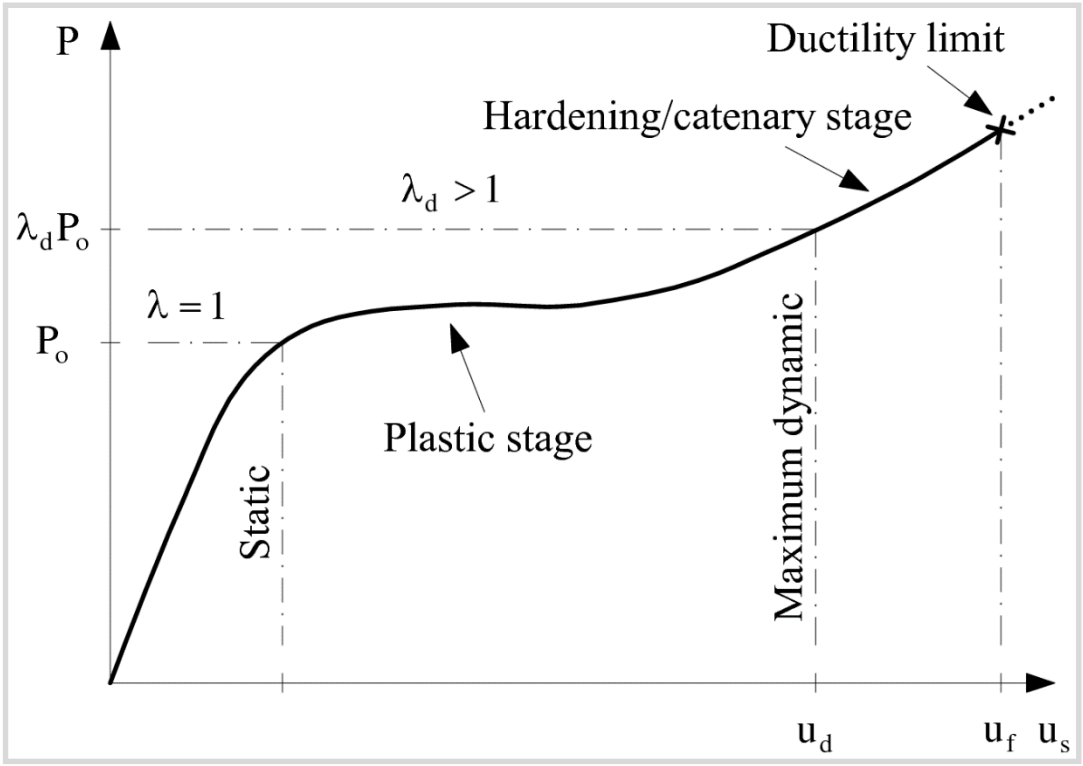
(a) Sudden column loss (b) Maximum dynamic response (c) Amplified static loading

Multi-level robustness assessment framework

Nonlinear static response

Sudden column loss similar to sudden application of gravity load to structure without column

- Maximum dynamic response can be approximated using amplified static loading (λ_d P)

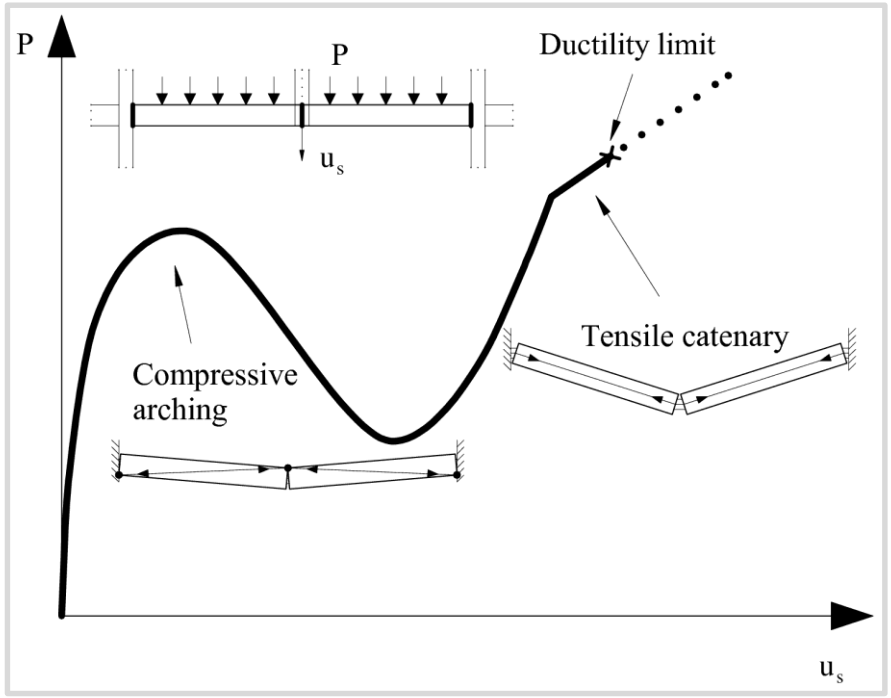


Multi-level robustness assessment framework

Nonlinear static response

Sudden column loss similar to sudden application of gravity load to structure without column

- Maximum dynamic response can be approximated using amplified static loading (λ_d P)
- Need models beyond conventional strength limit, including hardening, tensile catenary and compressive arching actions



Multi-level robustness assessment framework

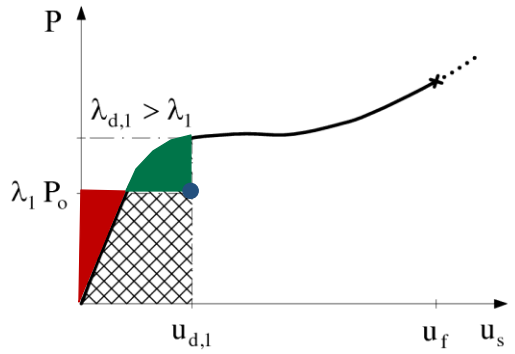
Simplified dynamic assessment

Based on conservation of energy

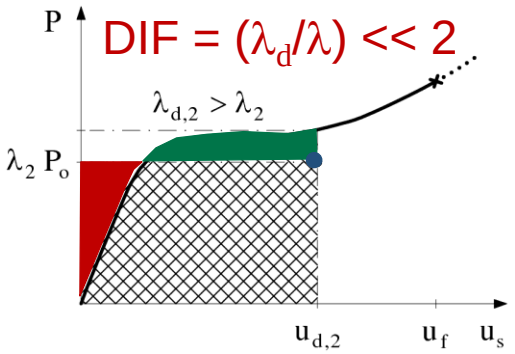
Work done by suddenly applied load equal to internal energy stored

Leads to maximum dynamic displacement (also to DIF)

