University of Cyprus

Department of Civil and Environmental Engineering

The cost of satisfying structural design requirements on progressive collapse resistance

A. Kontogiannis and D.C. Charmpis

Final Conference
COST Action TU0601 'Robustness of Structures'
Prague, Czech Republic
30-31 May 2011

Local / global requirements in design codes

- **Contemporary design codes (e.g. Eurocodes) ensure structural safety through calibrated explicit requirements at the component / element / connection level (LOCAL REQUIREMENTS)**
- **Structural system performance not accounted for explicitly (no explicit GLOBAL REQUIREMENTS specified)**
- **Global requirements:**
  - system resistance requirements ***(collapse resistance)***
  - robustness requirements ***(progressive collapse resistance)***
- **The incorporation of explicit global requirements in the design process will typically increase the cost of the structural system designed: need for additional material**

2

The cost of satisfying global requirements

- **It is believed that, in several design cases, the satisfaction of global requirements (on top of local ones) will increase the cost of the structural system only *marginally***
- **This additional cost actually depends on:**
  - 'how much' system resistance and robustness we require
  - effectiveness of utilized tools and measures to satisfy new requirements
- **Investigation needed on the additional cost induced by global requirements**
- **This investigation is performed in the framework of**
  structural design optimization of elastoplastic steel frames

3

Application

- **Structural design optimization of elastoplastic steel frames**
- **Integrated design optimization approach accounting for**
  ***local and global* structural performance requirements**
- **Aims:**
  - Progressive collapse resistance assessment of elastoplastic steel frames
  - Investigation of cost due to additional system performance requirements
  - Gain insight on the way the optimization procedure manages
    to meet system performance / robustness requirements

  Thus, actual aim is to:
  'discover' how to meet robustness requirements with minimum cost
  (learn from optimization results)
- **Input to:**
  Activity 8: Robustness assessment of selected classes/types of structures/materials.

4

Measuring progressive collapse resistance

Intact structure

Limit load factor
α_c

'Damaged' structure
(notional column removal)

Limit load factor
α_{cd}

Progressive collapse resistance index: $\rho = \dfrac{\alpha_{cd}}{\alpha_c}$

5

Code-based design

Design variable vector

Find $\mathbf{d}$

subject to $g_j(\mathbf{d}) \geq 0,\ \ j=1,\ldots,n_g$

$d_i \in D,\ \ i=1,\ldots,n_d$

Constraints
(e.g. satisfaction of Eurocodes provisions)

Design variable

Design space
(set of available design options)

6

Cost-oriented design optimization

Cost

minimize $C(\mathbf{d})$

subject to $g_j(\mathbf{d}) \geq 0, \; j=1,\ldots,n_g$

$d_i \in D, \; i=1,\ldots,n_d$

7

Cost-oriented design optimization with additional system performance requirements

minimize $C(\mathbf{d})$

subject to $g_j(\mathbf{d}) \geq 0, \; j=1,\ldots,n_g$

(design **d** *satisfies EC3 requirements)*

$\alpha_c(\mathbf{d}) \geq \alpha_{c,\min}$

$\rho(\mathbf{d}) \geq \rho_{\min}$

$d_i \in D, \; i=1,\ldots,n_d$

Collapse load factor of <u>undamaged</u> structure

Collapse resistance requirement

Progressive collapse resistance requirement

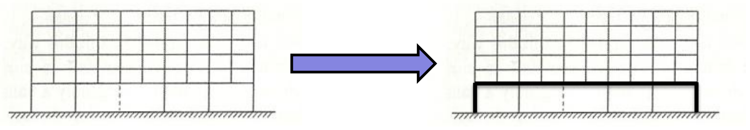
min allowable values

Progressive collapse resistance index $\rho = \dfrac{\alpha_{cd}}{\alpha_{c,\min}}$

