COST Action TU0601
Robustness of Structures

WG2
Modelling of exposures and vulnerability

Activity 5
Structural behaviour models

# General aspects, modelling and analysis

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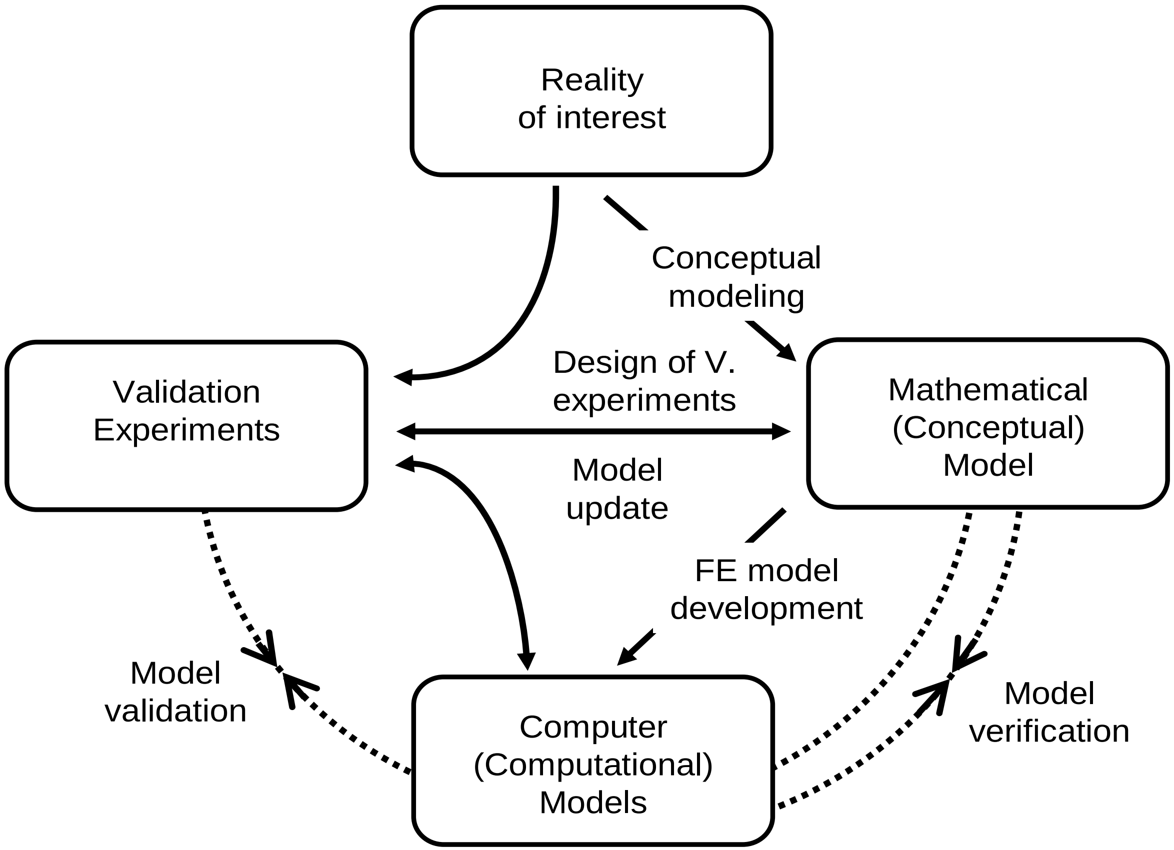



Modeling, verification and validation



# Before beginning structural modeling

objectives

reality of interest (physical model)

quantities of interest



General objectives of robustness analysis:

Estimate potential for progressive collapse (evaluation)

Mitigate effects of disproportional damage (improvement)



Structural models serving for:

Design – simplified procedures, flowcharts, elimination of Single Point Failure Mechanism (*simplicity*)