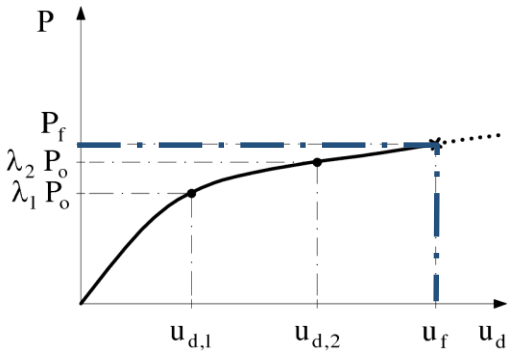
Definition of “pseudo-static” response



(a) Dynamic response ($P = \lambda_1 P_o$)



(b) Dynamic response ($P = \lambda_2 P_o$)



(c) Pseudo-static response

Multi-level robustness assessment framework

Ductility limit

Typically based on based on failure of connection components

- Rotational and axial deformations

Ductility limit based on first component failure is conservative

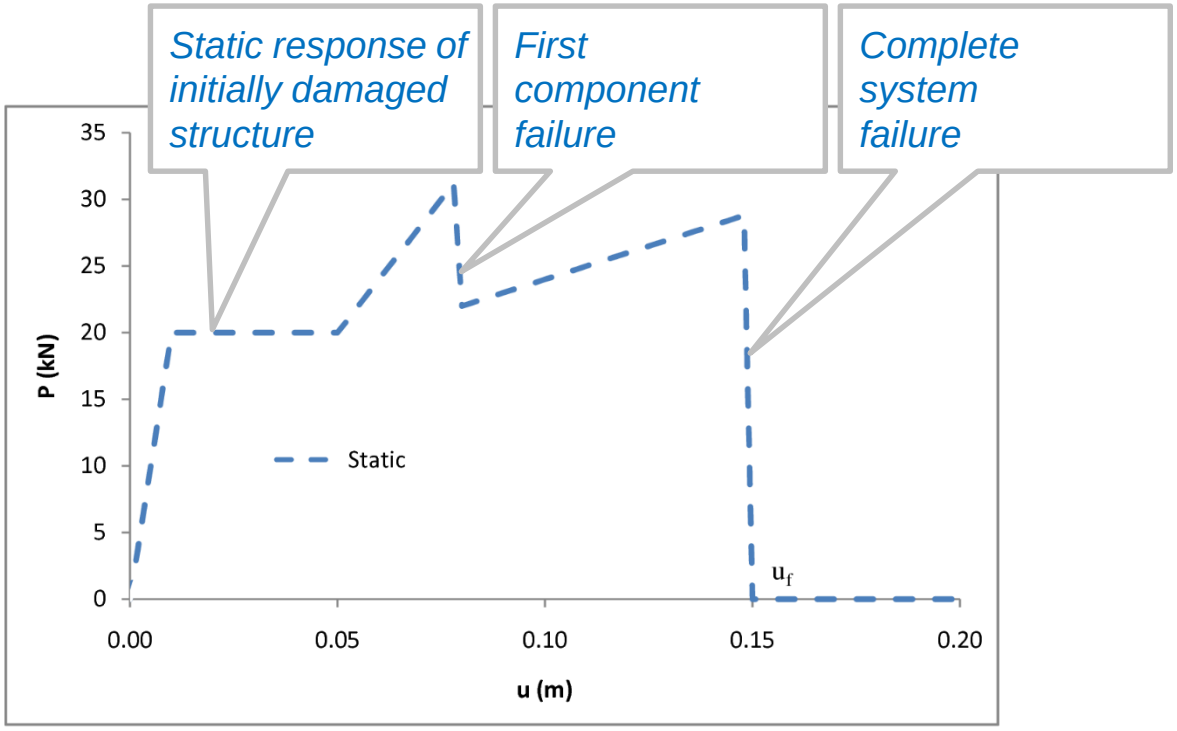
Successive component failures can be easily considered

- Dominant deformation mode
- No need to define ductility limit in terms of a specific drop in static resistance

Multi-level robustness assessment framework

Ductility limit

Flooring system subject to initial sudden column loss followed by a first component failure, then full system failure



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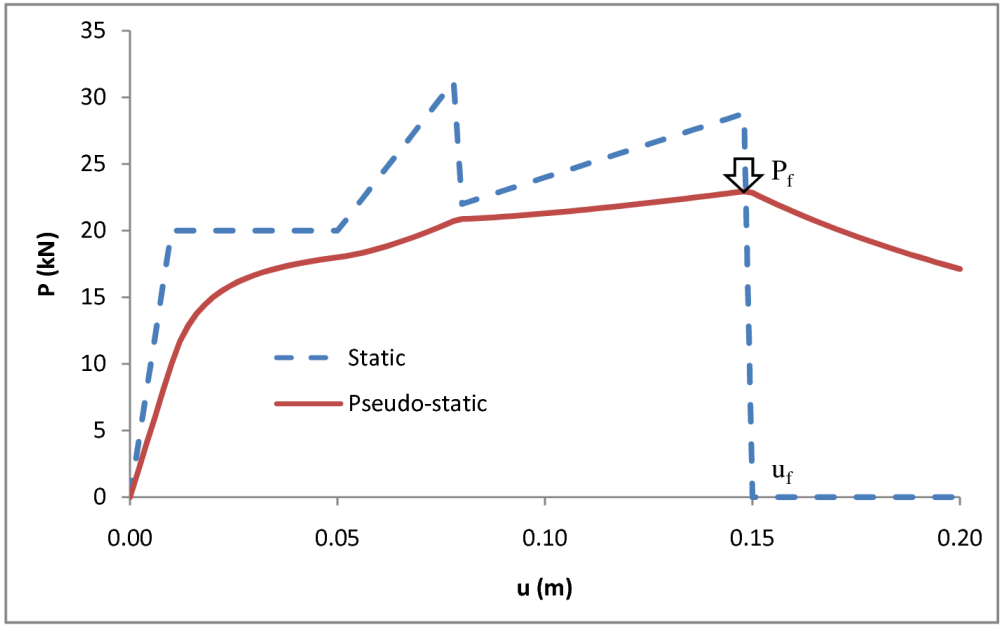
Multi-level robustness assessment framework

