

**Imperial College  
London**

**Simplified Assessment  
of Structural Robustness  
for Sudden Component Failures**

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# Overview

- Introduction
- Sudden Column Loss
- Sudden Component Failure
- Successive Component Failures
- Conclusion

# Introduction

- Structural robustness (UK Building Regulations, Eurocode EN 1990)
  - *ability to withstand extreme events without being damaged to an extent disproportionate to the original cause*
- UK Building Regulations: A3 Disproportionate Collapse
  - Class 2B buildings (up to 15 storeys)
    - Prescriptive tying force requirements
    - Notional member removal
    - Key element design
  - Class 3 buildings (more than 15 storeys)
    - Systematic risk assessment

More performance based

However, conventional design checks (ignoring large deformations)

Ignores dynamic effects

Unrealistic designs and damage assessment

# Introduction

- Recent specialist USA codes
  - GSA (2003): Progressive Collapse Analysis and Design Guidelines for New Federal Office Buildings and Major Modernization Projects
  - DoD (2005): Unified Facilities Criteria, Design of Buildings to Resist Progressive Collapse
- Consider sudden column loss as a design scenario
  - Detailed nonlinear dynamic analysis
  - Simplified equivalent static approach

Excessive dynamic amplification factor equal to 2

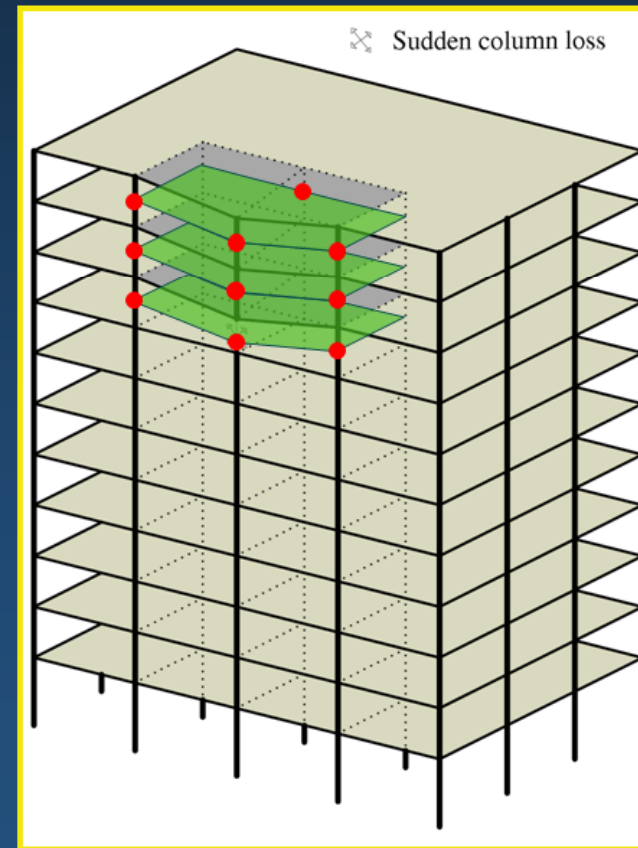
Conventional design checks

# Introduction

- Sudden column loss
  - Event-independent scenario presenting upper bound on deformation demands under blast loading
- Sudden component failures
  - Components contributing little to system deformations (e.g. welds, bolts)
    - Failing due to corrosion, fatigue, overload, poor design, etc.
  - Other components failing during dynamic response after local ductility limits are exceeded

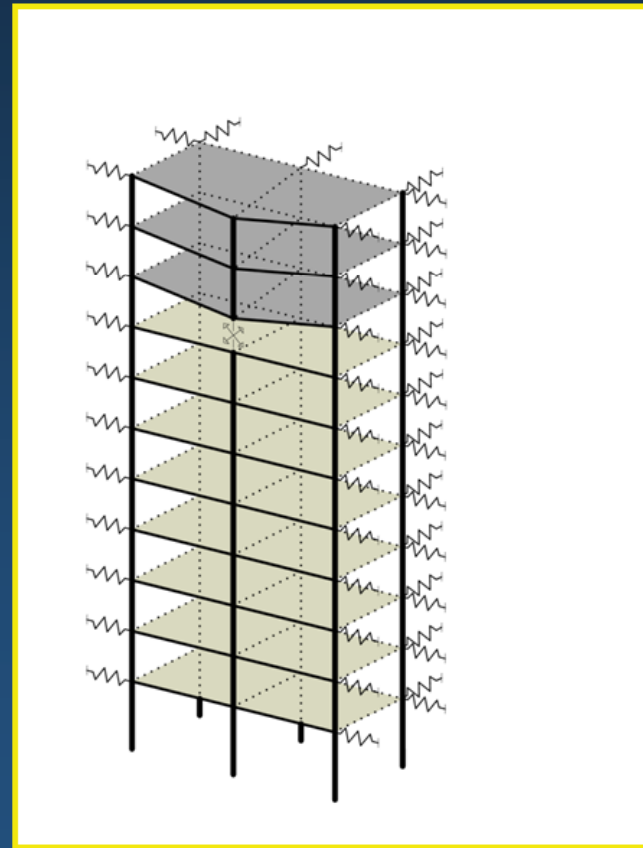
# Sudden Column Loss

- Limit state: dynamic failure of floors above
- Two stages of assessment
  - Nonlinear static response accounting for ductility limit
  - Simplified dynamic assessment



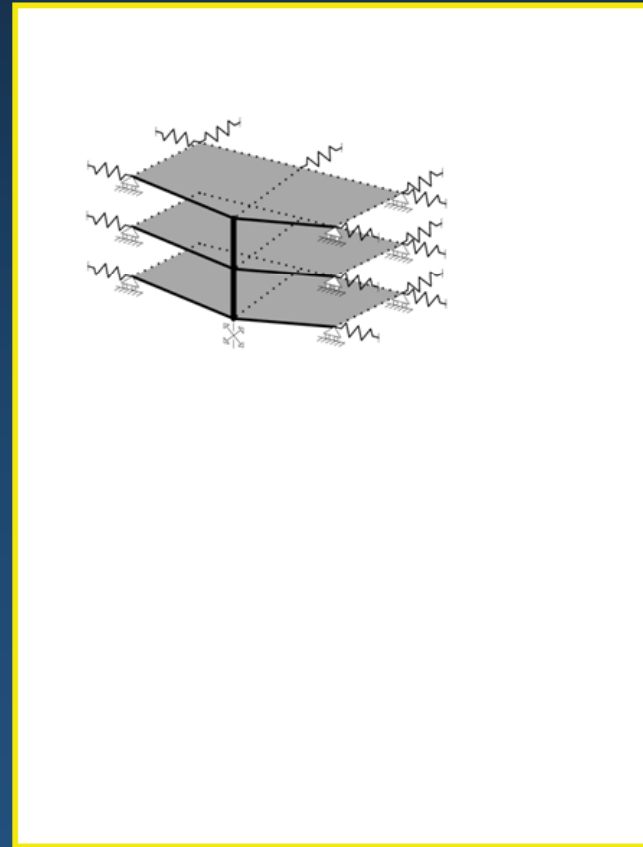
# Sudden Column Loss

- Maximum gravity load sustained under sudden column loss
- Applicable at various levels of structural idealisation
- Reduced model where deformation is concentrated