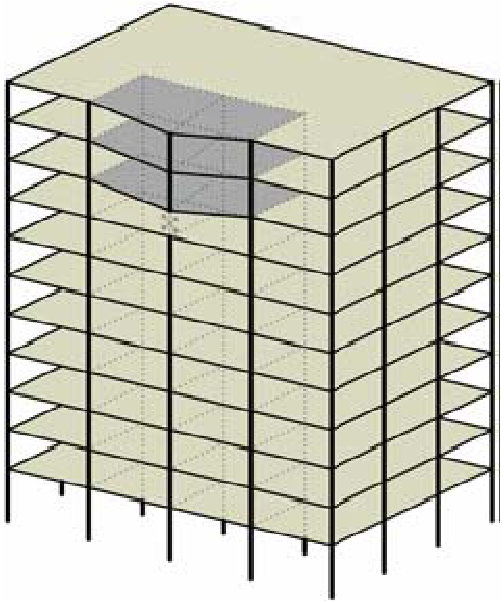
Robustness analysis – repeated calculations, probabilistic simulations (*efficiency*)

Research oriented – verification of procedures, reference material, case studies (*accuracy*)



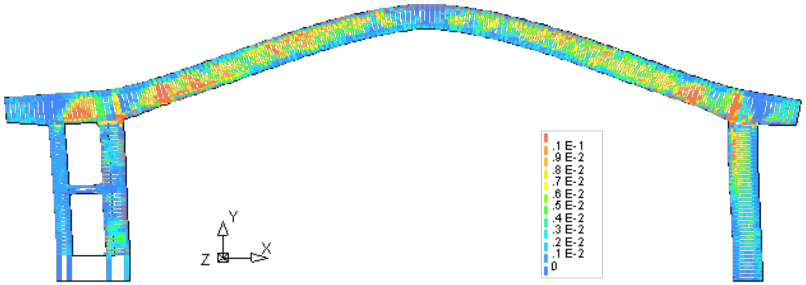
# Reality of interest (physical model)

Existing building



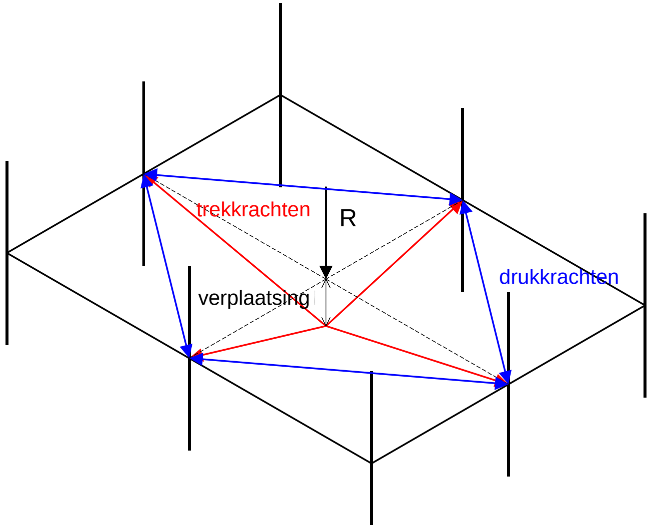
Designed structure (concept)

Structural element (e.g. frame)





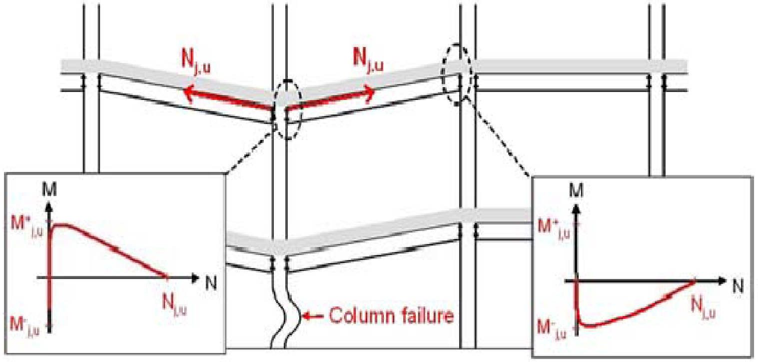
# Quantities of interest:




Internal forces after local damage

Extent of secondary damage

Overall structural behavior
after primary failure
(stresses, strain, displacements, energies)






Three aspects:

loading configurations including abnormal loads

global failure criteria quantitatively defining the collapse phenomenon

adequate analysis methods



# EN 1990 Basis of Design

- Accidental design situation

$$\sum_{j\geq 1} G_{k,j} + P_k + A_d + (\psi_{1,1} \text{ or } \psi_{2,1}) Q_{k,1} + \sum_{i>1} \psi_{2,i} Q_{k,i} \qquad (6.11b)$$