Ductility limit

Residual pseudo-static capacity after first component failure



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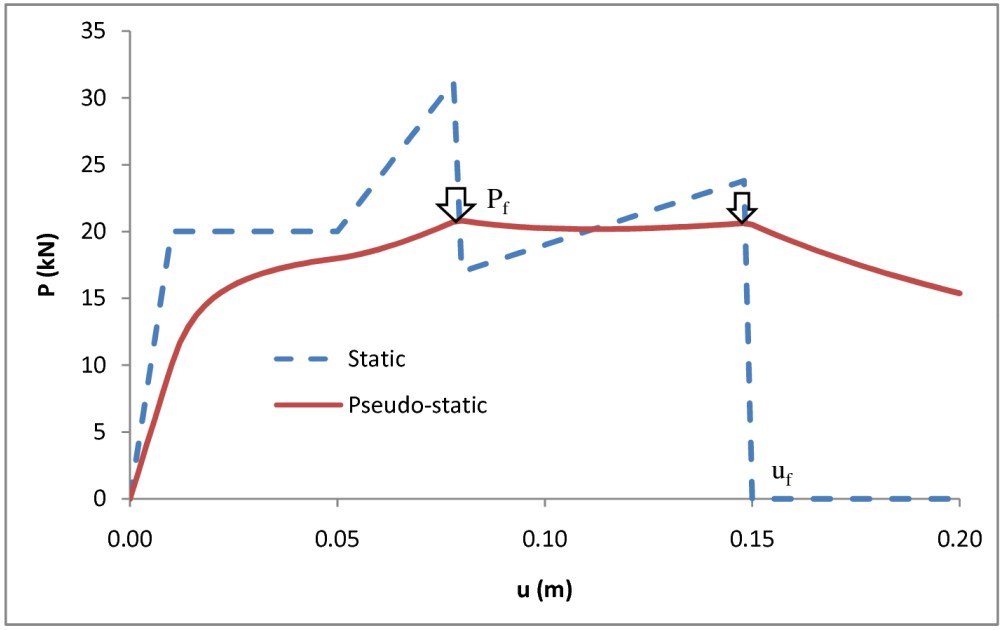
Multi-level robustness assessment framework

Ductility limit

…but not with more severe first component failure



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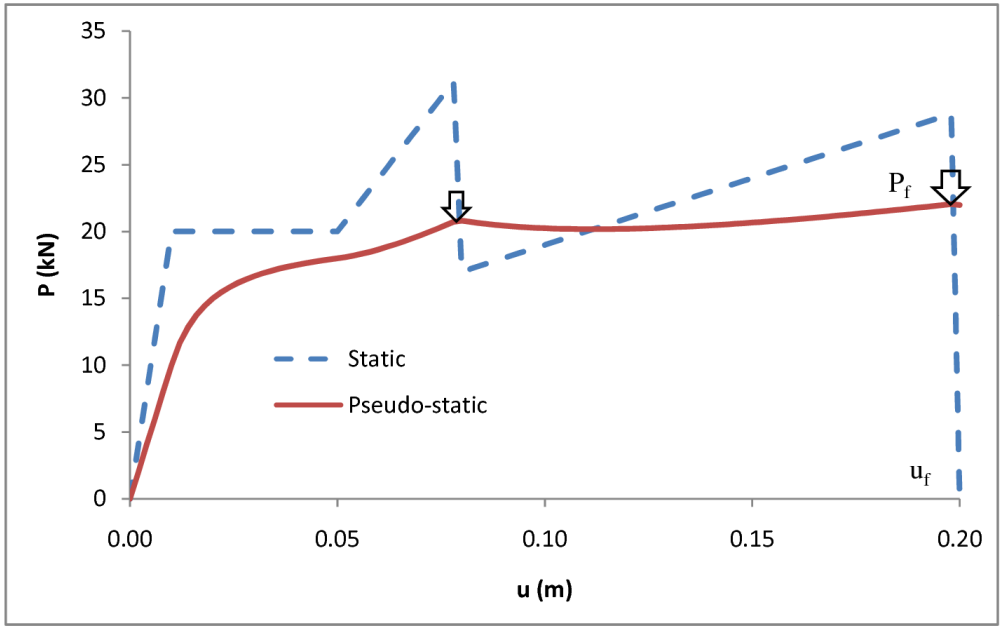
Multi-level robustness assessment framework

Ductility limit

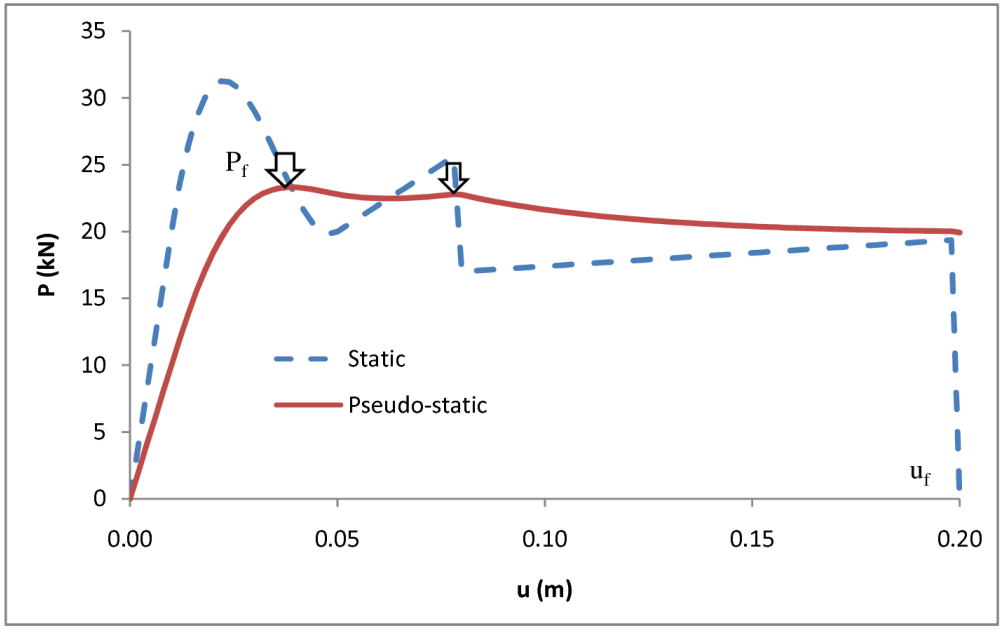
…unless system ductility and static resistance picks up



Multi-level robustness assessment framework

Ductility limit

Maximum pseudo-static capacity may not even be related to a specific ductility limit



Multi-level robustness assessment framework

Ductility limit

UFC code allows nonlinear static analysis, with DIF defined in terms of ductility limit

$$DIF = 1.04 + \frac{0.45}{m + 0.48}$$ (Marchand et al. [2008]: Concrete Structures)

$$DIF = 1.08 + \frac{0.76}{m + 0.83}$$ (Marchand et al. [2008]: Steel Structures)

$$DIF = 1.44\, m^{-0.12}$$ (Stevens et al. [2008]: Steel Structures)

