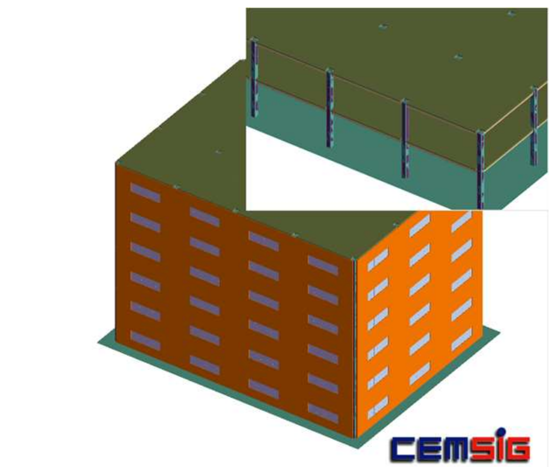
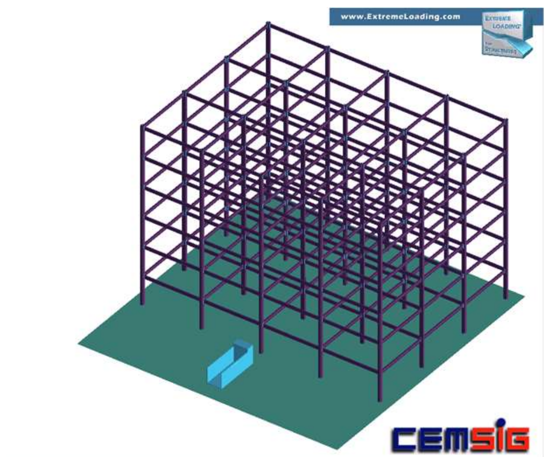
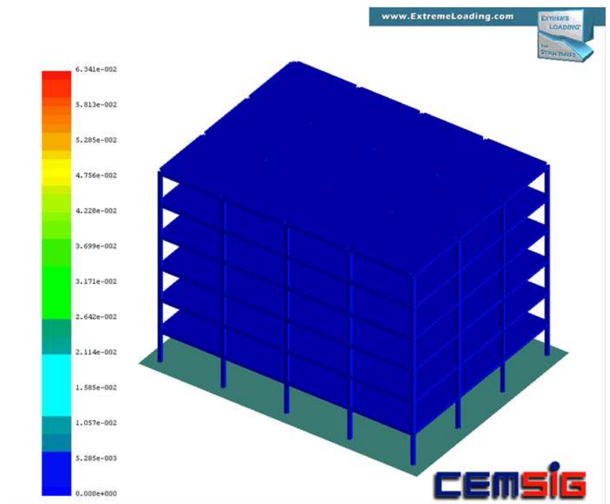
Universitatea Politehnica Timişoara

Robustness of structures

Blasts and explosions







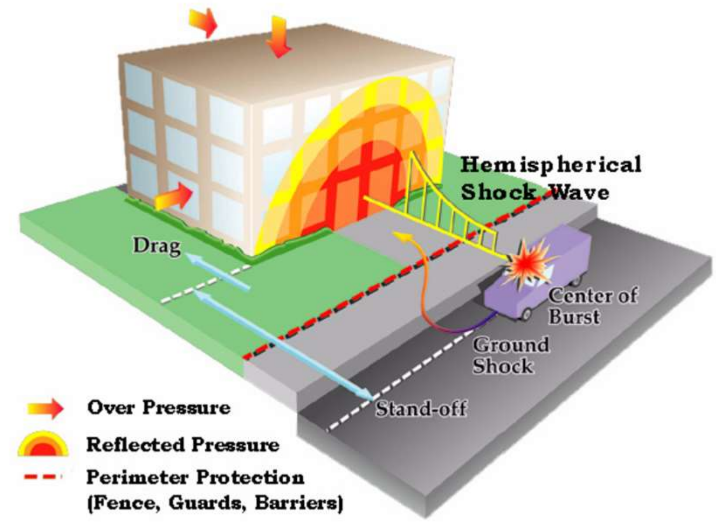
2018-2019

Main Text and Reference Materials :

1. Chopra, Anil. – Structural Dynamics
2. Krauthammer, T. – Modern Protective Structures, CRC Press, 2008
3. Smith, P. D. and Hetherington, J. G., “Blast and ballistic loading of structures.”
4. Baker, W. E., et al., “Explosion Hazards and Evaluation.”
5. Donald O. Dusenberry, Handbook for blast-resistant design of buildings
6. FEMA427, Risk Management Series Primer for Design of Commercial Buildings to Mitigate Terrorist Attacks, December 2003.
7. *Green Book,* Methods for the determination of possible damage to people and objects resulting from release of hazardous materials, CPR 16E, TNO, 1992.
8. Hopkinson, B. British Ordnance Board Minutes 13565, 1915.
9. Cranz, C. Lehrbuch der Ballistik, Springer-Verlag, Berlin, 1926.
10. UFC 3-340-02, Structures to resist the effects of accidental explosions, 2008 (with change 2, September 2014)