- G = permanent action
- Q = variable action
- A = accidental action
- P = prestressing



# Loading configurations

| | $\psi_0$ | $\psi_1$ | $\psi_2$ |
|---|---|---|---|
| Imposed loads in buildings, category | | | |
| Category A : residence | 0,7 | 0,5 | 0,3 |
| Category B : office | 0,7 | 0,5 | 0,3 |
| Category C : congregation | 0,7 | 0,7 | 0,6 |
| Category D : shops | 0,7 | 0,7 | 0,6 |
| Category E : storage | 1,0 | 0,9 | 0,8 |
| Category F : vehicles $\leq$ 30kN | 0,7 | 0,7 | 0,6 |
| Category G :vehicles 30-160 kN | 0,7 | 0,5 | 0,3 |
| Category H :roofs | 0 | 0 | 0 |
| Snow | 0,5 | 0,5 | 0 |
| Wind | 0,62 | 0,2 | 0 |
| Temperature | 0,6 | 0,5 | 0 |



# Loading configurations

**General Services Administration (GSA) (2000)**

**U.S. Department of Defense (DoD) (2002)**

Static analysis
Load = 2(DL + 0.25LL)

Dynamic analysis
Load = DL + 0.25LL

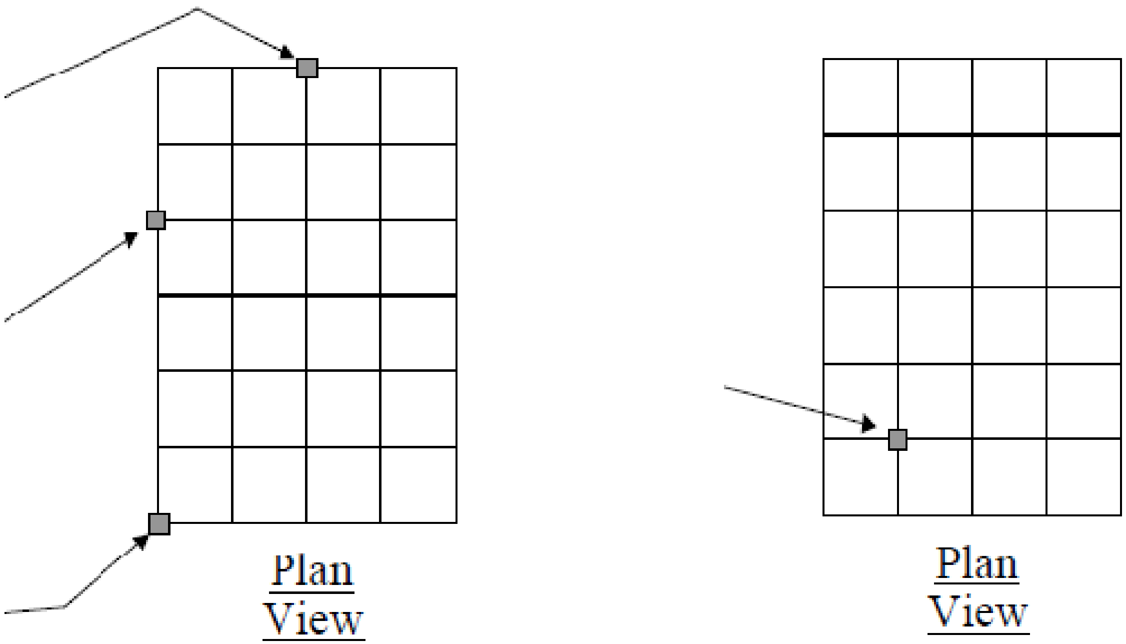
DL = dead load
LL = live load



# Loading configurations

abnormal loading:

notional removal of major bearing structural elements
threat independent approach




Recommended exterior and interior locations of notionally removed columns (GSA, 2000)



# Global failure criteria

## quantitatively defining the collapse phenomenon

(GSA, 2000)