# Sudden Column Loss

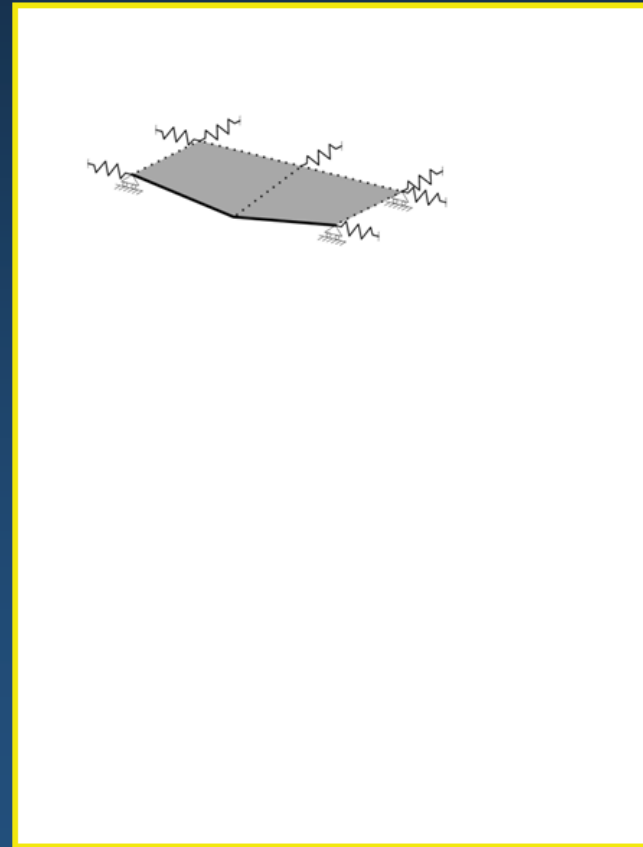
- Maximum gravity load sustained under sudden column loss
- Applicable at various levels of structural idealisation
- Columns can take re-distributed load





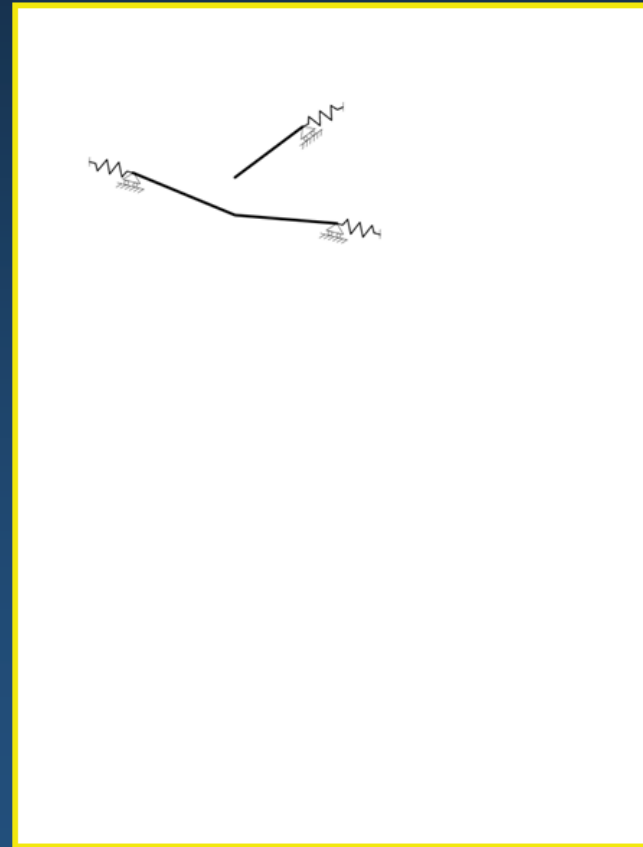
# Sudden Column Loss

- Maximum gravity load sustained under sudden column loss
- Applicable at various levels of structural idealisation
- Floors identical in components and loading



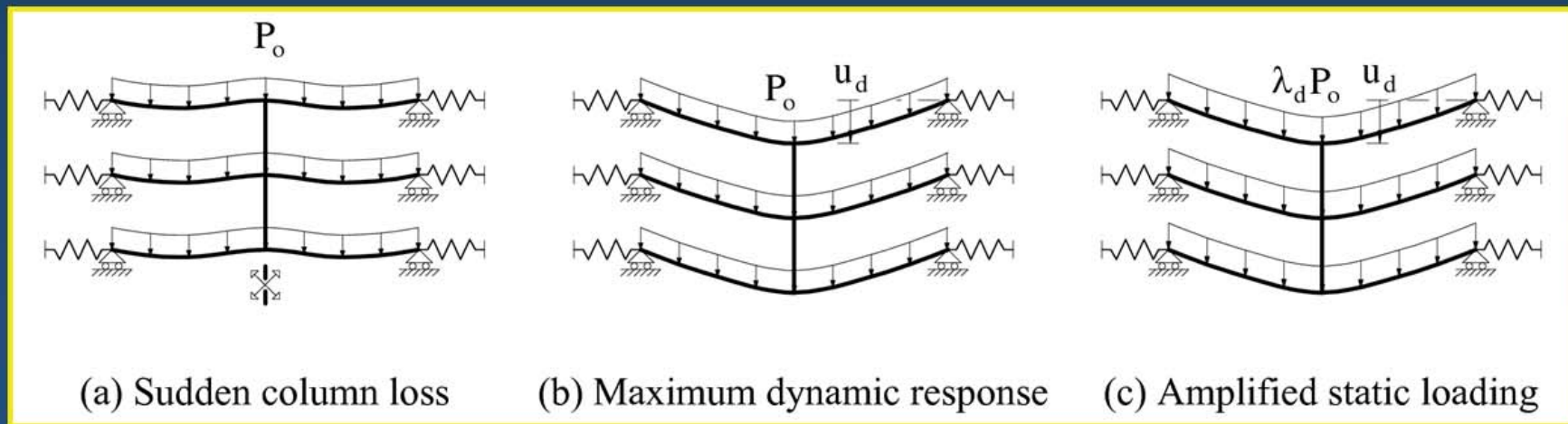
# Sudden Column Loss

- Maximum gravity load sustained under sudden column loss
- Applicable at various levels of structural idealisation
- Planar effects are neglected



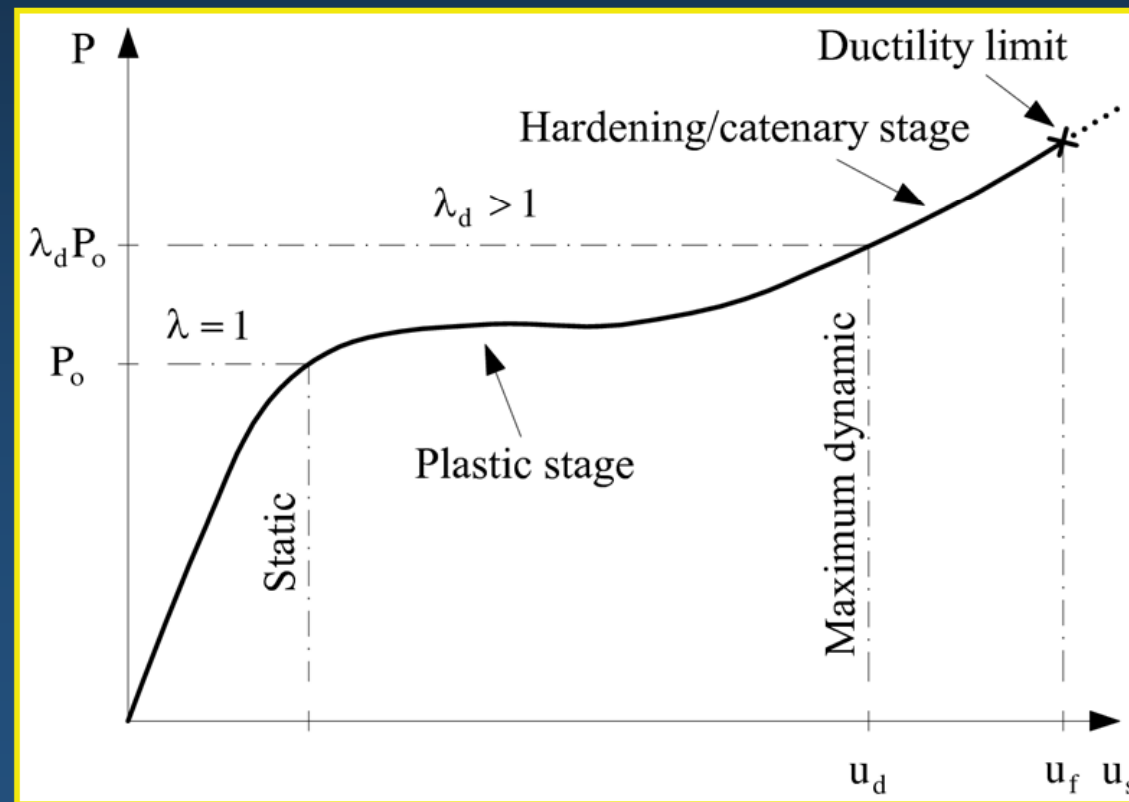
# Sudden Column Loss Nonlinear Static Response