Introduction

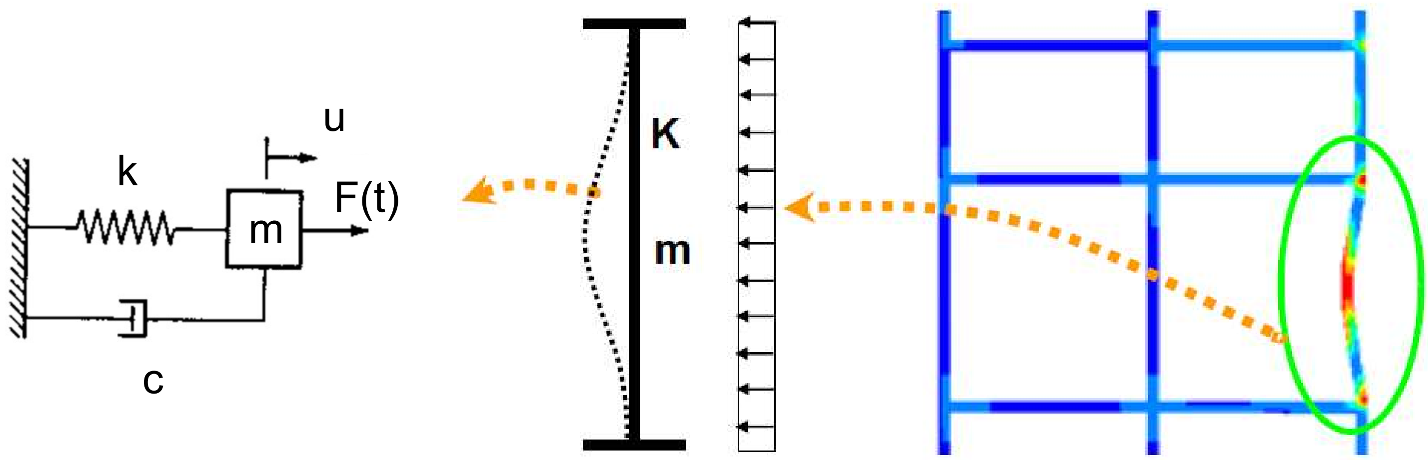
- Vulnerability of buildings, bridges, tunnels, and utilities in the midst of numerous recognized international social and political instabilities expanded the interest for explosion and blast resistant design
- Examples (no conflict zones):
  - World Trade Center's Tower One's underground parking garage rocked by a powerful explosion (1993)
  - Explosion that demolished the Alfred P. Murrah Federal Building in Oklahoma City in 1995
  - London Underground, 2005
  - Brussels bombing, 2016
- Engineers need training and information so that they can provide designs that effectively enhance a building's response to explosions



Blast loads on a building, FEMA427

Classification of dynamic loads on structures

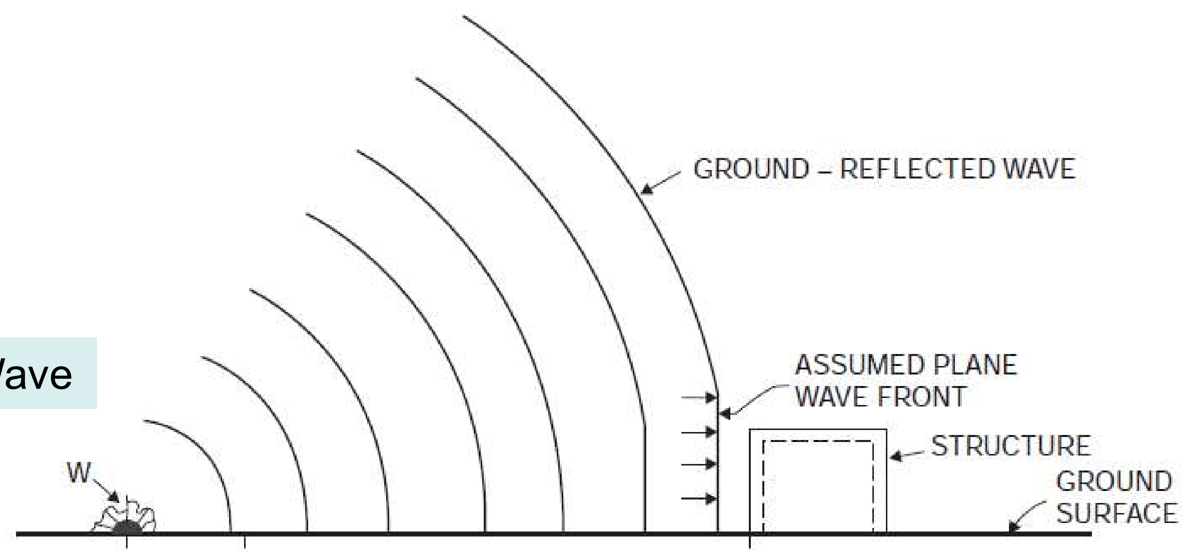
- Lower frequency dynamic loading: wind, earthquake ground motions – frequency up to a few Hertz
- Medium to high frequency dynamic loading: construction vibration; blast-induced ground excitation – Frequency order of 10's ~ 100's Hz
- Shock and impact loading, e.g. due to blast – pulse duration in the order of milliseconds



Blast phenomena

- Blast is a pressure disturbance caused by the sudden release of energy:
  - detonation of an explosive
  - flammable materials mixed with air can form vapor clouds that when ignited can cause very large blasts
  - bursting pressure vessel from which compressed air expands
  - rapid phase transition of a liquid to a gas
- The loads resulting from a blast are created by the rapid expansion of the energetic material, creating a pressure disturbance or blast wave radiating away from the explosion source, as shown in the figure