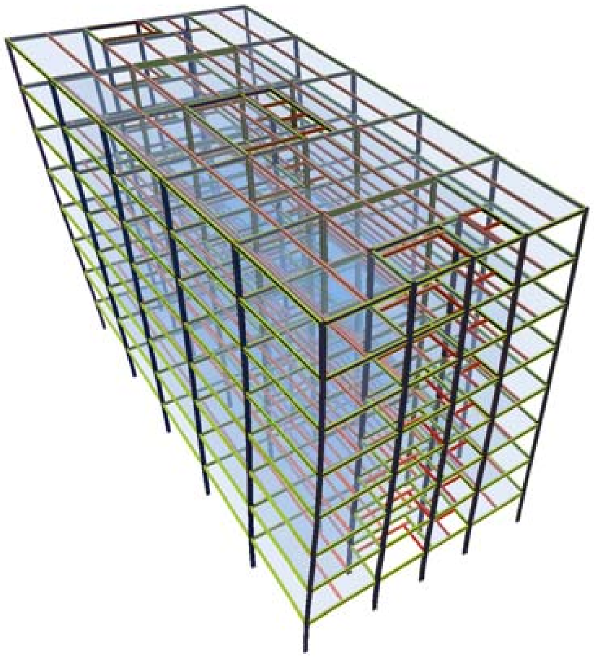
smaller of the following two areas:

- the area limited to structural bays directly associated with the instantaneously removed vertical member and located directly above the removed member,

- 167 m2 (1,800 ft2) at the floor level directly above the instantaneously removed vertical member.



# Analysis methods - categorization



Linear vs. Nonlinear

Static vs. Dynamic

Space discretization

Component level – multilevel strategy – global analysis



# Analysis methods

Linear behavior (analysis):

response proportional to the cause

Sources of nonlinearities:

Material behavior (material nonlinearity)
Large deformations (geometric nonlinearities)
Loading – change of direction and application point
Boundary conditions



# Analysis methods

Smooth nonlinearities

e.g. nonlinear strain-displacement equations, nonlinear elasticity, follower pressures

smooth at local level – global level can be not smooth (e.g. buckling, snapping)

continuous relations - equations

incremental-iterative methods

Rough nonlinearities

local response is nonsmooth

(flow-rule plasticity, contact, friction)

Inequalities, often history dependent

numerical problems

incremental methods



# Static vs. Dynamic

## Static analysis

inertial forces are ignored,
history time-like parameter

## Quasi-static analysis

inertial forces neglected
real-time measure
foundation settlement, creep deformation, rate-dependent plasticity

## Dynamic analysis

inertial forces
damping
rate effects (strain rate effects)
actual time (time derivatives)
stabilizing effect of inertial forces for nonlinear and discontinuous problems



# Explicit versus Implicit Time Integration

## Implicit time integrators

inertial problems
relatively long response time
incremental-iterative
smaller number of more computationally expensive cycles
rough nonlinearities – convergence problems



# Explicit versus Implicit Time Integration

## Explicit time integration

- dynamic transient problems
- stress wave propagation captured
- rough nonlinearities
- large deformations grow rapidly
- purely incremental methods
- central difference method
- very small time steps
- large number of less expensive integration cycles
- numerical instabilities, e.g. hourglass modes
- mass scaling
- shock effects - viscous global damping



# Space discretization

Finite Element Method (MES) - dominant

beam element models dominate

considerations are mosty confined to 2D subsystems

multilevel strategy:

- subsystem or component level
- simplified global model



# EXAMPLES

Marjanishvili evaluated four successively more sophisticated analysis:

linear-elastic static
nonlinear static
linear-elastic dynamic
nonlinear dynamic

The nonlinear time history (dynamic) analysis:

is recognized as giving the most realistic results

due to its high complexity, it is prone to incorrect assumptions and modeling errors

Marjanishvili SM. Progressive analysis procedure for progressive collapse. J Perform Constructed Facilities ASCE 2004; 18(2):79–85.