8

The alternate path method with notional column removal

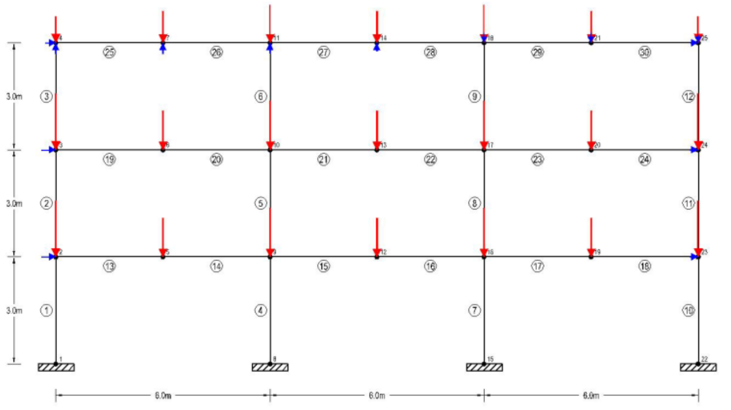
- **Aims:**
  - redistribution of loads on damaged structure to remaining undamaged members
  - loads safely transferred to ground through alternate load paths
- Obvious implementation of alternate path method:
  'bridge' formation over damaged region



Notional column removal — 'Bridge' (strong beams/columns) over damaged region

- **Disadvantages of 'bridge'-philosophy:**
  - local strengthening only *(column removal at storey higher than the 'bridge'?)*
  - is it the most economical way of strengthening?
- The design optimization approach of the present work ensures the satisfaction of progressive collapse resistance requirements using the alternate path method with **minimum cost**

Test example 1: 3-storey frame

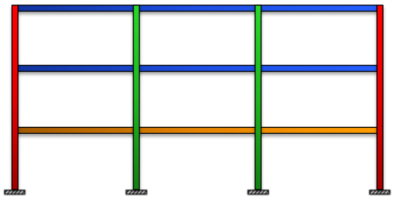


Internal frame

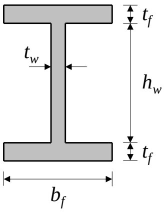
- Subjected to dead, live and wind load
- For limit load elastoplactic analysis
  - Constant dead and live loads
  - Variable wind loads

Test example 1: 3-storey frame

- Modeling
  - **4 member categories (16 design variables)**
    - 1st Cat. – Corner columns
    - 2nd Cat. – Internal columns
    - 3rd Cat. – Beams of storey 1
    - 4th Cat. – Beams of storeys 2-3

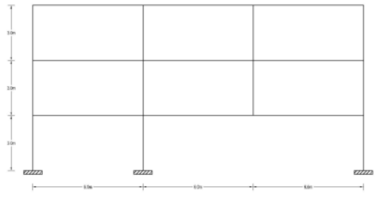


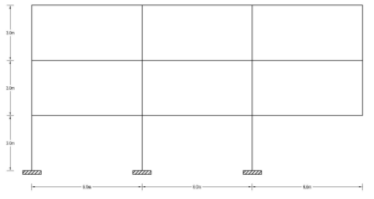
  - **Each member category: 4 design variables**



Test example 1: 3-storey frame

- **Damage scenarios analyzed**
  - Removal of an internal column
  - Removal of a corner column





- **Optimization analysis**
  - Aim: minimize total material volume of intact structure
  - Results obtained for $\alpha_{c,min}$=30 and various values of ρ_{min} imposed

Test example 1: 3-storey frame

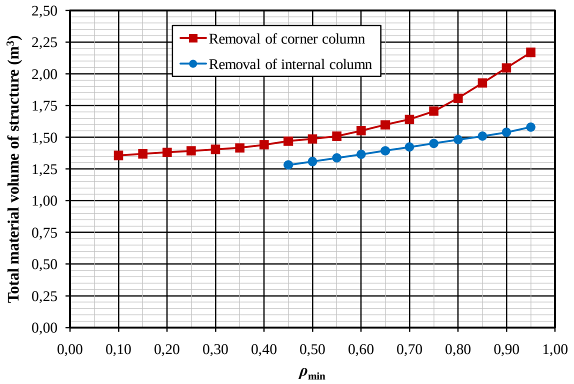
- Total material volume of structure
  - **Removal of internal column**