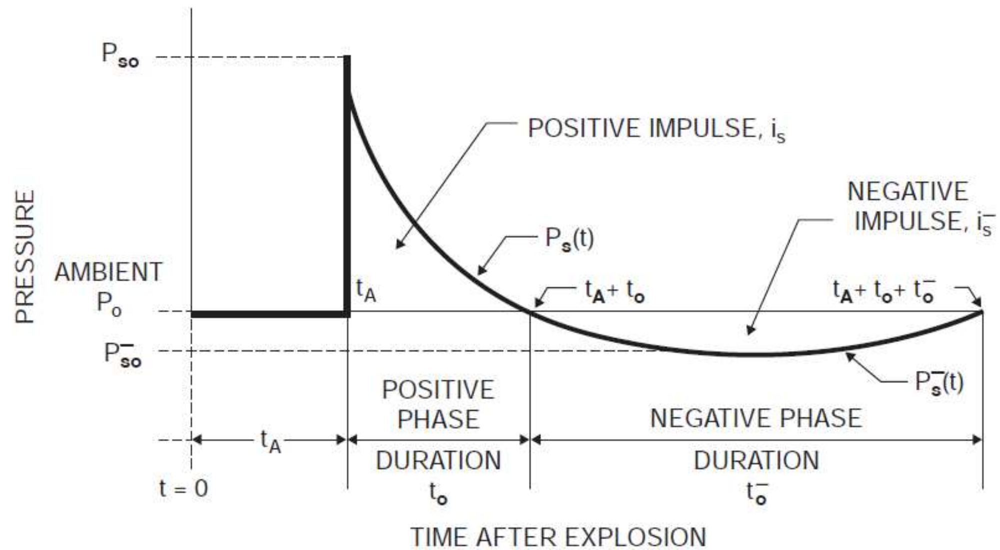
Propagating Blast Wave



Blast pressure

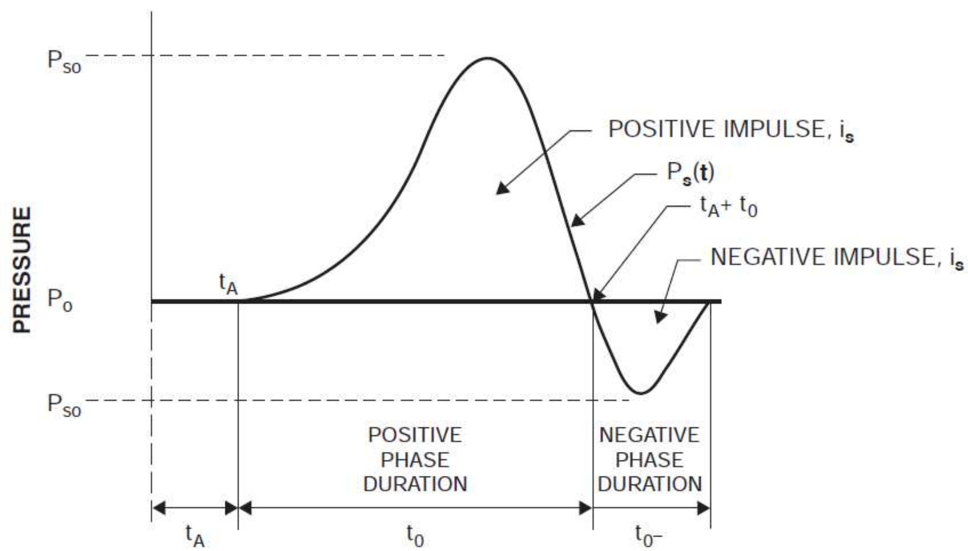
- Shock waves :
  - are high-pressure blast waves that travel faster than the speed of sound.
  - shock waves are characterized by an instantaneous increase in pressure followed by a rapid decay.
- Pressure waves:
  - are lower amplitude and travel below the speed of sound.
  - are characterized by a more gradual increase in pressure than a shock wave, with a decay of pressure much slower than a shock wave
- Shock waves have a greater potential for damage and injury than pressure waves.

Shock Wave from Detonation



In a detonation, the reaction front propagates supersonically, usually many times faster than the speed of sound

Pressure Wave from Deflagration



A deflagration is an oxidation reaction that propagates at a rate less than the speed of sound in the unreacted material

- Explosive materials (solid materials, combustible gases) can be broadly categorized based on their state:
  a. High explosives (capable to produce detonation): e.g. TNT
  b. Propellants and pyrotechnics (also known as low explosives) - do not typically detonate (e.g. black powder)
  c. Vapor cloud explosions (overpressures produced by vapor cloud explosions are substantially lower than those produced by high explosive)
- Energy output and standoff distance are key to accurately determining blast loads acting on a structure.

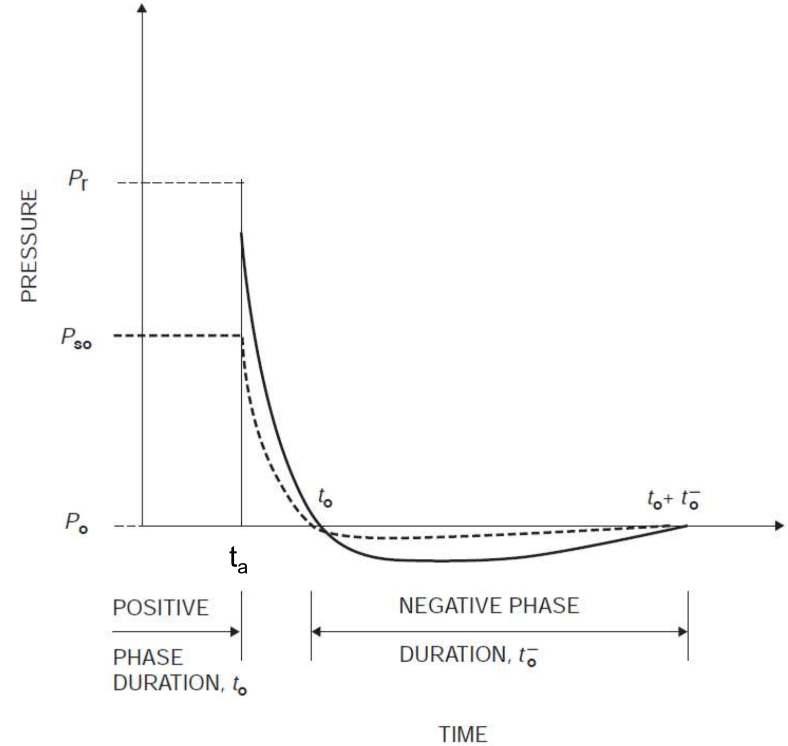
a)

b)

c)

Characteristics of blast waves

- Key parameters of a blast load are presented in the figure
- Blast pressures, load duration, impulse, shock wave velocity, arrival times, and other blast parameters are frequently presented in scaled form - the most common form of scaling is called "cube root scaling" - blast parameters are scaled by the cube root of the explosion energy
- Prediction of blast parameters – very important for calculation of the loads imposed to the structure



P_o = Ambient pressure
P_{so} = Peak positive side-on overpressure
P_{so}^- = Peak negative side-on overpressure
$P_s(t)$ = Time varying positive overpressure
$P_s^-(t)$ = Time varying negative overpressure
P_r = Peak reflecte overpressure
I_s = Positive-phase-specifi impulse, the integration of the positive phase pressure-time history
i_s^- = Negative-phase-specifi impulse, the integration of the negative phase pressure-time history
t_a = Time of arrival
t_o = Positive phase duration
t_o^- = Negative phase duration

High Explosives

- Blast parameter curves typically plot air-blast parameters versus scaled distance (for both air-burst and surface-burst configurations) (e.g. Hopkinson-Cranz, or cube root, scaling method)
- The scaled distance is obtained by dividing the standoff distance from the charge to the point of interest by the cube root of the charge weight (Hopkinson-Cranz law)
- For explosives, this takes the form of:

$$Z = R/W^{1/3}$$

where:
Z = scaled distance (ft/lb$^{1/3}$)
R = standoff distance (ft)
W = explosives weight (lb)

1 pound = 0.45 kg
1 ft = 0.30 m
1 psi=6.89kN/m^2

Example: Oklahoma City Bombing.