# EXAMPLES



**Table 1.** Analysis Procedures Summary

| Analysis procedures | Advantages | Disadvantages | Limitations | Steps required to perform the analysis | Performance evaluation criteria |
|---|---|---|---|---|---|
| Linear-elastic static analysis | 1. Relative simplicity<br>2. Calculations done quickly<br>3. Easy to perform<br>4. Easy to evaluate and validate results | 1. Does not consider dynamic effects<br>2. Does not consider material nonlinearity | 1. Analysis of complex structures cannot be evaluated with confidence<br>2. Limited to simple structures with predictable behavior | 1. Build computer model<br>2. Perform static analysis<br>3. Perform stability analysis<br>4. Verify, validate, and evaluate the results | Very conservative |
| Nonlinear static analysis | 1. Includes material nonlinear behavior | 1. Does not consider dynamic effects<br>2. Relative complexity<br>3. Could be time consuming<br>4. Leads to overly conservative results | 1. Limited to relatively simple structures with predictable behavior<br>2. Cannot be effectively used for progressive collapse analysis | 1. Build computer model<br>2. Perform stability analysis<br>3. Estimate element capacities and force-displacement relationship<br>4. Perform nonlinear static analysis<br>5. Verify, validate, and evaluate the results | Very conservative |
| Linear-elastic dynamic analysis | 1. Includes dynamic behavior | 1. Does not account for material nonlinear behavior<br>2. Could be time consuming for large computer models<br>3. Moderate complexity<br>4. Requires additional calculations to obtain time-step and internal forces<br>5. Dynamic amplification, inertia and damping forces may be incorrectly calculated for structures that exhibit large plastic deformations | 1. Limited to structures that do not exhibit large plastic deformations | 1. Build computer model<br>2. Perform static analysis to determine internal forces<br>3. Determine "at rest" force distribution<br>4. Estimate load time step<br>5. Perform time history analysis<br>6. Verify, validate, and evaluate the results | Conservative for structures that exhibit nearly elastic behavior and could become nonconservative for structures that exhibit large plastic deformations |
| Nonlinear dynamic analysis | 1. Provides most realistic results<br>2. Includes dynamic behavior<br>3. Includes material nonlinear behavior | 1. Could be very time consuming<br>2. Requires extensive verification and validation of findings<br>3. Hard to evaluate the results. In most of the cases the results of nonlinear dynamic analysis have to be verified and validated independently. Independent peer review analysis, alternate modeling, and sensitivity studies could validate the accuracy of the analyses.<br>4. High complexity<br>5. Incorrect assumptions or incorrect modeling may lead to erroneous results | 1. Nonlinear time history analysis can be very time consuming, which may limit the number of nonlinearities in order to reduce the model and subsequently the computation time | 1. Build computer model<br>2. Determine "at rest" force distribution<br>3. Perform stability analysis<br>4. Estimate load time step<br>5. Estimate element capacities and force-displacement relationship<br>6. Perform nonlinear time history analysis<br>7. Verify, validate, and evaluate the results<br>8. Perform validation and various sensitivity studies to verify the results | Most realistic |

Marjanishvili SM. Progressive analysis procedure for progressive collapse. J Perform Constructed Facilities ASCE 2004; 18(2):79–85.



# EXAMPLES

Multistory buildings

Design-oriented methodology

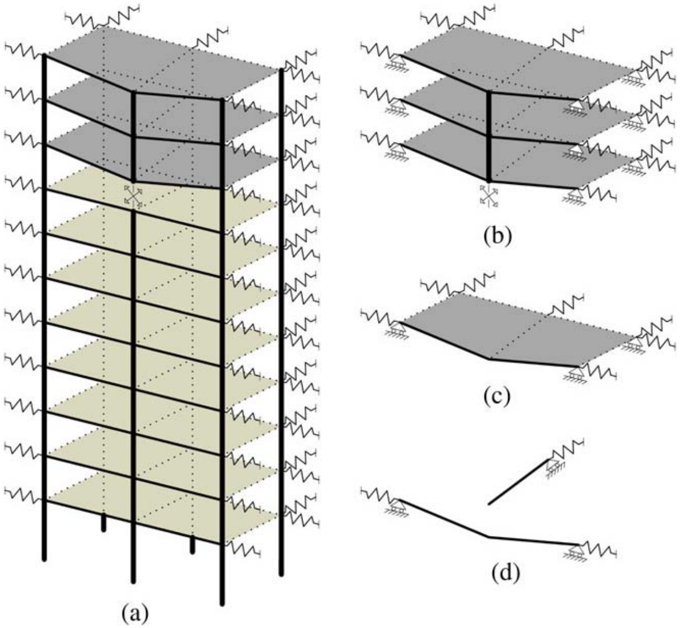
Multilevel approach - three stages:

nonlinear static response of the damaged structure under gravity loading,

simplified dynamic assessment to establish pseudo static curves,

ductility assessment of the connections

ADAPTIC
Beam FE models
Component-based approach applied to the joints




Izzuddin BA, Vlassis AG, Elghazouli AY, Nethercot DA. Progressive collapse of multi-storey buildings due to sudden column loss -Part I & II, Engineering Structures 2008.



# EXAMPLES

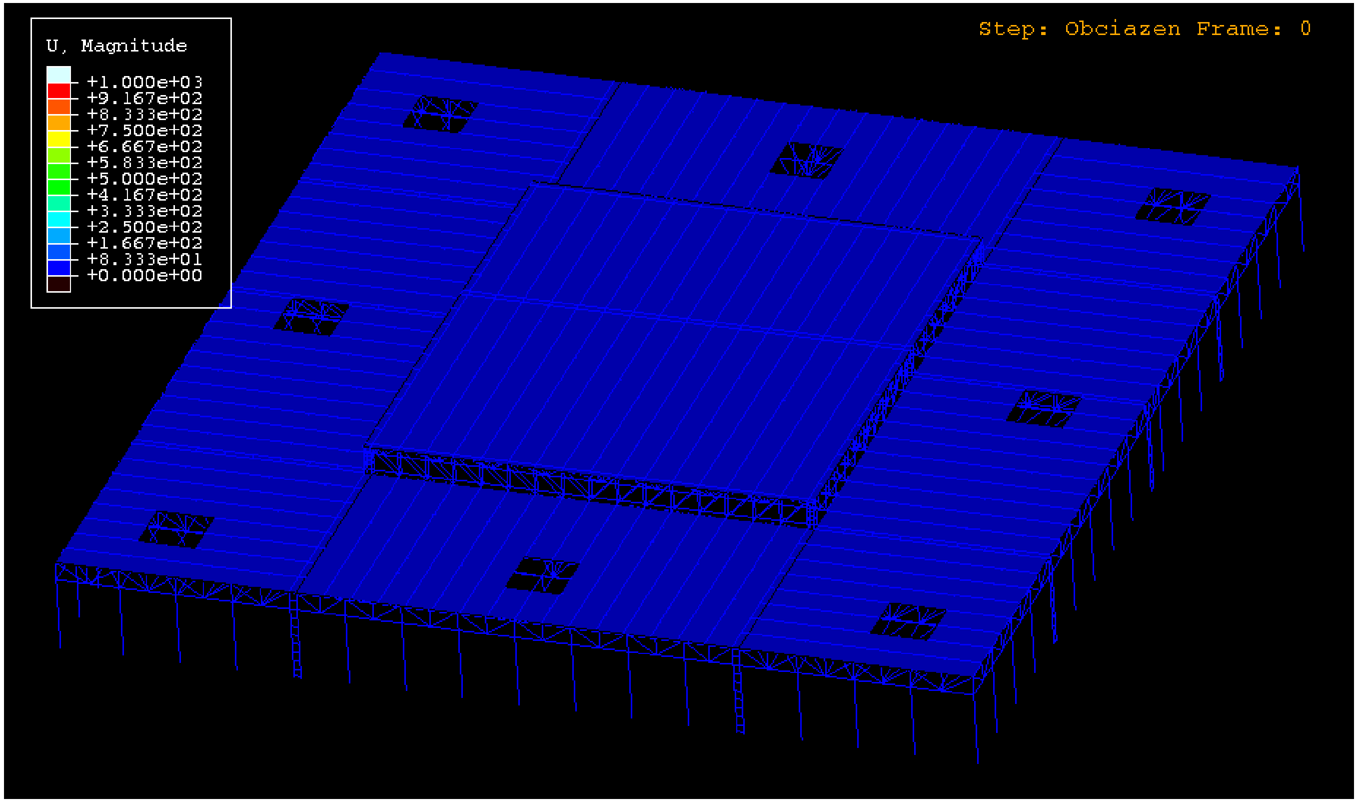
Chorzow Trade Hall roof collapse under snow loads in 2006