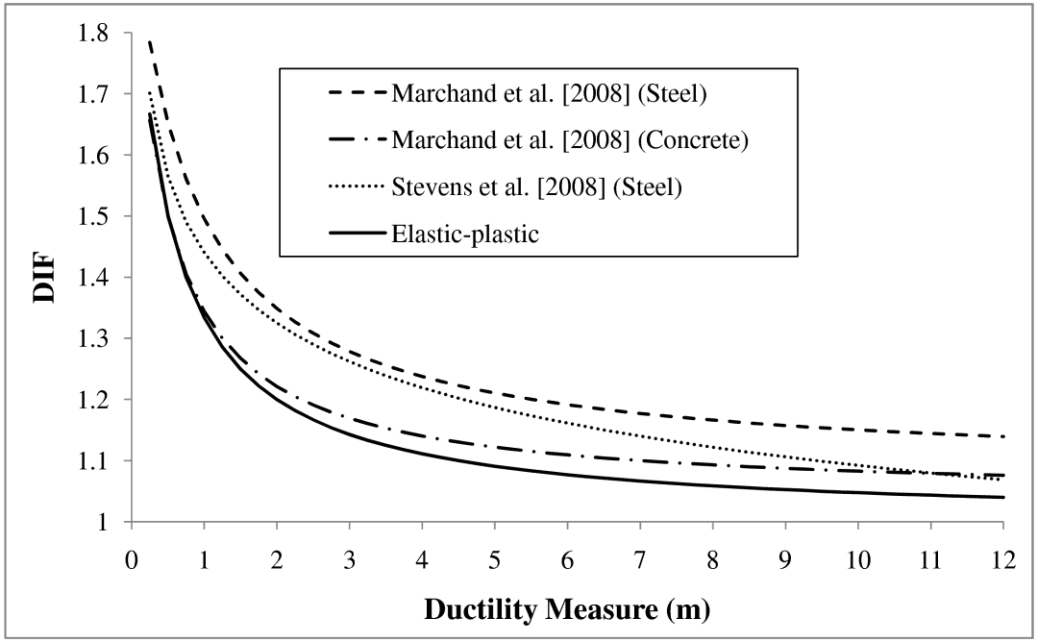
$$m = \frac{\text{plastic deformation}}{\text{yield deformation}} = \frac{u_f}{u_y} - 1$$

Multi-level robustness assessment framework

Ductility limit

UFC code allows nonlinear static analysis, with DIF defined in terms of ductility limit

- Consistent with elastic-plastic response



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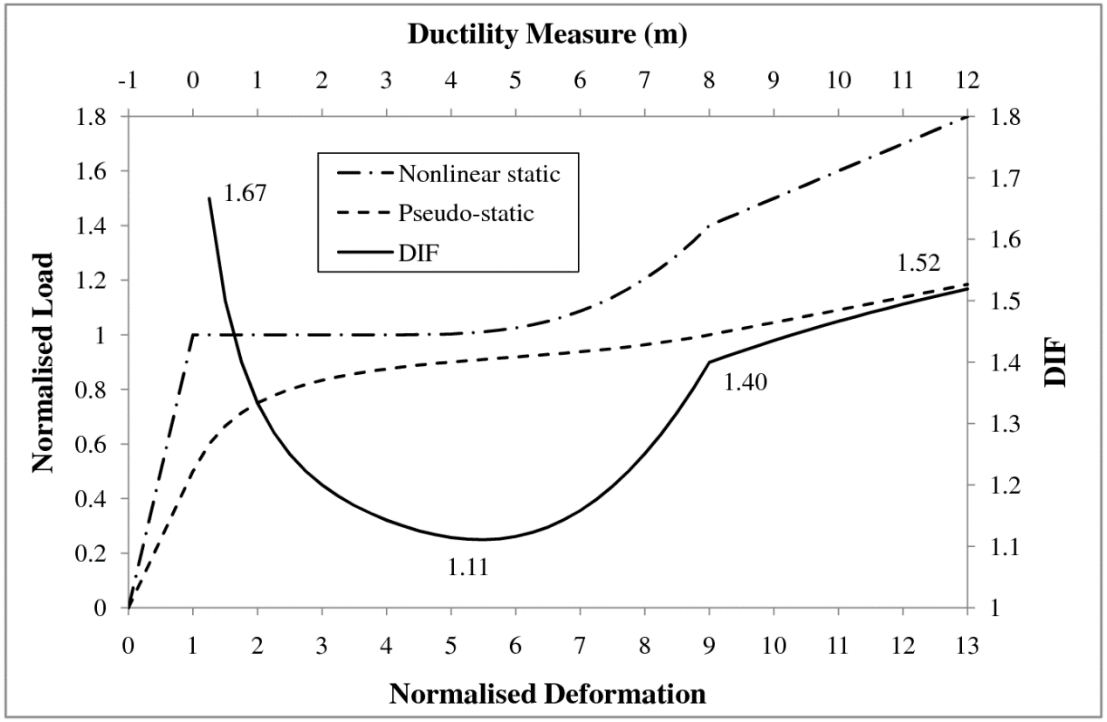
Multi-level robustness assessment framework

Ductility limit

UFC code allows nonlinear static analysis, with DIF defined in terms of ductility limit

- Consistent with elastic-plastic response
- Can be grossly incorrect and unsafe with catenary or compressive arching action



Multi-level robustness assessment framework

Ductility limit

UFC code allows nonlinear static analysis, with DIF defined in terms of ductility limit

- Consistent with elastic-plastic response
- Can be grossly incorrect and unsafe with catenary or compressive arching action

Pseudo-static energy balance approach

- Rational application with nonlinear static analysis
- Avoids demanding nonlinear dynamic analysis
- ‘Pseudo-static capacity’ as a rational performance-based measure of structural robustness
- Combines redundancy, ductility and energy absorption within a simplified framework

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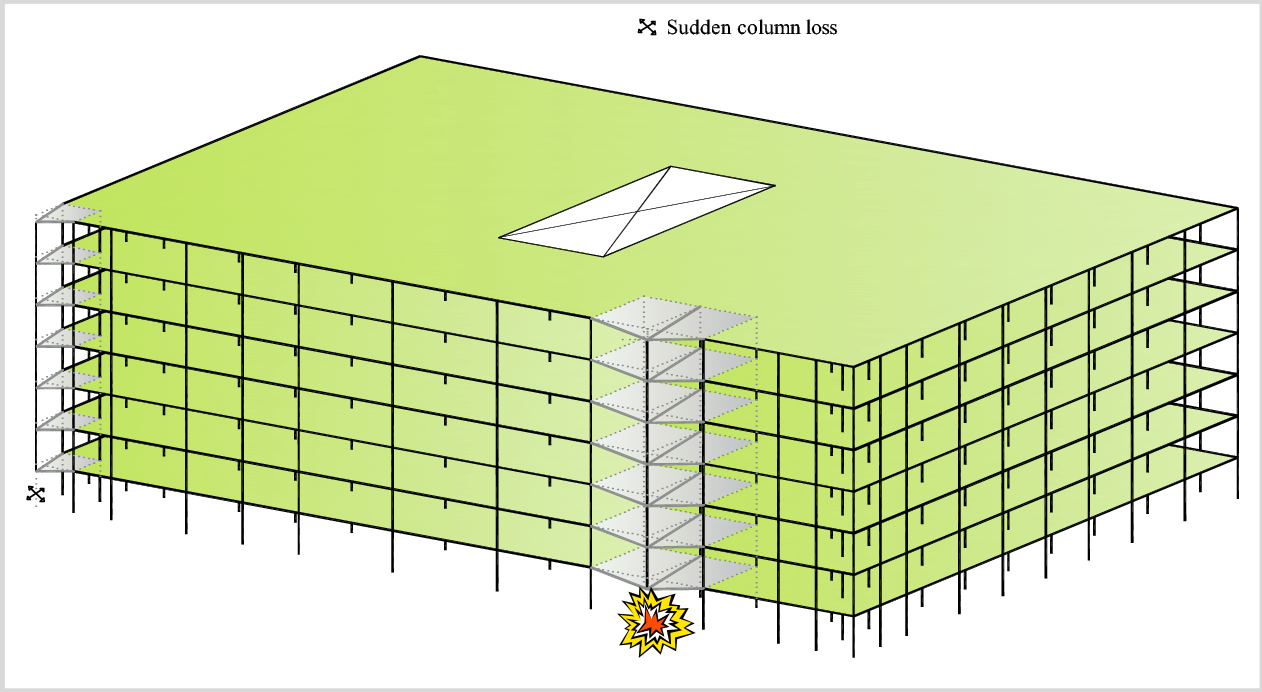
Significance of modelling assumption