- event equivalent to the detonation of 4,000 lbs of TNT at essentially the ground surface.
- If a location of interest is 100 ft away, the scaled distance is

$$Z = 100/(4000)^{1/3} = 6.30 \text{ ft/lb}^{1/3}$$

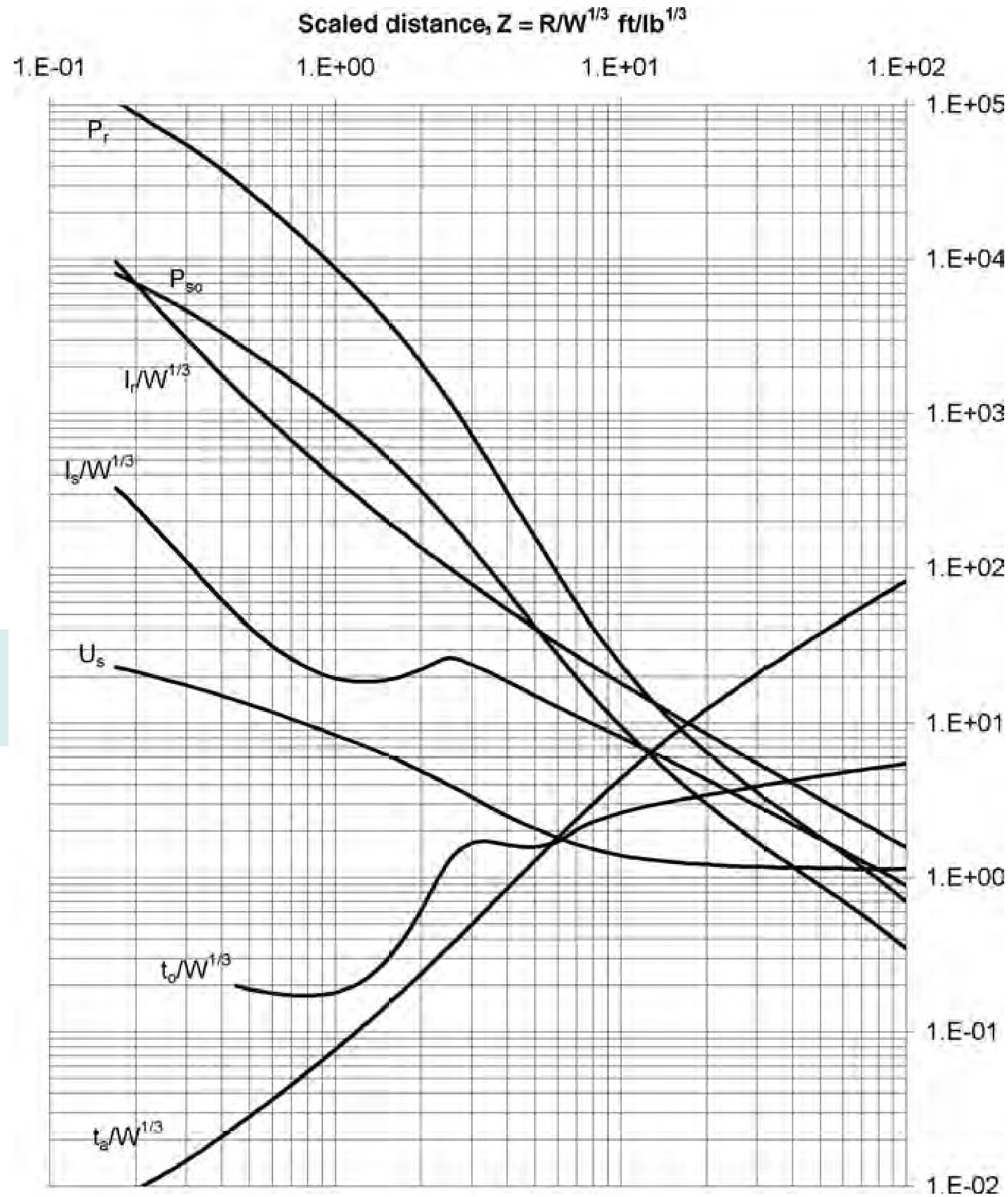
- We have an incident pressure of P_{so} = 24.9 psi and a reflected pressure of P_r = 79.5 psi at this scaled range (see diagram plotted on the next slide)
- The scaled positive phase duration is:

$$t_o/W^{1/3} = 1.77 \text{ msec/lb}^{1/3}$$

- The positive phase duration is:

$$t_o = 1.77 \times (4000)^{1/3} = 28.1 \text{ msec}$$

Blast Parameters for TNT Surface Bursts

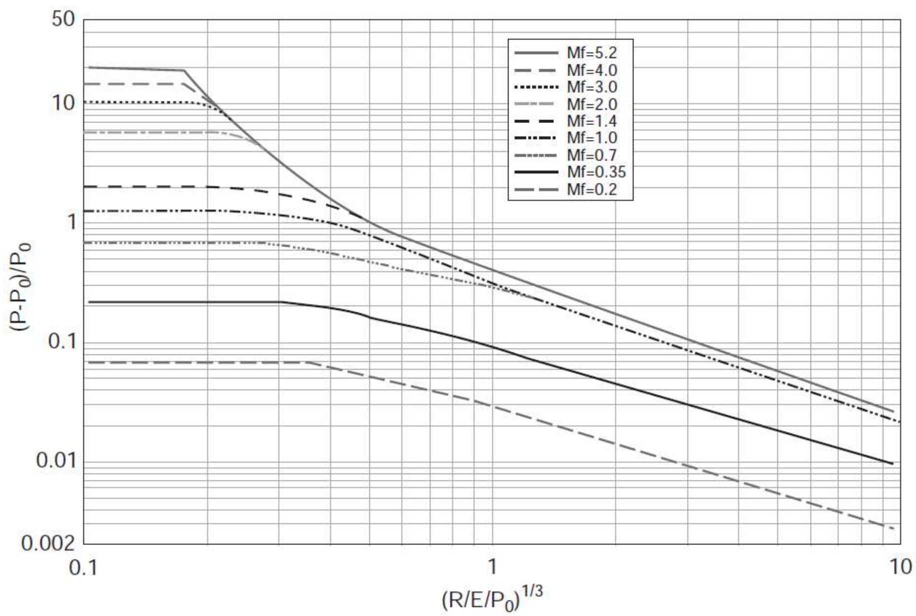


Vapor Cloud Explosions

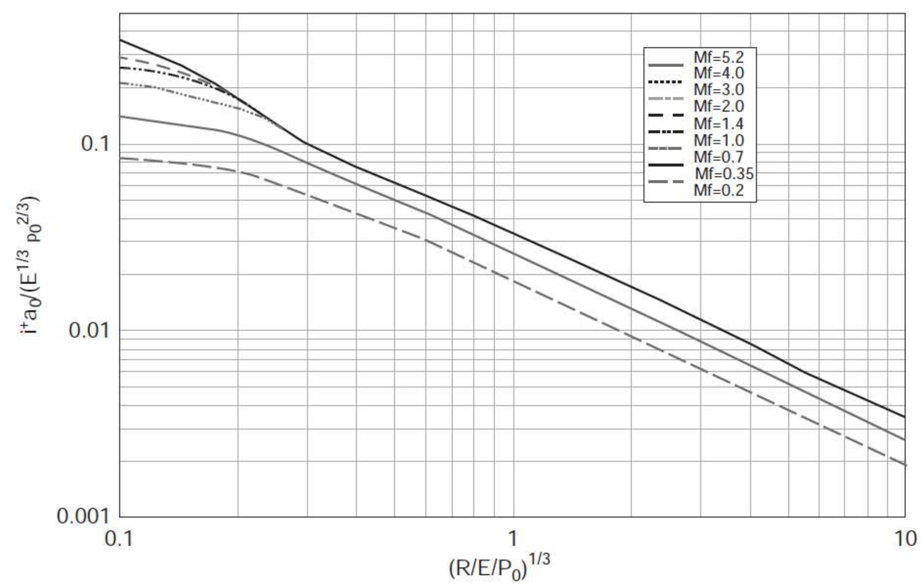
- Prediction of blast loads for vapor cloud explosions can be more complex than loads for high explosive detonations:
  - It is necessary to develop the release scenario for the flammable material
  - Three method are mainly used: TNT equivalence method, blast curves of pressure and impulse method, and detailed numerical simulations (computational fluid dynamics CFD)

Blast curves method

- The scaled standoff is computed by using distance from the center of the explosion to the point of interest and the energy content of the confined/congested flammable mass
- Scaled pressure and impulse values are read from blast charts containing flam speed curves
- The two most commonly used methods are the Baker-Strehlow-Tang (BST) and TNO Multi-energy Method (MEM)



Peak Pressure for Vapor Cloud Explosions—BST



Impulse for Vapor Cloud Explosions—BST

$R_{bar} = R(p_o/E)^{1/3}$

where:

R_{bar} = scaled distance
R = standoff distance
p_o = ambient pressure
E = heat of detonation

M_f = flame speed (Mach number)

$\rightarrow$ $P_{bar} = (P/p_o)$
$i_{bar} = i\, a_o/(E\, p_o)^{1/3}$ $\rightarrow$ P, i $\rightarrow$ t_0

P_{bar} = scaled pressure
i_{bar} = scaled impulse
a_o = ambient sound velocity

$t_o = 2i/P$
t_0 is the equivalent triangular duration

Blast loading

- Empirical method consists of equations, graphs, tables, and figures that allow to determine the principal loading of a blast wave on a building or a similar structure.
- Software has also been developed to automate calculations based on the same source information.
- More comprehensive methods, such as computational fluid dynamics (CFD), require specialized software, operator training (is potentially time consuming)
- Most data are based on plain rectangular target structures located in open terrain.
- Explosions are assumed to be either an air blast or surface blast.
- There are three blast loading situations:
  - a blast wave interaction with a rectangular structure of finite size - the structure is blast-loaded on all sides (a significant lateral force applied to the structure)
  - a blast wave interacting with a relatively small structure, such as a vehicle, that is effectively engulfed with blast pressure acting on all sides of the structure at once
  - a blast wave acting on a relatively large structure, such as a large office building, where the magnitude of the blast wave varies significantly across the surfaces of the structure. Some surfaces of these structures may see little or any external blast loading

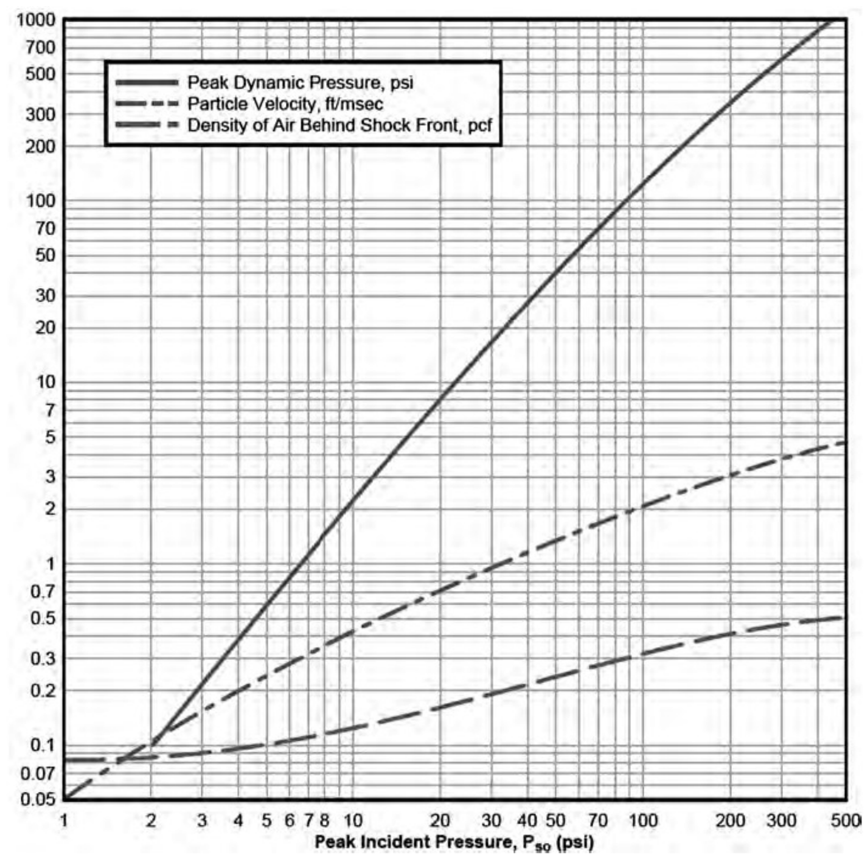
Determination of building loads

- Key input parameters for the determination of building loads are:
  - the peak side-on overpressure, P_{so}
  - the positive phase duration, t_o
  - the shock front velocity, U_s
- Another parameter necessary for the determination of building blast loads is the dynamic wind pressure, q_o (see figure)