Implicit dynamic analysis

Global model

Beam and shell element model

ABAQUS

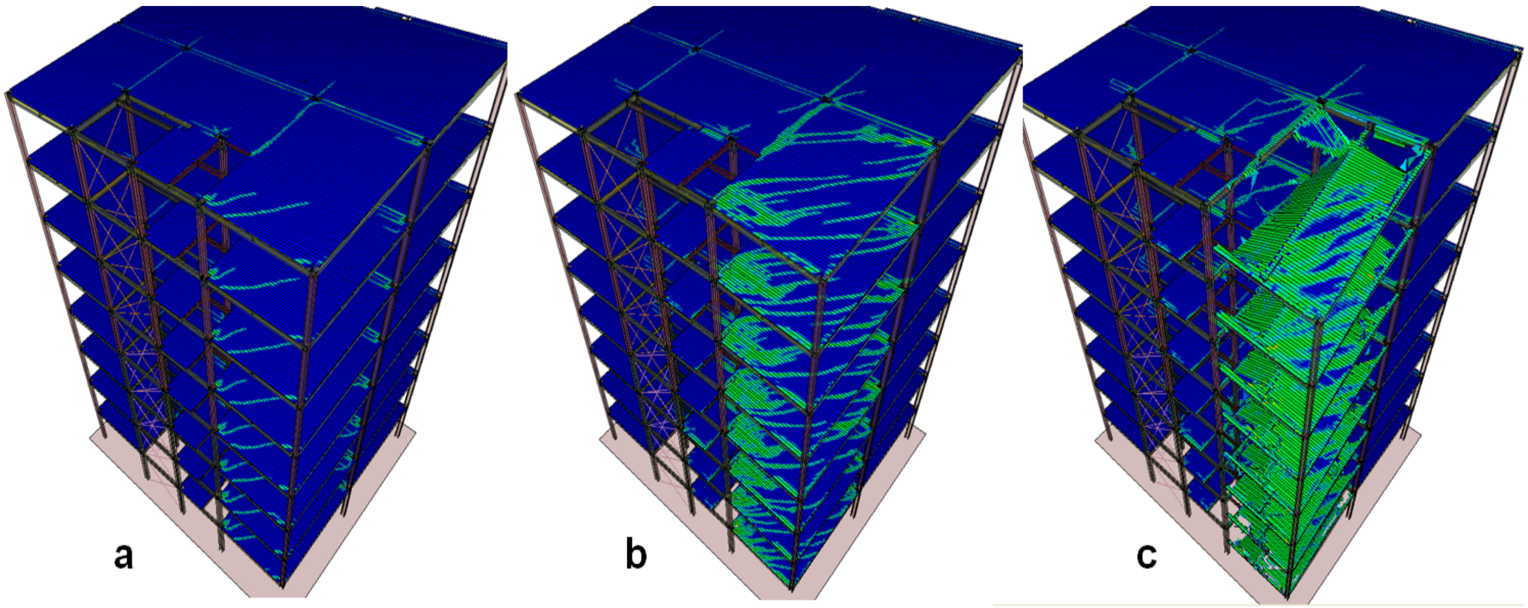



Lutomirski, S. Kwasniewski, L. Kozyra, Z. Winnicki, A. Failure analysis of Chorzów Trade Hall roof collapse. 23rd Conference „Structural Failures”. Szczecin – Miedzyzdroje, Poland, 2007



# EXAMPLES

Multistory building (Cardington Large Building Test Facility)
Explicit transient dynamic analysis
Sheel elemnts – local effects
3D models of beams and columns
Global model
LS-DYNA




*t* = 3 s     *t* = 9 s     *t* = 10 s

Kwasniewski, L.  Nonlinear dynamic simulations of progressive collapse for a multistory building, 3rd WG Meetings March 2-3, 2009, Coimbra, Portugal



# SUMMARY

Tendencies:

Commercial nonlinear FE programs

Beam element models dominate

2D subsystems

Both static and dynamic

Multilevel strategy

Recommendation:

At the current stage different research paths should be explored