7-storey steel framed composite building with simple frame design



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Significance of modelling assumption

Pseudo-static response of individual beams

Simplified assembly to obtain pseudo-static capacity of floor slab

Importance of connection ductility, additional reinforcement and axial restraint

Inadequacy of prescriptive tying force requirements

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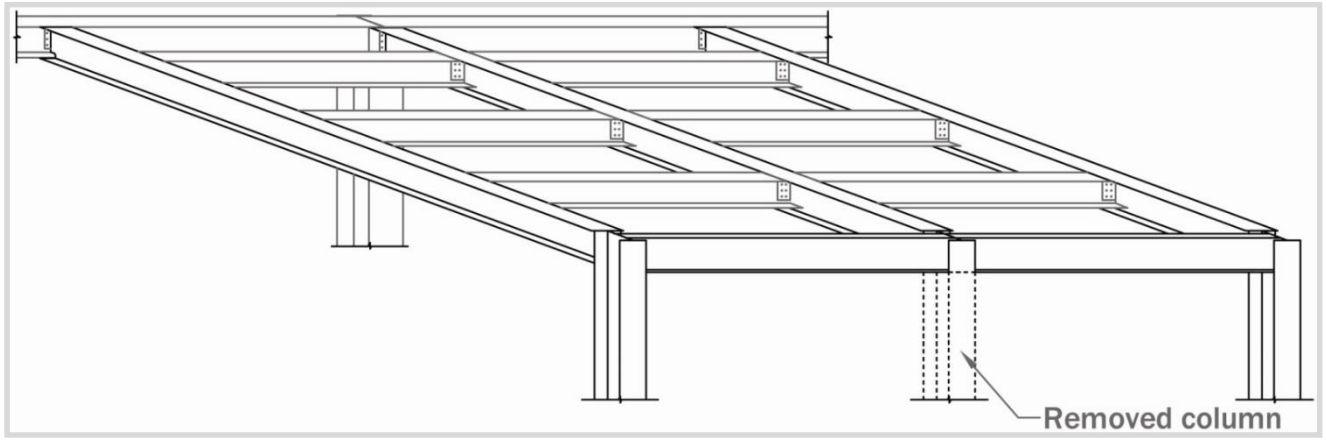
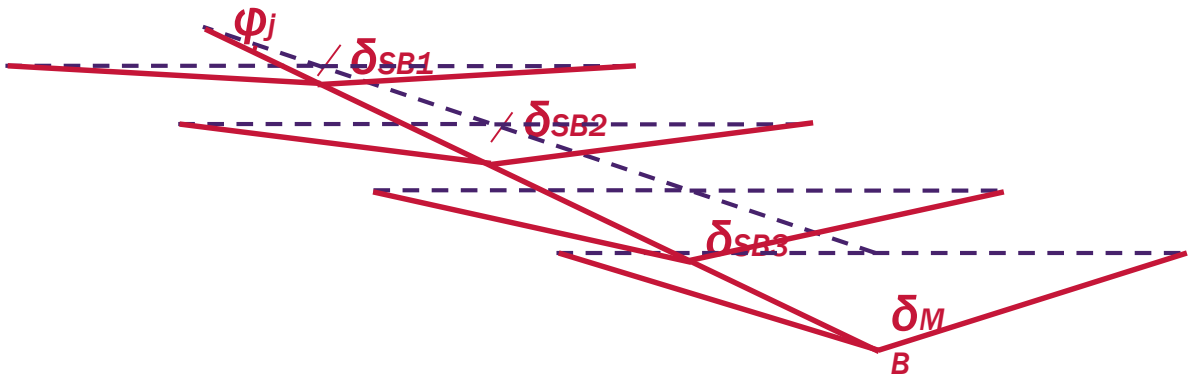
Significance of modelling assumption

- Assumed deformation mode defines ductility limit





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Significance of modelling assumption

- Assumed deformation mode defines ductility limit

Case No.	Deformation profile				
	$\varphi_{d,TB}$ (rad)	$u_{d,IB1}$ (mm)	$u_{d,IB2}$ (mm)	$u_{d,IB3}$ (mm)	$u_{d,EB}$ (mm)
1	0.0364	54.6	163.7	272.9	359.3
2	0.0381	57.2	171.6	286.0	376.5
3	0.0359	53.8	161.3	268.9	354.0
4	0.0623	93.5	280.5	467.6	615.6

ρ_{min}, EC4, w/ axial restraint

ρ = 2%, w/ axial restraint

ρ = 2%, w/o axial restraint

Bare-steel frame, w/ axial restraint

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Significance of modelling assumption

- Assumed deformation mode defines ductility limit
- Case 2 (ρ=2% with axial restraint) is just about adequate
- Inadequacy of prescriptive tying force requirements

Case No.	Capacity P (N)	Demand P_o (N)	Capacity/Demand ratio
1	598729	741990	0.81
2	774358	741990	1.04
3	709675	741990	0.96
4	148530	741990	0.20