- Sudden column removal similar to sudden application of gravity load
  - Maximum dynamic response can be approximated using amplified static loading ( $\lambda_d P$ )



# Sudden Column Loss Nonlinear Static Response

- Sudden column removal similar to sudden application of gravity load

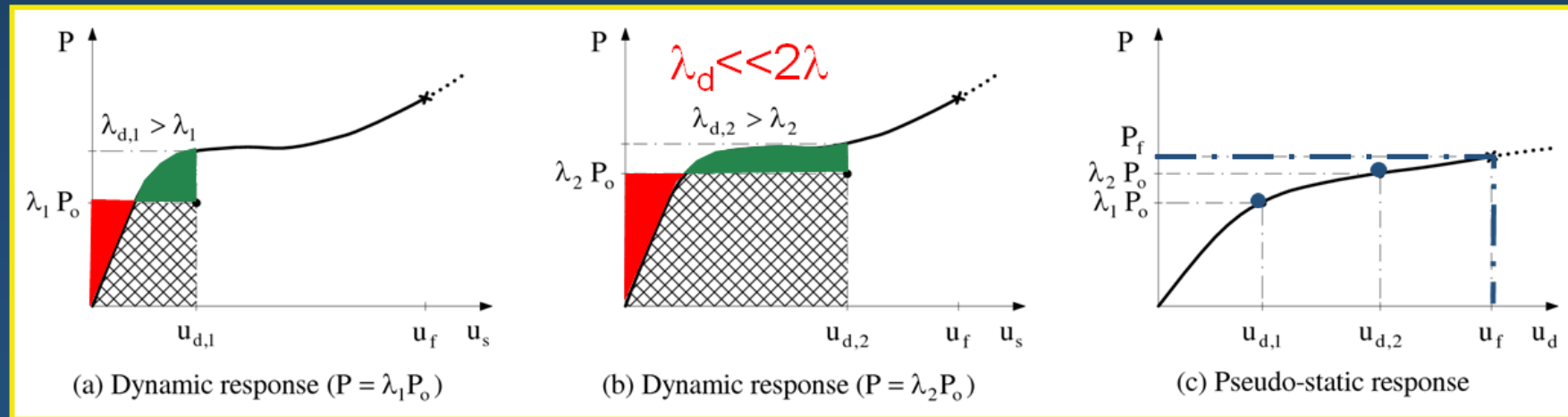


# Sudden Column Loss Simplified Dynamic Assessment

- Applicable at various levels of structural idealisation
  - Based on conservation of energy
  - Work done by suddenly applied load equal to internal energy stored
  - Leads to maximum dynamic displacement (also to load dynamic amplification)
  - Definition of “pseudo-static” response

# Sudden Column Loss Simplified Dynamic Assessment

- Applicable at various levels of structural idealisation
  - Based on conservation of energy



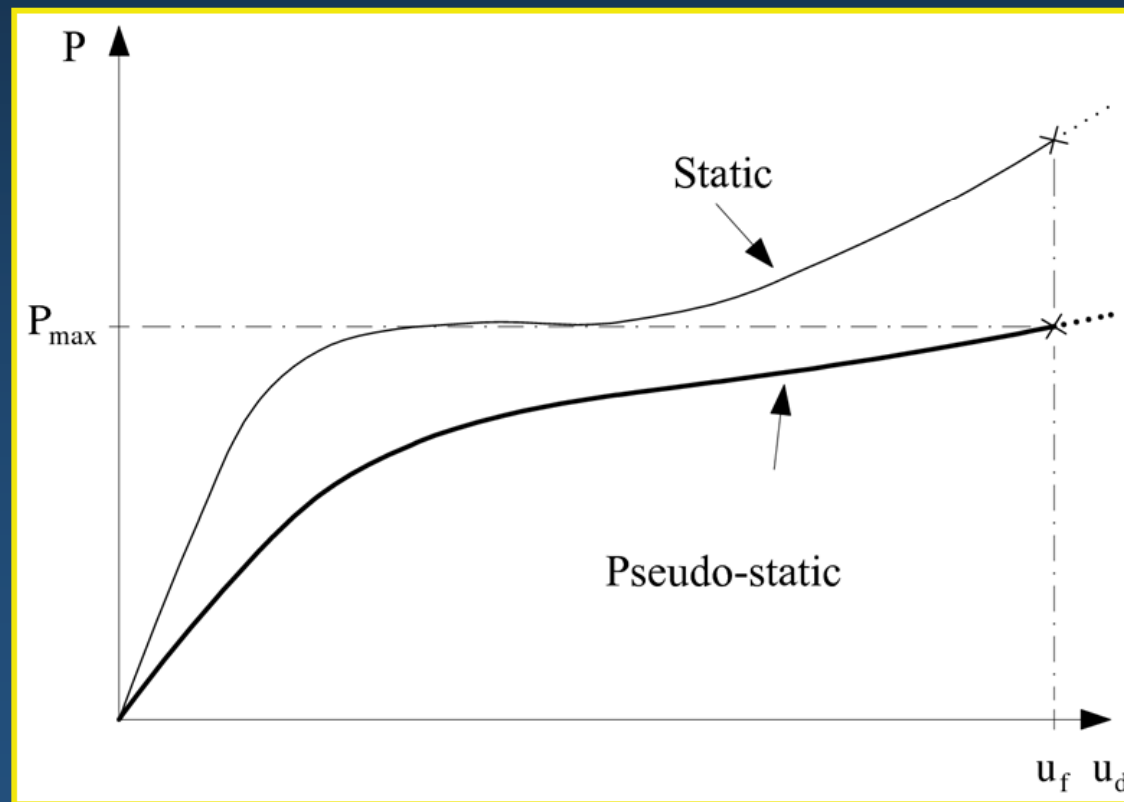
# Sudden Column Loss

## Simplified Dynamic Assessment

- Dynamic “pseudo-static” ( $P, u_d$ ) response constructed from corresponding nonlinear static ( $P, u_s$ ) response
  - Represents response to sudden application of gravity load ( $P$ )
  - Provides valuable information about influence of different levels of gravity load under sudden column loss
  - Dynamic analysis would require excessive runs to obtain similar information