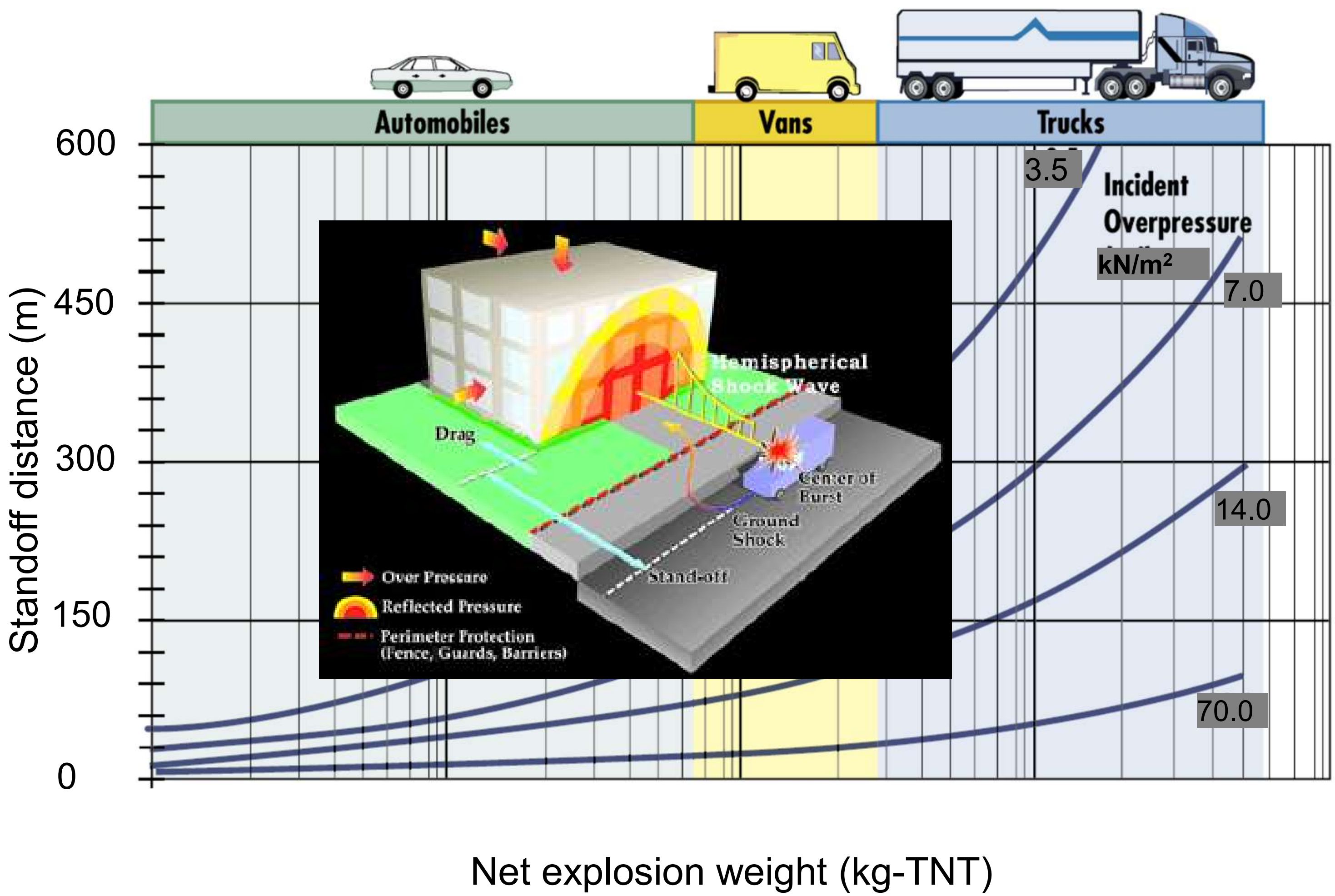
Alternatively $q_o = 0.022\,(P_{so})^2$

- The pressure exerted on a structural element is the dynamic wind pressure, q_0, multiplied by a drag coefficient, C_d
- C_d is 2 for structural shapes, 1.25 for box shapes, and 0.8 for cylinders

1Psi = 6.89 kN/m^2



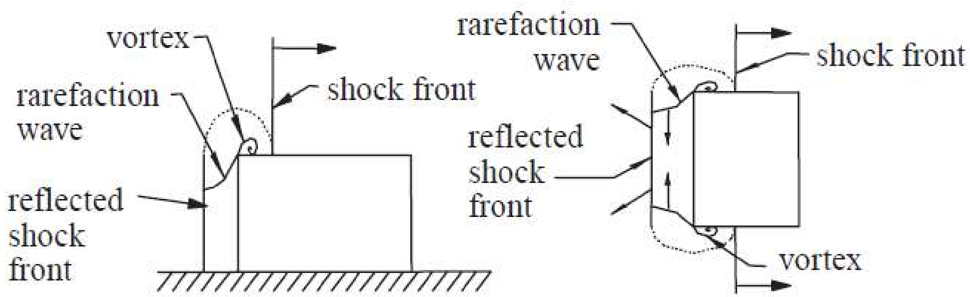
Peak Incident Pressure versus Peak Dynamic Pressure, Density of Air Behind the Shock Front, and Particle Velocity (UFC 3-340-02)



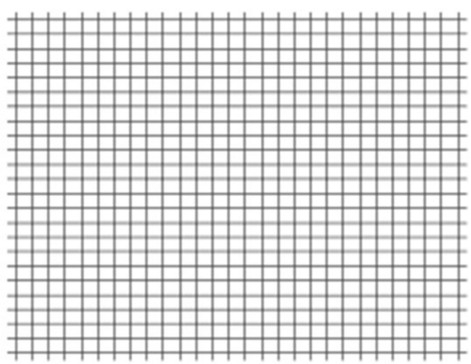
Vehicle Bomb Sizes, Standoffs and Overpressures