ρ_{min}, EC4, w/ axial restraint

ρ = 2%, w/ axial restraint

ρ = 2%, w/o axial restraint

Bare-steel frame, w/ axial restraint

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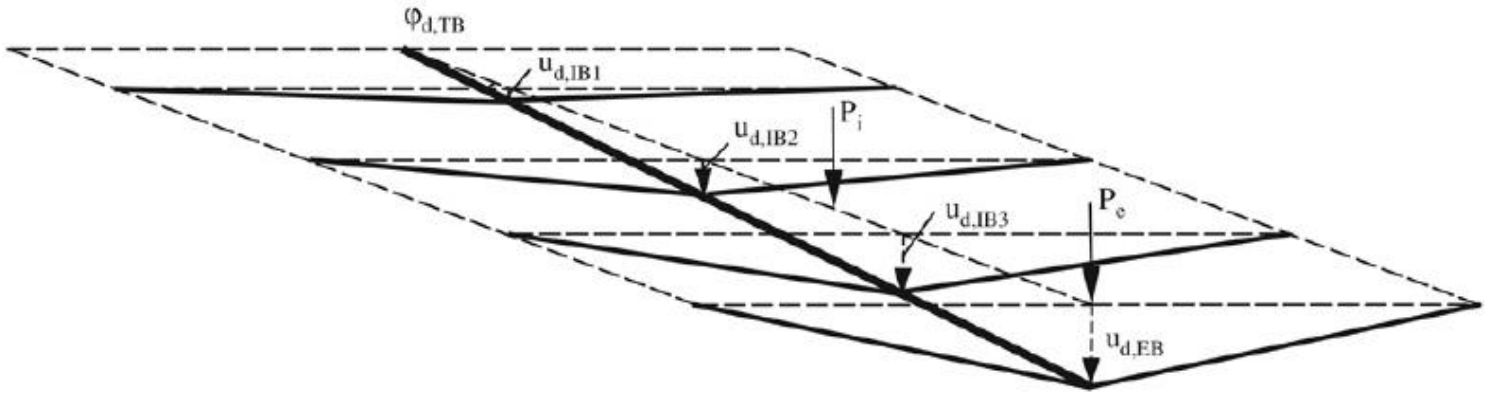
Significance of modelling assumption

Realistic modelling of composite floor

Model	Pseudo-Static Capacity (kN)	Maximum Deflection (mm)	Capacity/Demand Ratio
Simplified Grillage(*)	846	392.3	1.135
Detailed Grillage	1057	359.5	1.420
Composite Floor	1166	356.9	1.564



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Significance of modelling assumption

Realistic modelling of composite floor

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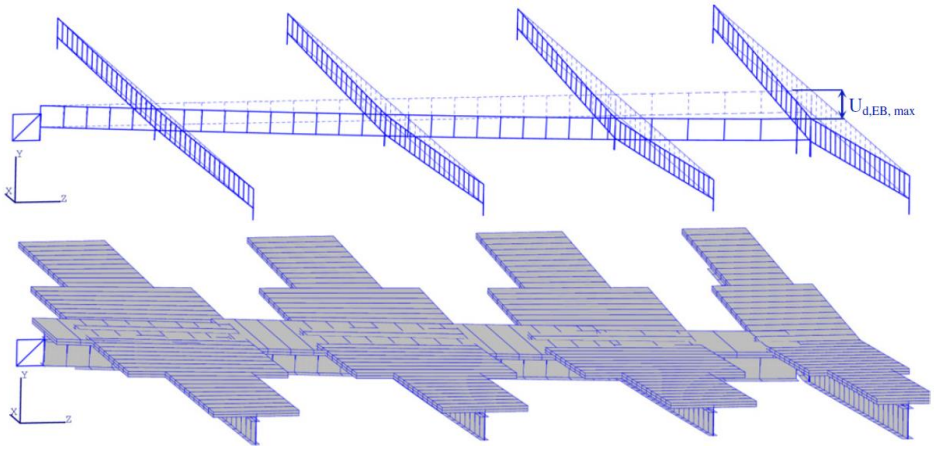
Simplified Grillage(*)	846	392.3	1.135
Detailed Grillage	1057	359.5	1.420
Composite Floor	1166	356.9	1.564

+25%



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Significance of modelling assumption

Realistic modelling of composite floor

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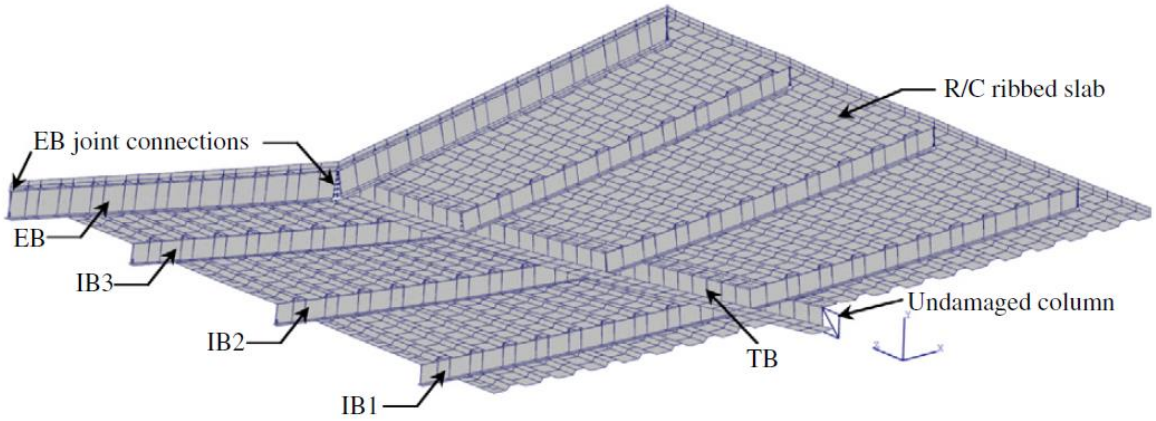
Simplified Grillage(*)	846	392.3	1.135
Detailed Grillage	1057	359.5	1.420
Composite Floor	1166	356.9	1.564

+38%



Significance of modelling assumption

Contribution of infill panels

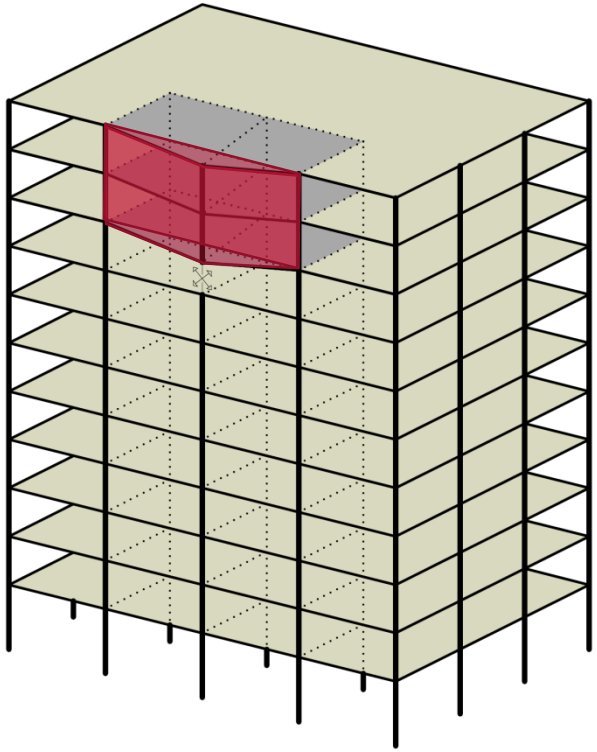
Pseudo-static response of individual infill panels