    ρ_{min}=0.45 (α_c=30 → α_c=15)

    For demand ρ_{min}=0.95 → 23% increase in total material volume
  - **Removal of corner column**

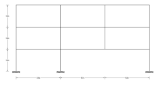
    ρ_{min}=0.10 (α_c=30 → α_c=3)

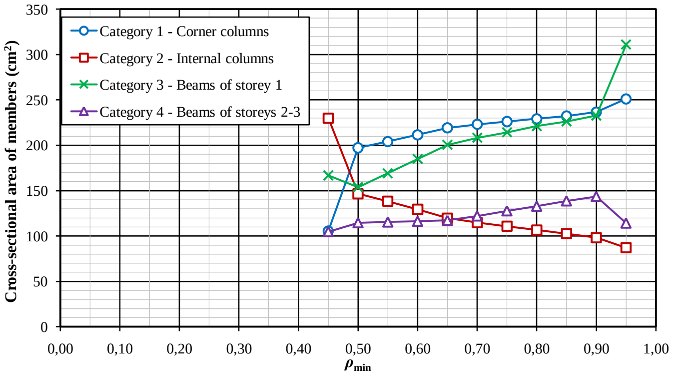
    For demand ρ_{min}=0.95 → 60% increase in total material volume



Test example 1: 3-storey frame

- **Removal of internal column**

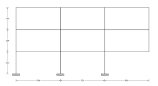


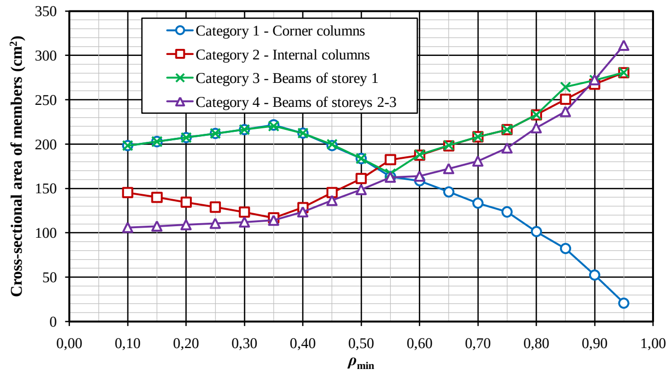


- Behavior
  - Gradual strengthening of corner columns and beams of storey 1 – **‘bridge’**
  - Mild strengthening of beams of storeys 2-3
  - Gradual decrease in the dimensions of the internal columns

Test example 1: 3-storey frame

- **Removal of corner column**

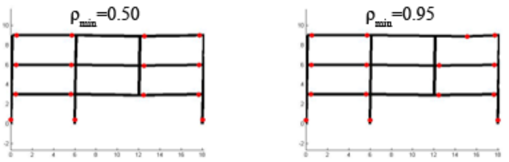




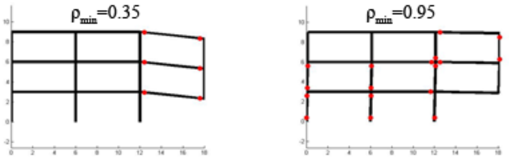
- Behavior
  - Low resistance demands: Local approach with the formation of 'bridge'
  - High resistance demands: Global approach with the strengthening of all members except for corner columns

Test example 1: 3-storey frame

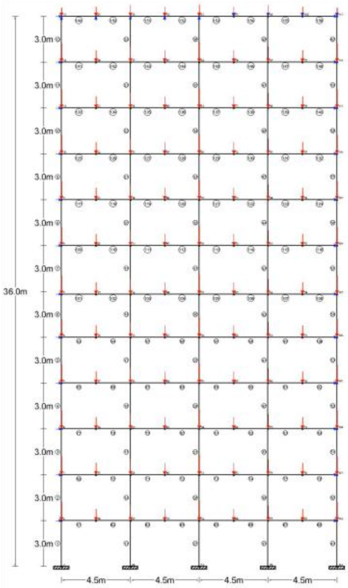
- Collapse mechanism of the damaged frame
  - Removal of internal column