# Sudden Column Loss Simplified Dynamic Assessment

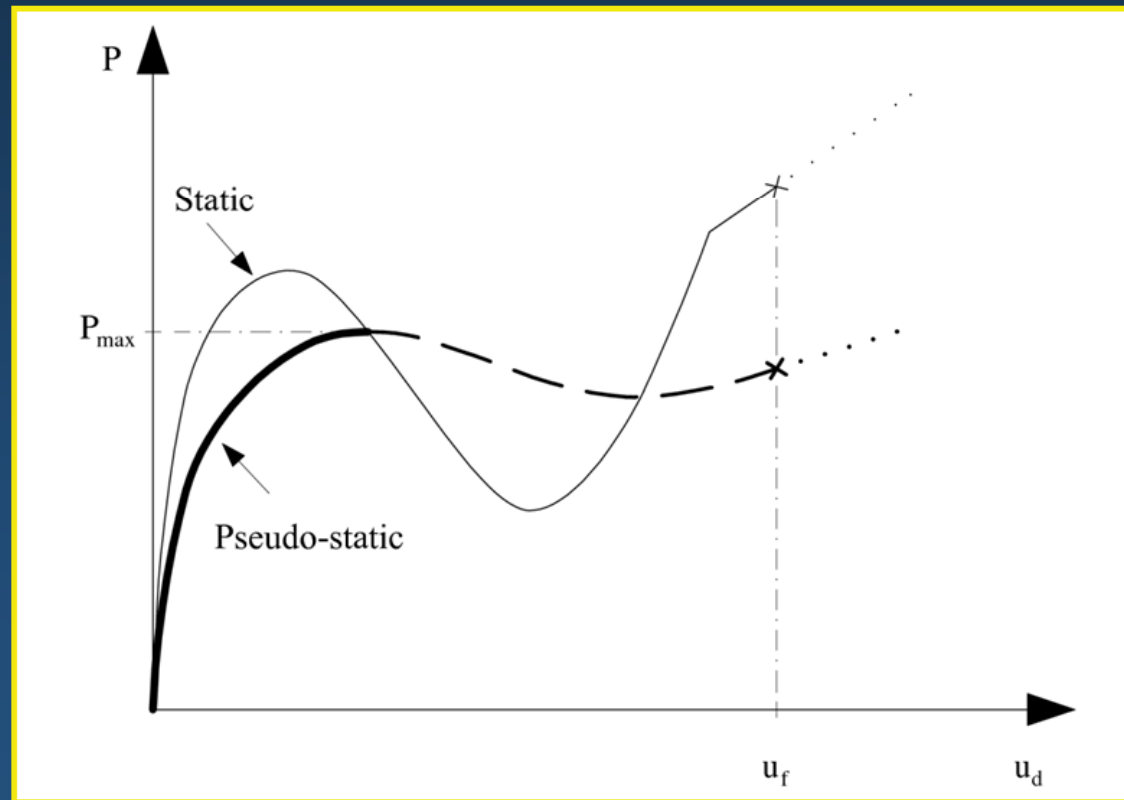
- $P_{\max}$  corresponds to ( $u_d = u_f$ ) for monotonic static response





# Sudden Column Loss Simplified Dynamic Assessment

- Not necessarily for softening static response



# Sudden Column Loss

## Simplified Dynamic Assessment

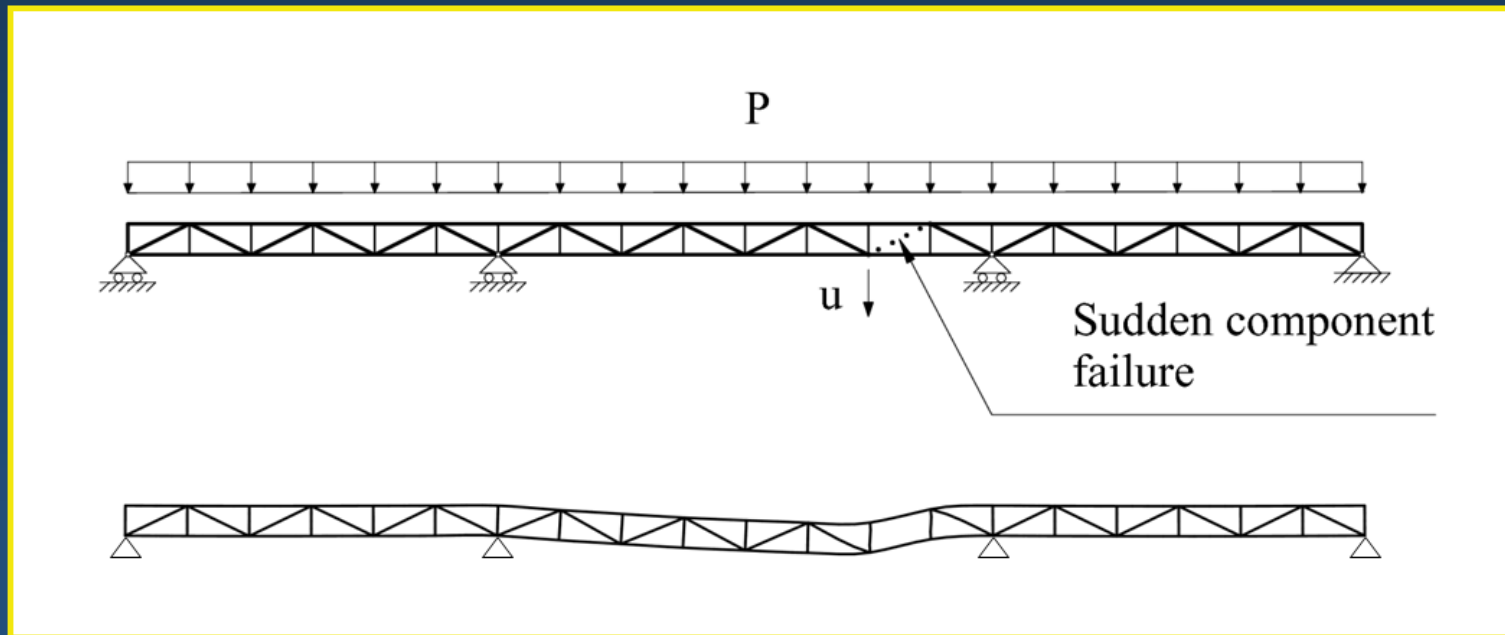
- ‘Pseudo-static capacity’ as a rational performance-based measure of structural robustness
  - Emphasis not on dynamic amplification of static loads with conventional design, but on dynamic demand within ductility limit
  - Combines redundancy, ductility and energy absorption within a simplified framework

# Sudden Component Failure

- Pseudo-static approach also applicable to sudden failure of other components
  - Provided dynamic response is dominated by a single mode
  - Pseudo-static response obtained from nonlinear static response of *damaged* structure, as before