- May be assembled at different levels of structural idealisation

May be considered at single floor level, subject to regularity, but should be scaled

$$R_{panel/\,floor} = \frac{(n-1)\,R_{panel}}{n}$$

Number of floors above removed column

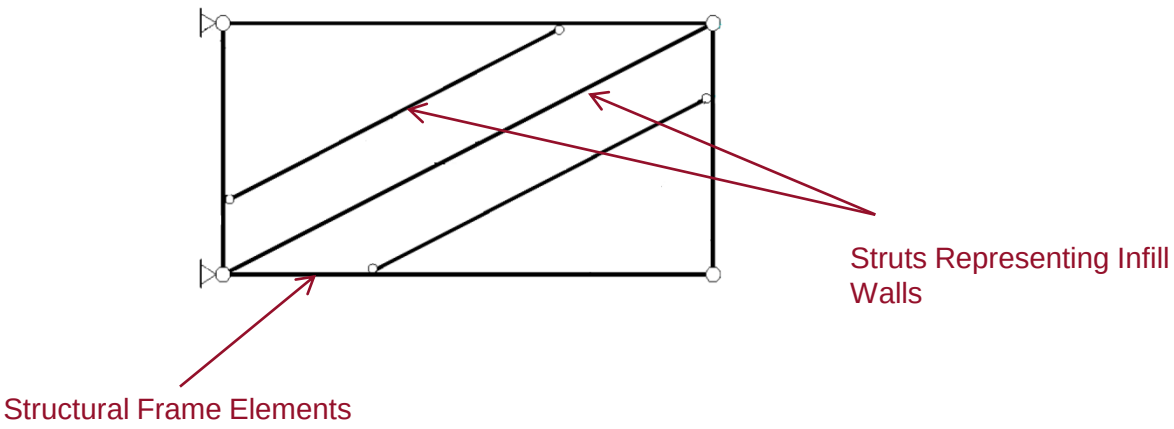


Significance of modelling assumption

Contribution of infill panels

Modelling of infill panels

- Simplified strut models



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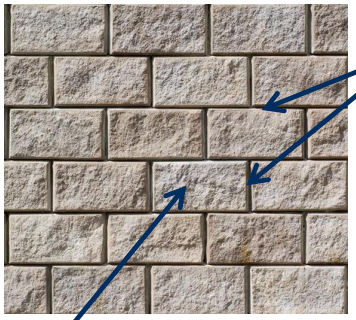
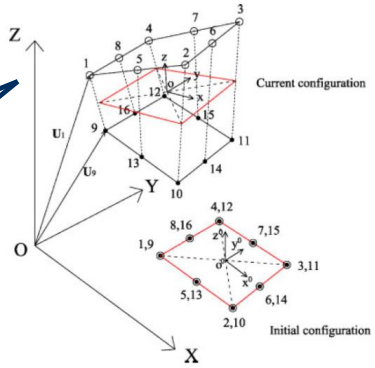
Significance of modelling assumption

Contribution of infill panels

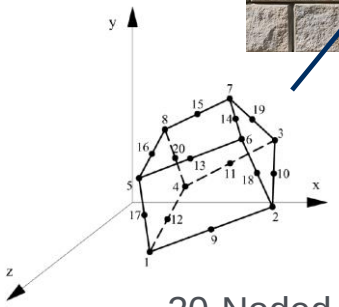
Modelling of infill panels

- Simplified strut models
- Advanced mesoscale NLFE models





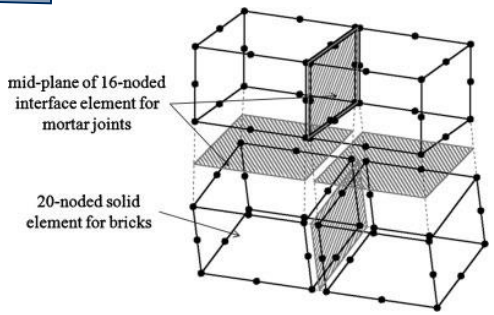
16-Noded Interface FE



20-Noded Solid FE

Structural Frame Elements

Full 3D Model

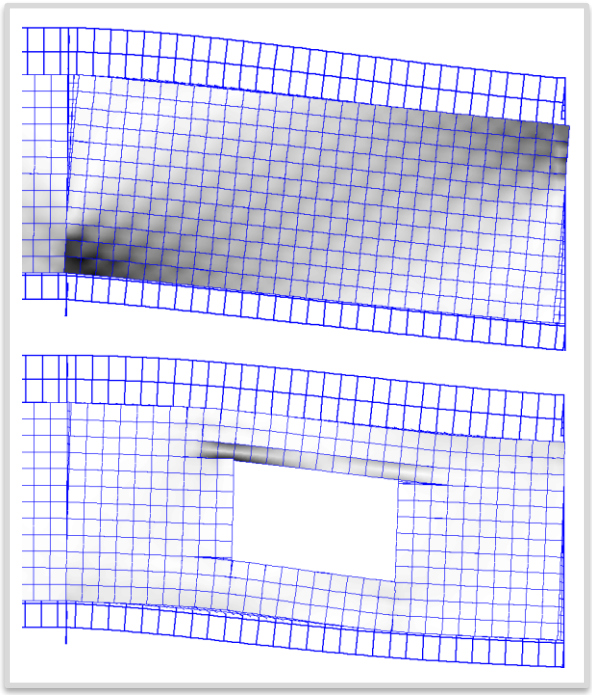


Significance of modelling assumption

Contribution of infill panels

Modelling of infill panels

- Simplified strut models
- Advanced mesoscale NLFE models



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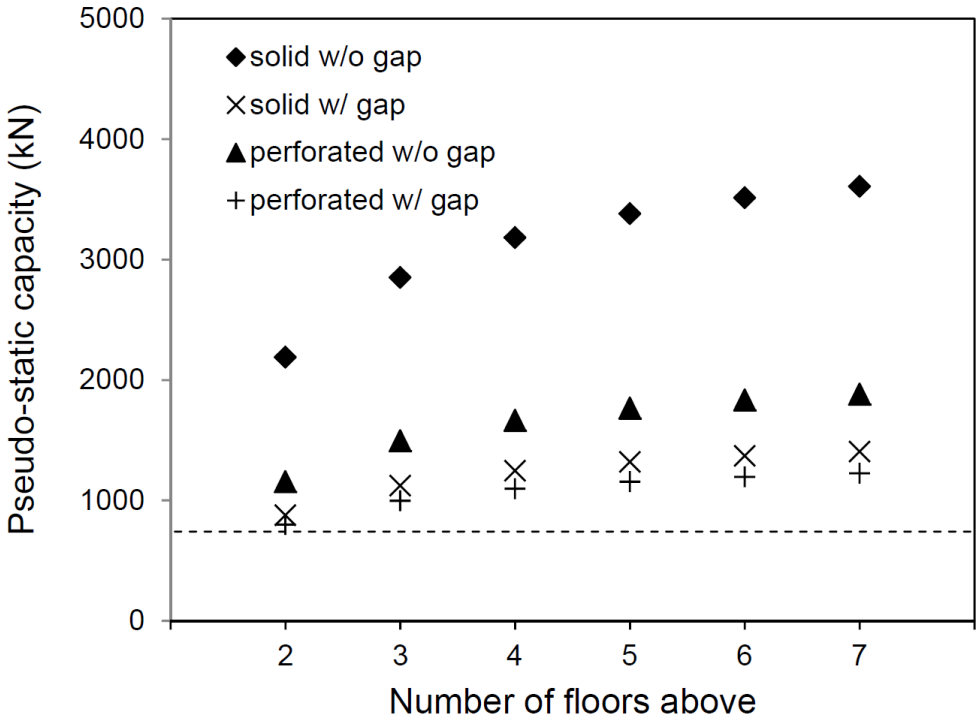
Significance of modelling assumption