Front wall loads

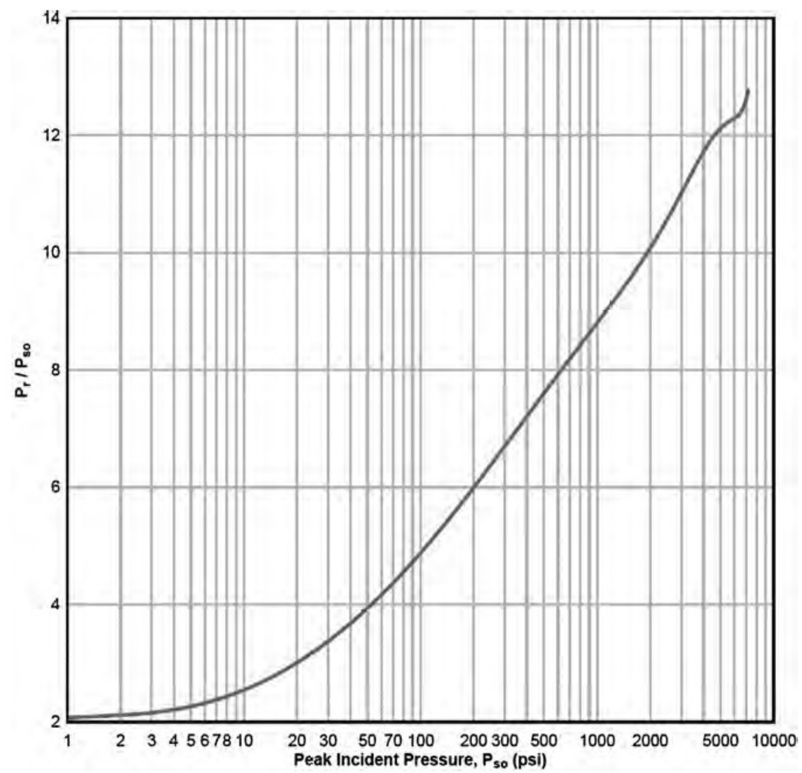
- The wall facing the explosion source is subjected to a reflection effect
- The reflection effect amplifies the blast pressure on the front or facing side of the building



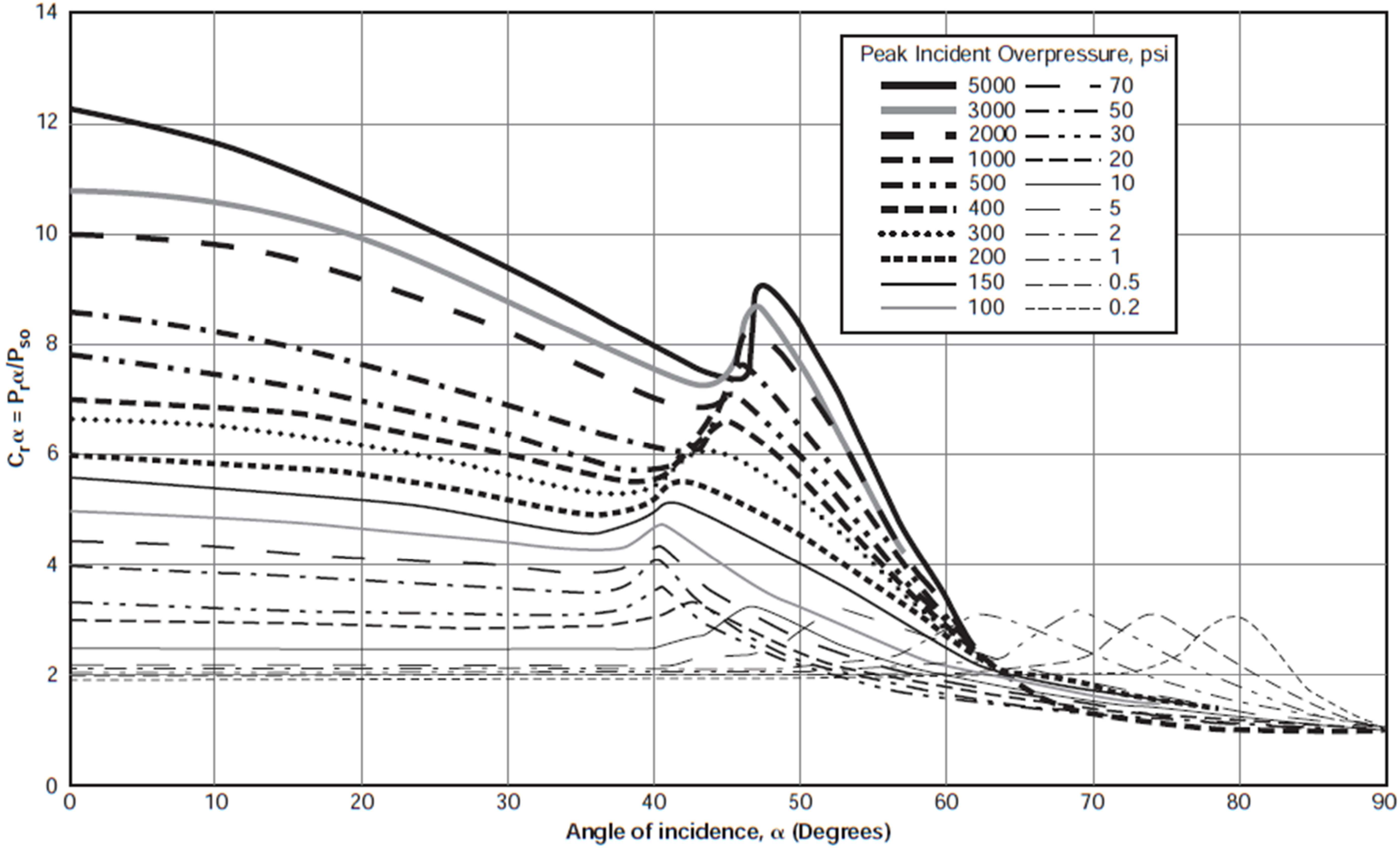
Blast Wave at Front Wall (TNO Green Book)



Example of rarefaction - a phase in a sound wave



Peak Incident Pressure versus the Ratio of Normal Reflected Pressure/ Incident Pressure for a Free-Air Burst (UFC 3-340-02)