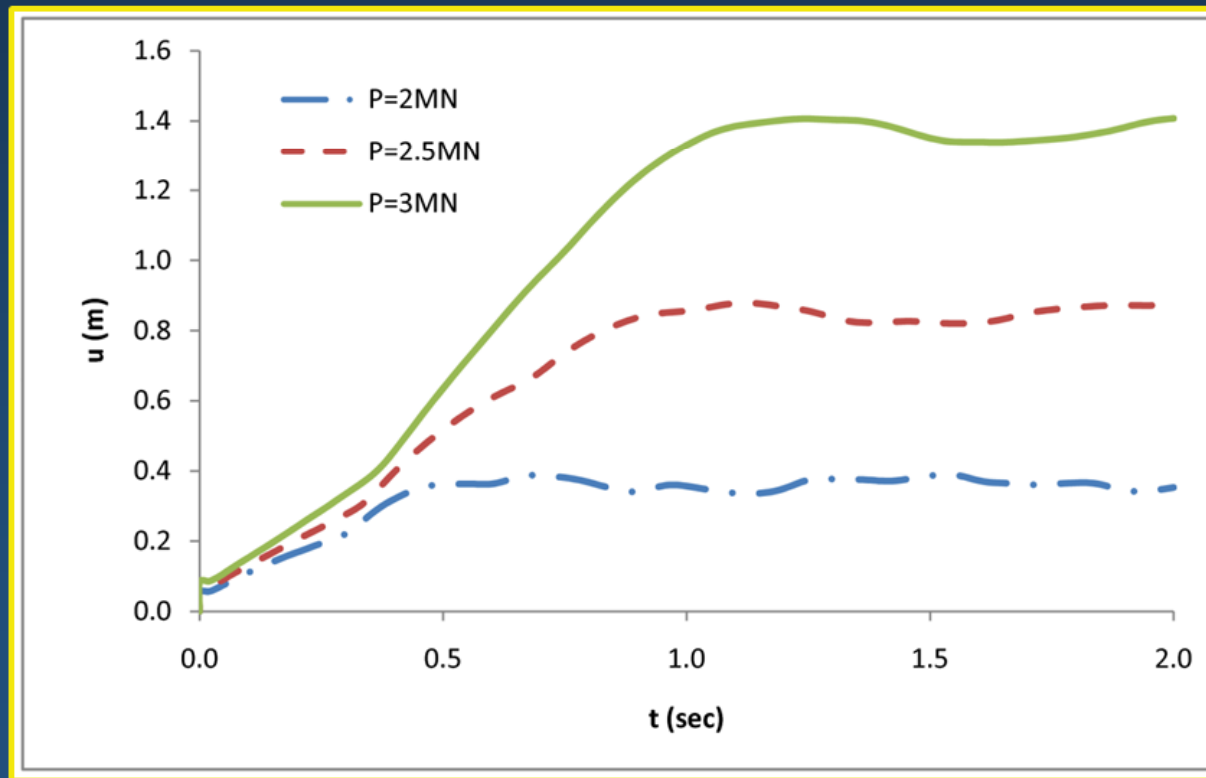
# Sudden Component Failure

- Truss subject to sudden brace failure (e.g. due to sudden connection failure)