  - Removal of corner column



Test example 2: 12-storey frame



Internal frame

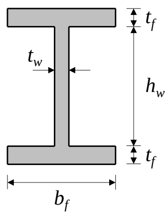
- Subjected to dead, live and wind load
- For limit load elastoplactic analysis
  - Constant dead and live loads
  - Variable wind loads

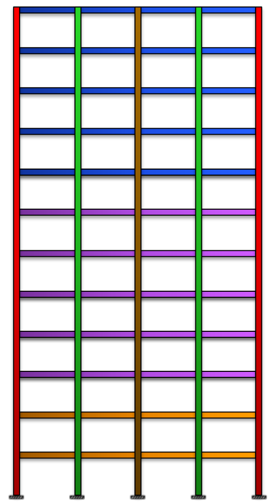
Test example 2: 12-storey frame

- Modeling
  - 6 member categories (24 design variables)

    1st Cat. – Corner columns
    2nd Cat. – Internal columns
    3rd Cat. – Central columns
    4th Cat. – Beams of storeys 1-2
    5th Cat. – Beams of storeys 3-7
    6th Cat. – Beams of storeys 8-12

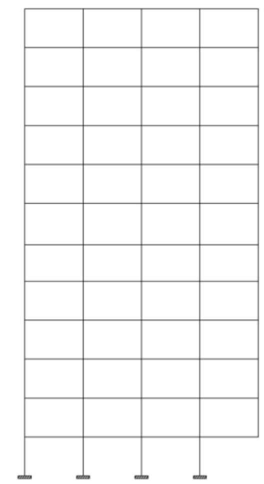
  - Each member category: 4 design variables





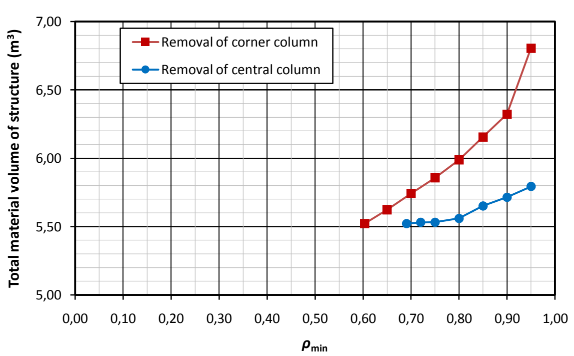
Test example 2: 12-storey frame

- Damage scenarios analyzed
  - Removal of a central column
  - Removal of a corner column
- Optimization analysis
  - Aim: minimize total material volume of intact structure
  - Results obtained for $\alpha_{c,min}$=7 and various values of ρ_{minn} imposed



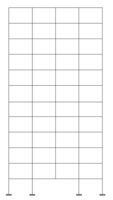
Test example 2: 12-storey frame

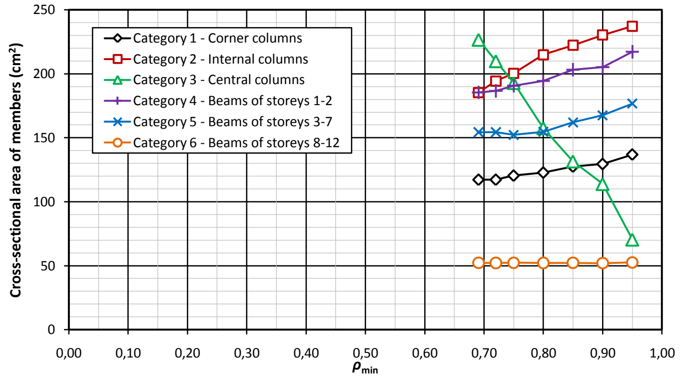
- <u>Total material volume of structure</u>
  - **Removal of central column**
    ρ_{min}=0.69 (α_c=7 → α_c=4.8)
    For demand ρ_{min}=0.95 → 4.9% increase in total material volume
  - **Removal of corner column**
    ρ_{min}=0.60 (α_c=7 → α_c=4.2)
    For demand ρ_{min}=0.95 → 23.2% increase in total material volume