Contribution of infill panels

Significant enhancement of pseudo-static capacity, particularly for lower column loss

- For solid/perforated panels, with/without gaps

Pseudo-static capacity achieved at relatively small displacements of 10-15mm



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Significance of modelling assumption

Influence of steel rate-sensitivity

Instantaneous column loss

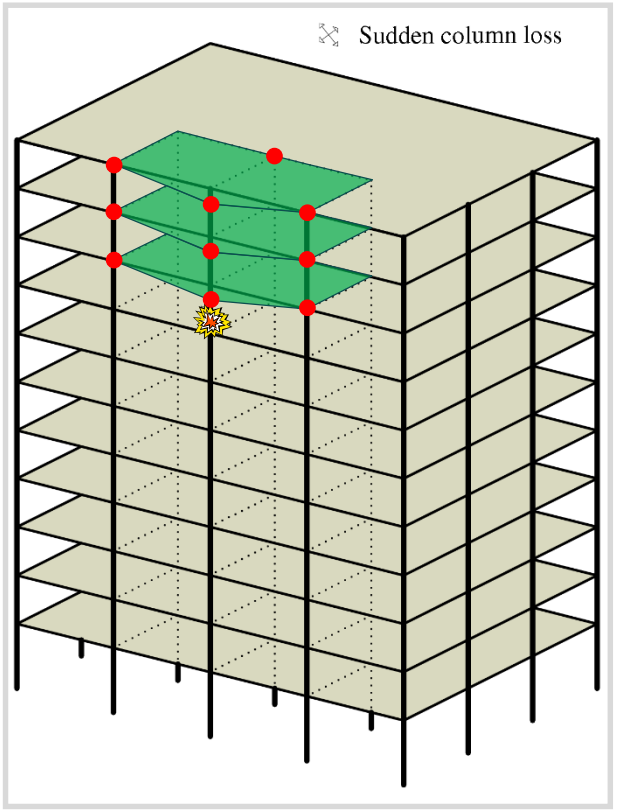
Subsequent dynamic floor deformation

- Typical duration of ~0.5s from rest to maximum displacement
- Strain-rate ~0.3s^{-1} in critical steel components

Potential increase in dynamic yield strength between 10-50%

$$\Delta\sigma(\dot{\varepsilon}_p) = \sigma_y \left(\frac{\dot{\varepsilon}_p}{D} \right)^{\frac{1}{q}}$$

Material	Source	q	D	$\Delta\sigma_{\dot{\varepsilon}=0.3/s}$
Mild steel	Cowper & Symonds (1957)	5	40.4	0.38 σ_y
	Abramowicz & Jones (1986)	3.585	802	0.11 σ_y
	Schneider & Jones (2004)	4.67	7.39	0.50 σ_y
	Hsu & Jones (2004)	5.56	114	0.34 σ_y
	Marais *et al.* (2004)	3	844	0.09 σ_y



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Significance of modelling assumption

Influence of steel rate-sensitivity

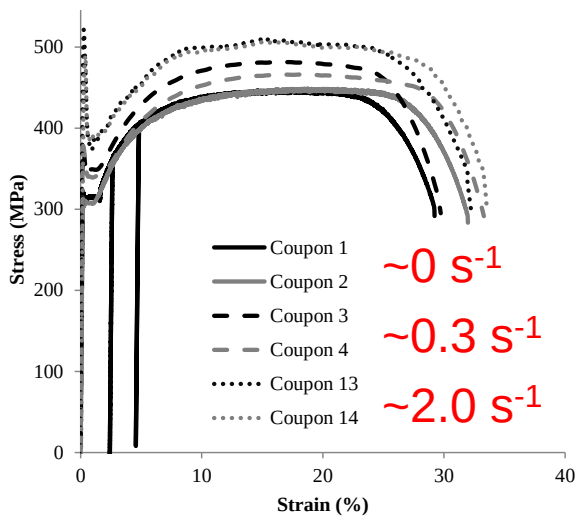
Collaborative experimental programme with University of Trento

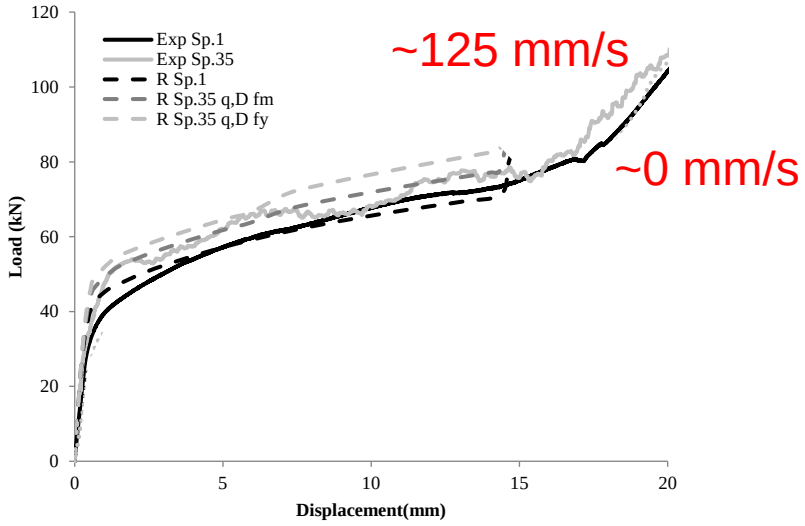
- Coupon and T-stub tests on mild steel specimens
- Deformation rates representative of robustness limit state

Enhancement of material yield and ultimate strength 6-15%

Enhancement of T-stub resistance 2-10%

Influence rate-sensitivity on overall pseudo-static capacity, hence robustness, is insignificant





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Conclusions

Simplified robustness assessment framework

- Multi-storey buildings subject to sudden column loss
- Multi-level framework utilising nonlinear static response
- Simplified dynamic assessment using energy balance
- Pseudo-static capacity as rational measure of robustness

Inadequacy of DIF approach in UFC 4-023-03

Significance of modelling assumptions

- Modelling composite slab with 2D shell elements can enhance pseudo-static capacity by ~40% compared to grillage models
- Masonry infill can enhance pseudo-static capacity by ~60%-500% depending on openings, gaps and number of floors above
- Steel rate-sensitivity has a negligible influence on robustness under sudden column loss

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