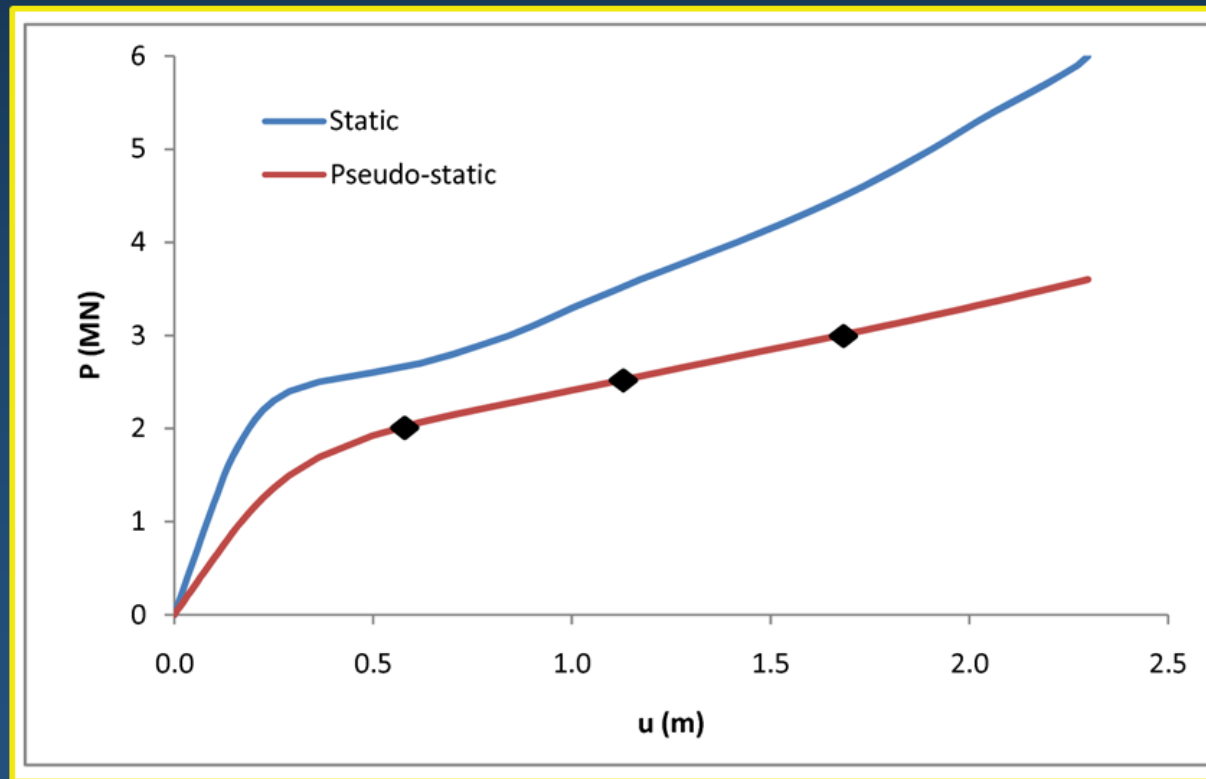
# Sudden Component Failure

- Nonlinear dynamic response under 3 levels of gravity loading



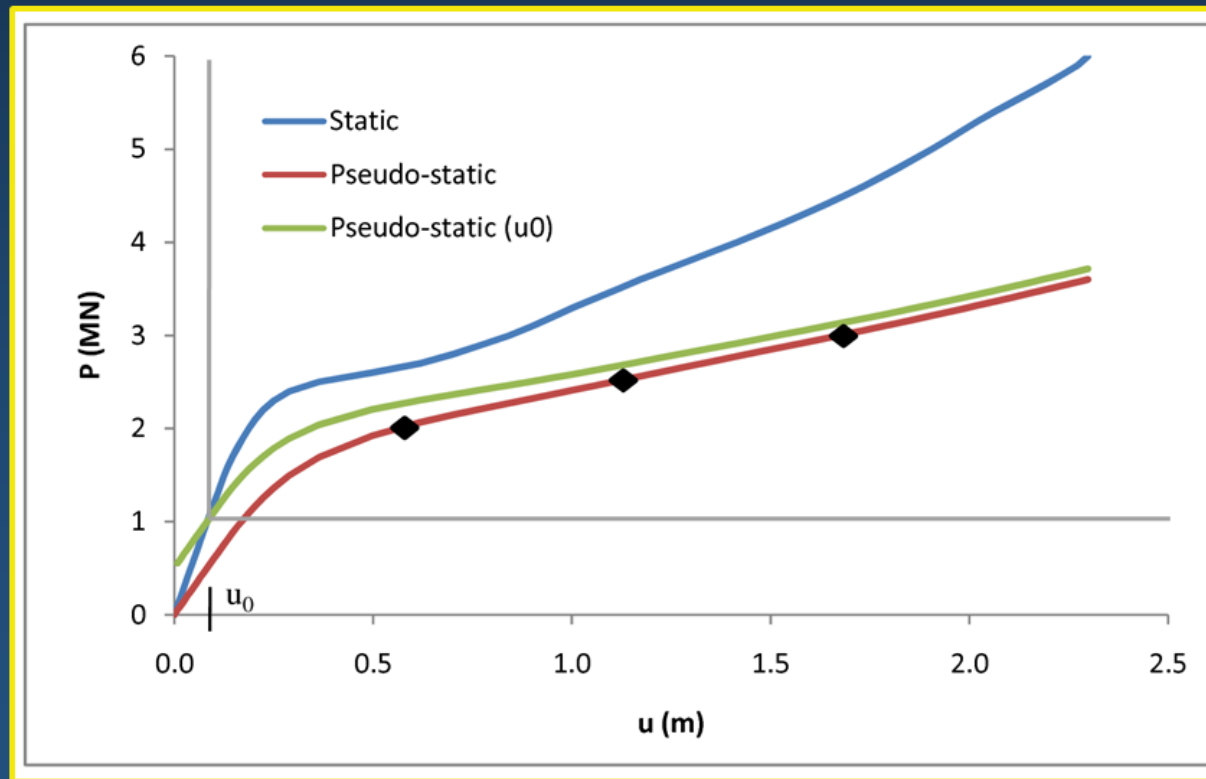
# Sudden Component Failure

- Maximum dynamic displacements from pseudo-static response at three load levels



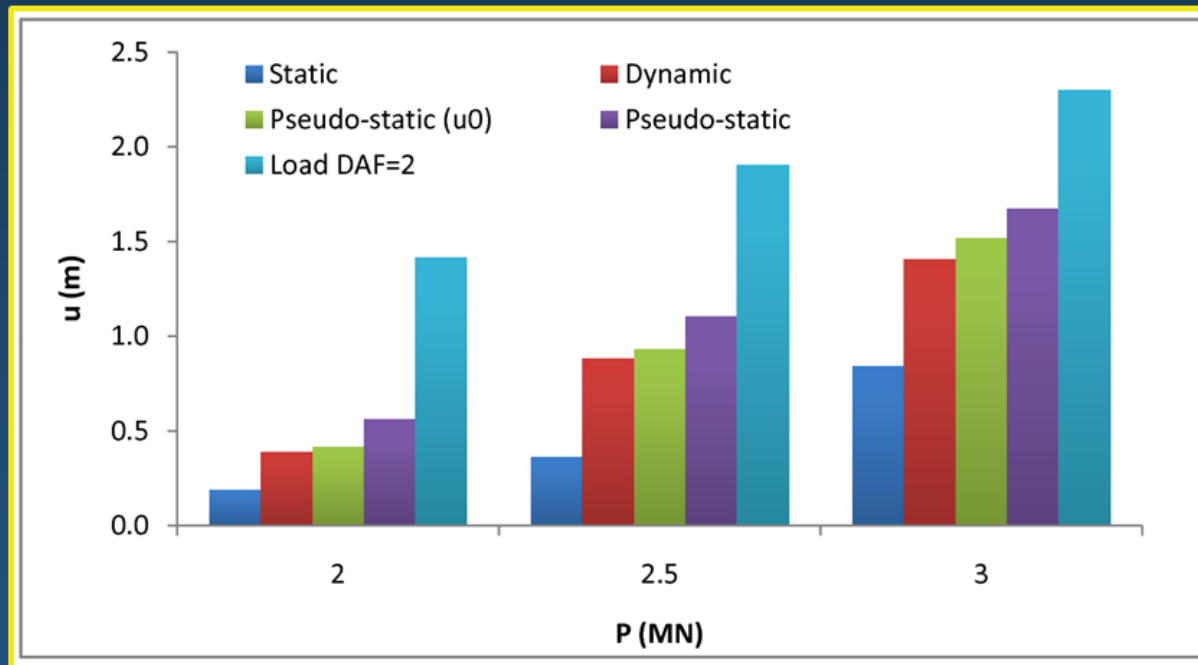
# Sudden Component Failure

- Accounting for initial deflections in pseudo-static response



# Sudden Component Failure

- Excellent comparison between pseudo-static approach and nonlinear dynamic analysis



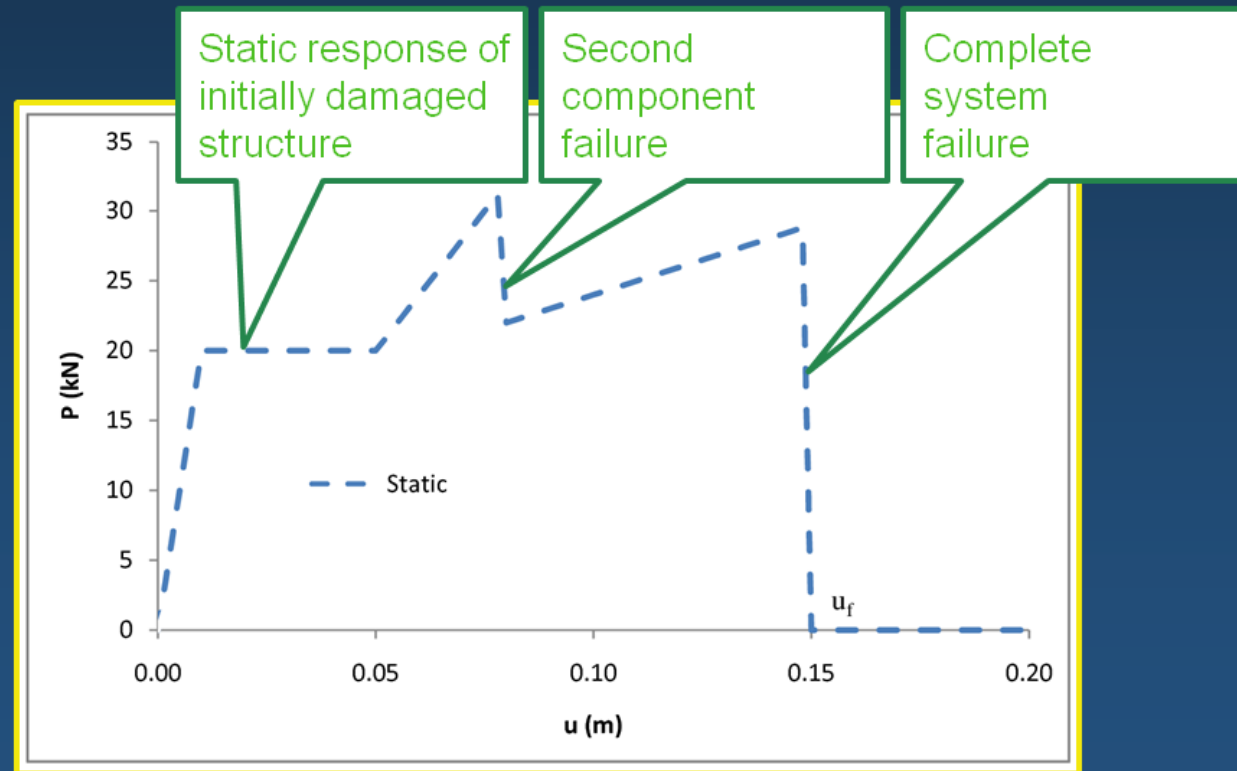


# Successive Component Failures

- Further component failures could occur during dynamic response, without necessarily defining overall dynamic system resistance
- Pseudo-static approach can still be applied:
  - Single dominant mode
  - Nonlinear static response of initially damaged structures
  - Reduction in nonlinear static response due to component failure