Test example 2: 12-storey frame

- Removal of central column

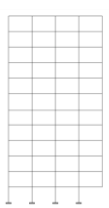


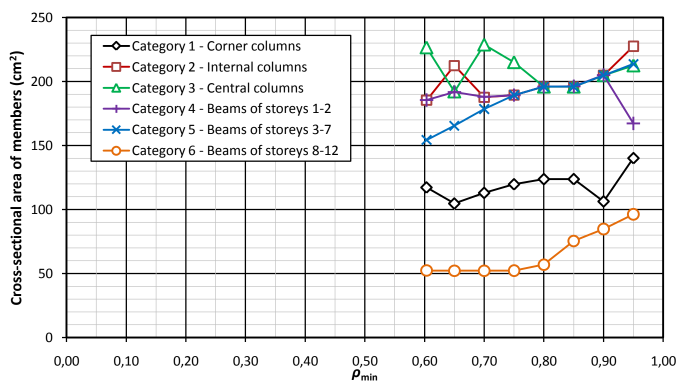


- Behavior
  - Gradual strengthening of all elements (except central columns)
  - Incline towards strong columns (mostly internal) – central columns with decreased participation
  - Reduced participation of beams of higher storeys

Test example 2: 12-storey frame

- Removal of corner column

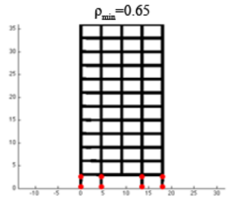


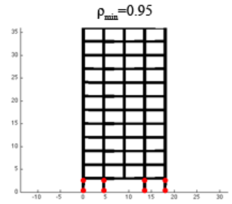


- Behavior
  - Similar behavior as previously
  - Gradual strengthening of all elements
  - Incline towards strong columns – corner columns at lower levels
  - Reduced participation of beams of higher storeys

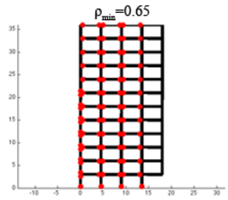
Test example 2: 12-storey frame

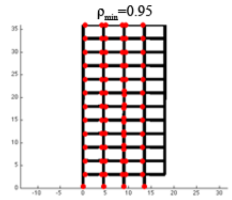
- Collapse mechanism of the damaged frame
  - Removal of central column





  - Removal of corner column





Conclusions

- **It is not possible to know a-priori the *optimal* amount and allocation of additional material required, in order to satisfy progressive collapse resistance constraints**
  (depends on structural system, material/geometric properties, loads, demand on collapse resistance, etc.)

  ➔ ***Every problem is a case of its own, which has to be optimized explicitly***
  ➔ ***Practically infeasible to fully substitute optimization by simple guidelines***
  ➔ ***Rather macroscopic conclusions obtainable, not detailed quantified rules***

- The increase in material demand varies almost linearly for low and moderate progressive collapse resistance requirements.
  For high progressive collapse resistance requirements this relation becomes non-linear causing higher demands in material.

Conclusions

- **Low-rise buildings** (e.g. 3-storey frame)

  Internal column removed:
  the optimizer tends to produce strong corner columns and strong beams at storey 1, forming this way a type of **'bridge'** over the damaged region
  (structural system activated locally)

  Corner column removed:
  for relatively high progressive collapse resistance requirements, the optimizer tends to yield strong internal columns and **strong beams at all storeys**, while corner columns contribute very little ***(structural system activated globally)***

- **High-rise buildings** (e.g. 12-storey frame)

  Central or corner column removed:
  the optimizer tends to introduce strong columns and **strong beams at all storeys** except for the few highest storeys ***(structural system activated globally)***

  As the demand for progressive collapse resistance becomes higher, the optimizer invokes more and stronger beams over the height of the structure
  (activation of the structure as a system against the damage effect)

25