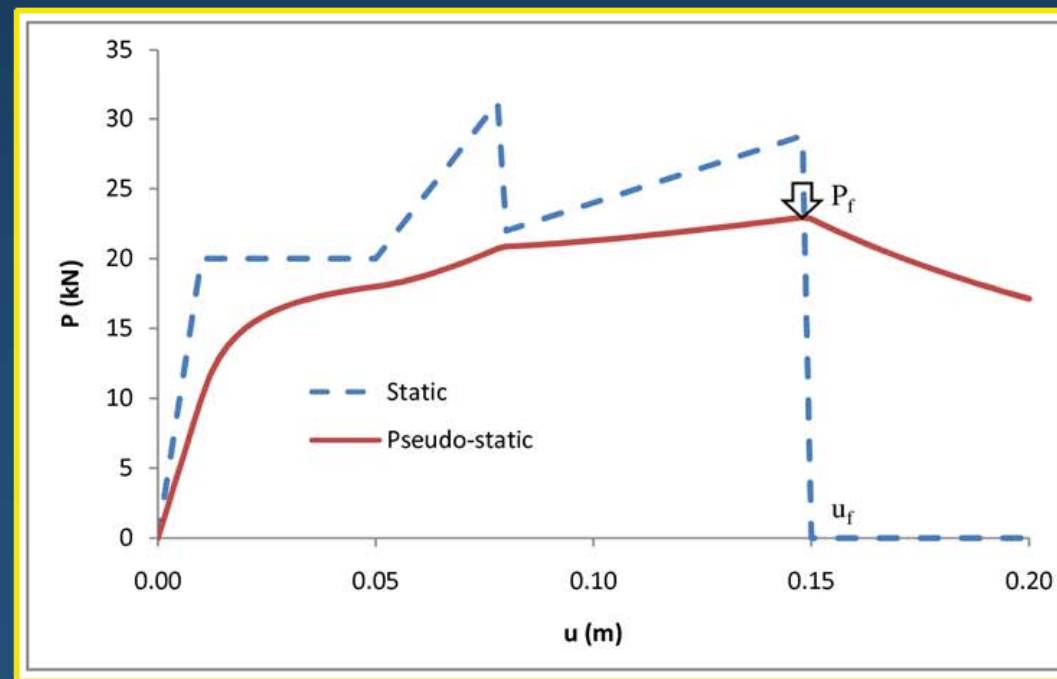
# Successive Component Failures

- Structural system subject to initial damage followed by second component failure



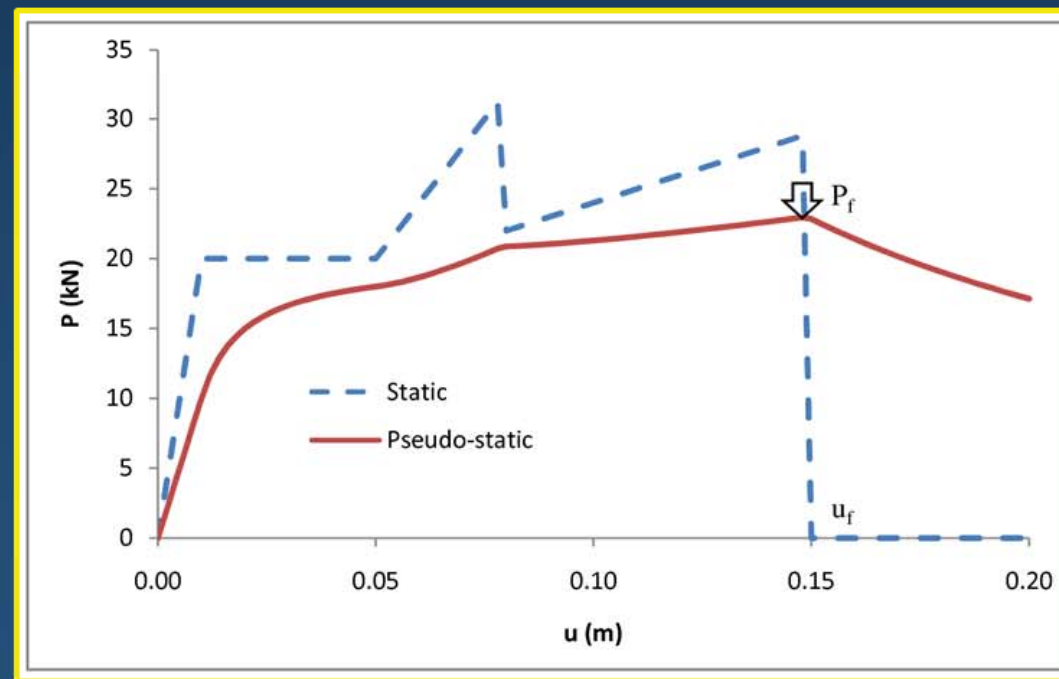
# Successive Component Failures

- Maximum load at intersection between pseudo-static and descending static curves



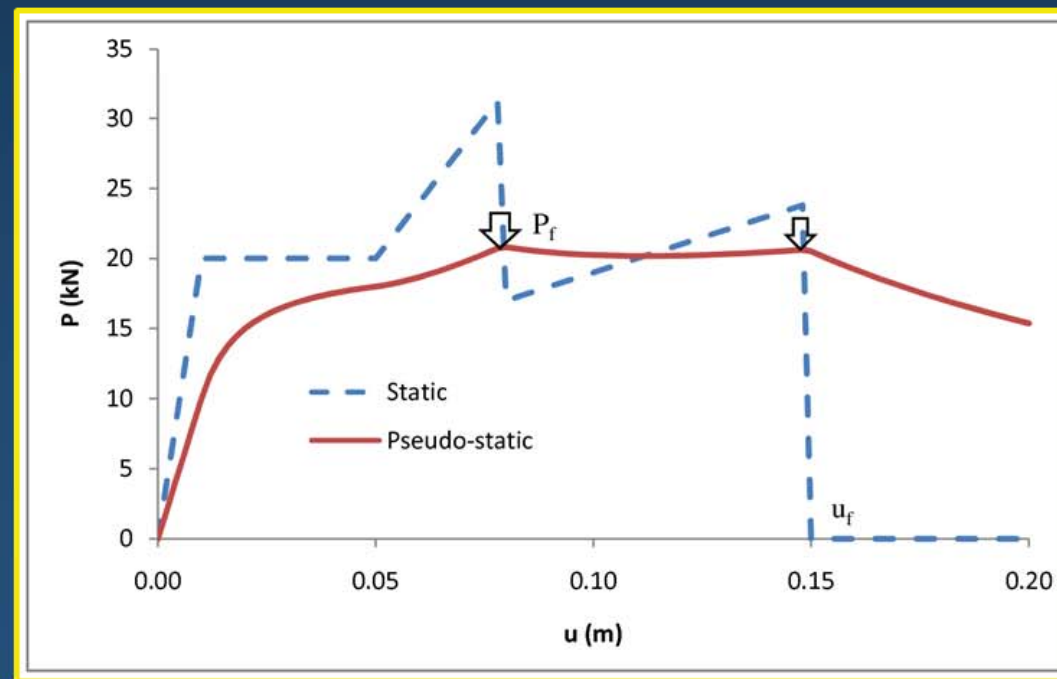
# Successive Component Failures

- Residual pseudo-static capacity after second component failure



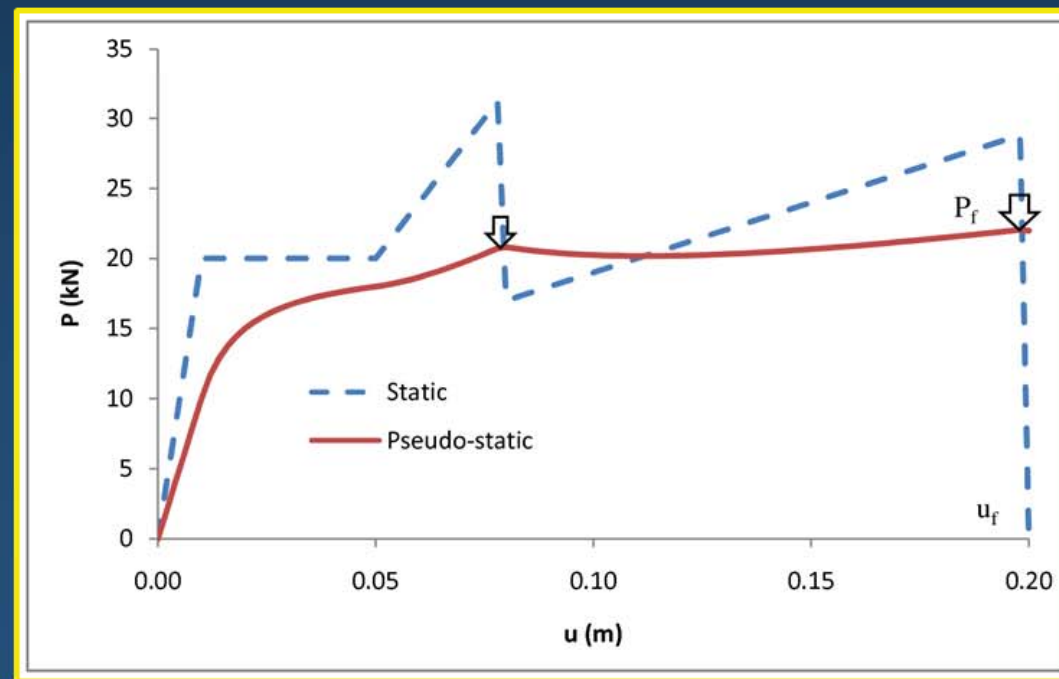
# Successive Component Failures

- ...but not with more severe second component failure



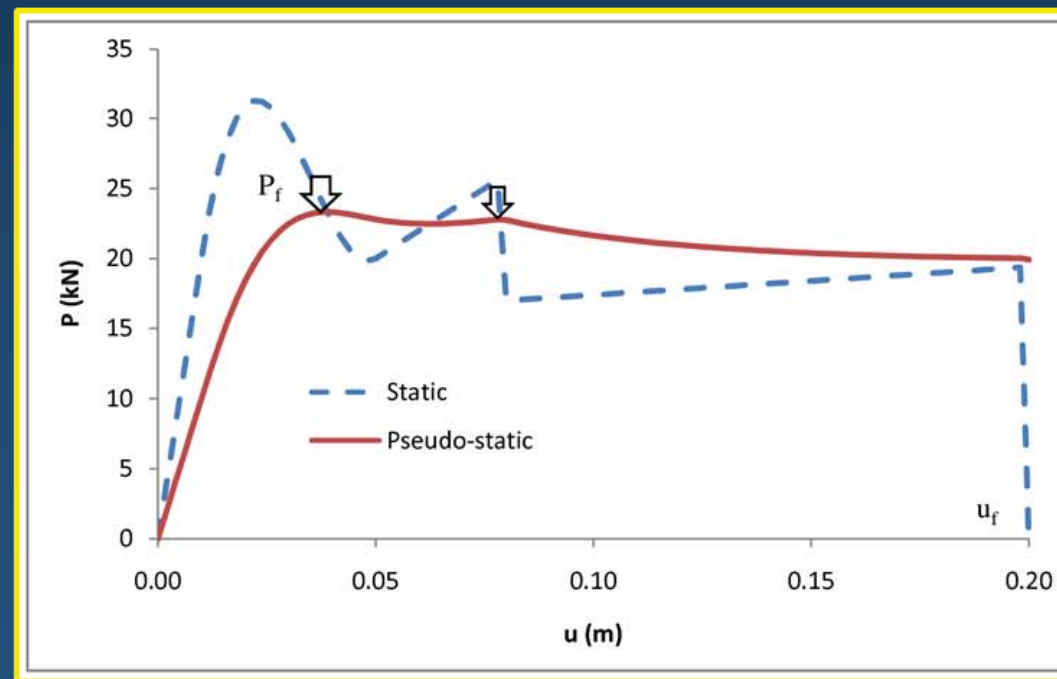
# Successive Component Failures

- ...unless system ductility and static resistance picks up



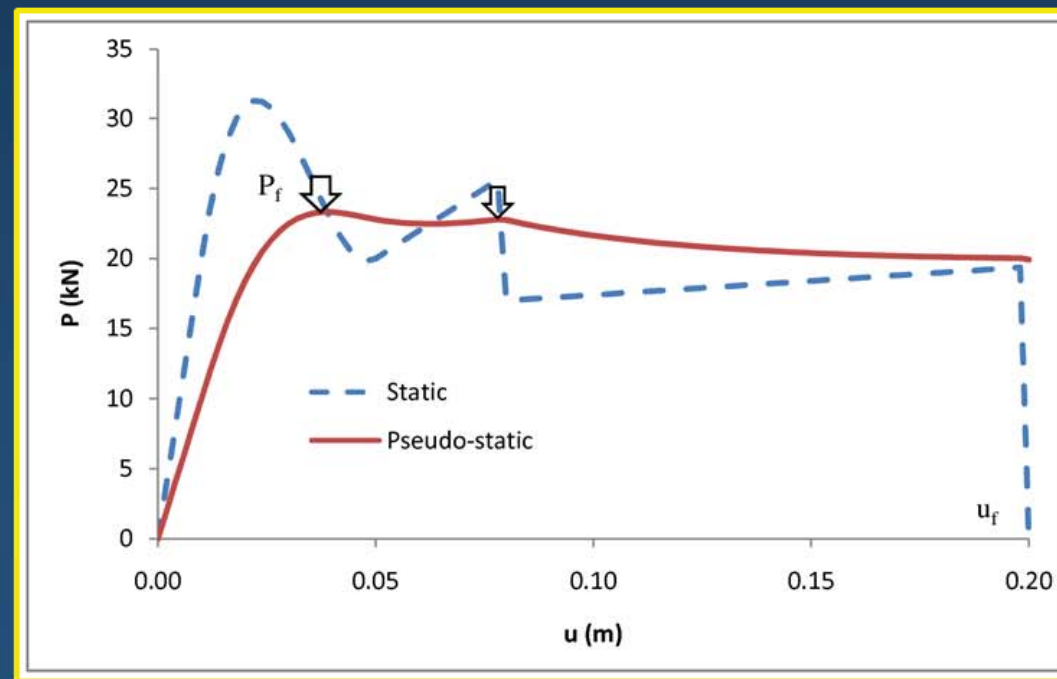
# Successive Component Failures

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



# Successive Component Failures

- ... for instance following a compressive arching stage





# Conclusion

- Simplified dynamic assessment proposed for sudden column loss
  - Superior to static analysis and load dynamic amplification
  - Only requires nonlinear static response
  - Design-oriented framework providing rational measure of structural robustness, including ductility, redundancy and energy absorption capacity
  - Notion of pseudo-static capacity

# Conclusion

- Applicability of pseudo-static approach to sudden failure of other types of component
- Applicable also to successive component failures
  - Provided single dominant mode
  - Intuitive graphical assessment with static and pseudo-static curves
  - Establishes whether a specific component failure determines overall dynamic resistance
- Potential limitations when component failures lead to more than one dominant mode