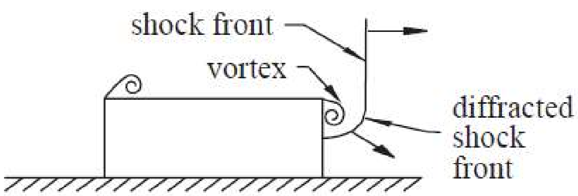
Reflected pressure coefficient versus Angle of Incidence (UFC 3-340-02)

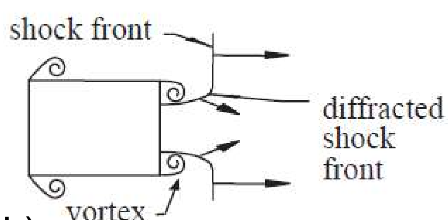
Side wall and roof

- Roofs and side walls represent surfaces that are parallel to the path of the advancing blast wave
- There is no reflection effect for this situation; however, the average pressure applicable to a specific area, for example a structural element depends on the length of the blast wave and the length of the structural element
- For the calculation of roof and side wall dynamic wind pressure, a drag coefficient C_d, determined from the table is used with the q_o value

Rear wall

- The rear wall is the wall facing directly away from the blast source, as illustrated in figure below
- The calculation of rear wall blast loads is similar to that for the side walls or roof.
- For the calculation of rear wall dynamic wind pressure, a drag coefficient Cd is used with the q_o value





Rear Wall (TNO Green Book)

Roof, Side Wall, and Rear Wall Drag Coefficient

Peak dynamic pressure	Drag coefficien
0–25 psi	−0.40
25–50 psi	−0.30
50–130 psi	−0.20

Steel building frames subjected to close-in detonations

STRUCTURAL CONCEPTION AND COLLAPSE CONTROL PERFORMANCE BASED DESIGN OF MULTISTORY STRUCTURES UNDER ACCIDENTAL ACTIONS

Preliminary investigations

↓

Design of experimental and numerical program

↓

Experimental program materials, weld details and macro-components | Experimental program on joints | Experimental program on sub-assemblies

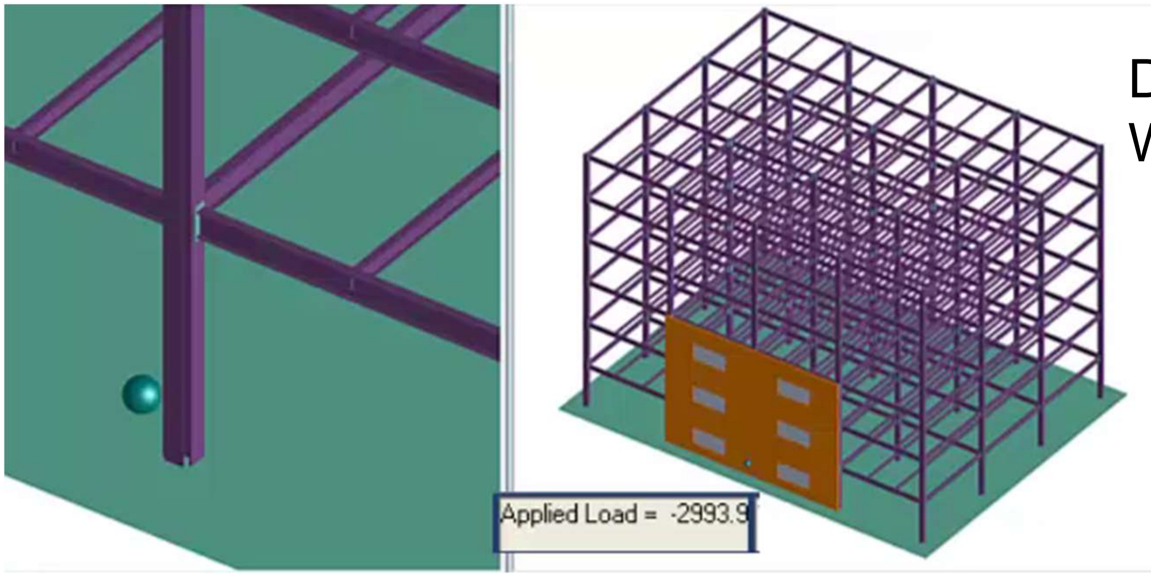
↓

Numerical program/ Analytical developments

↓

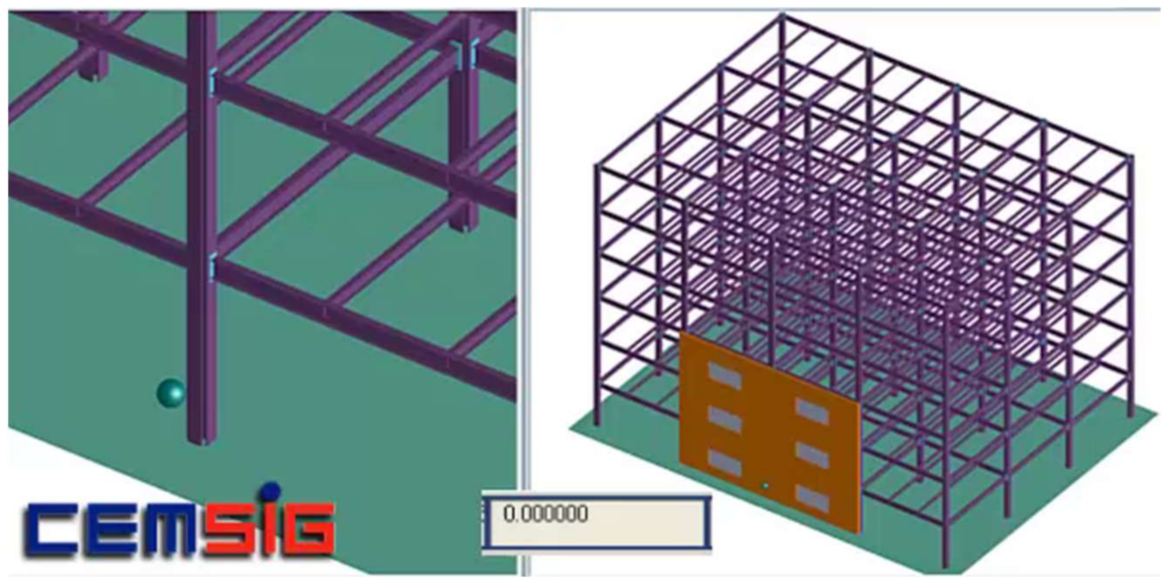
Design guidelines and recommendations

CODEC
2012-2016

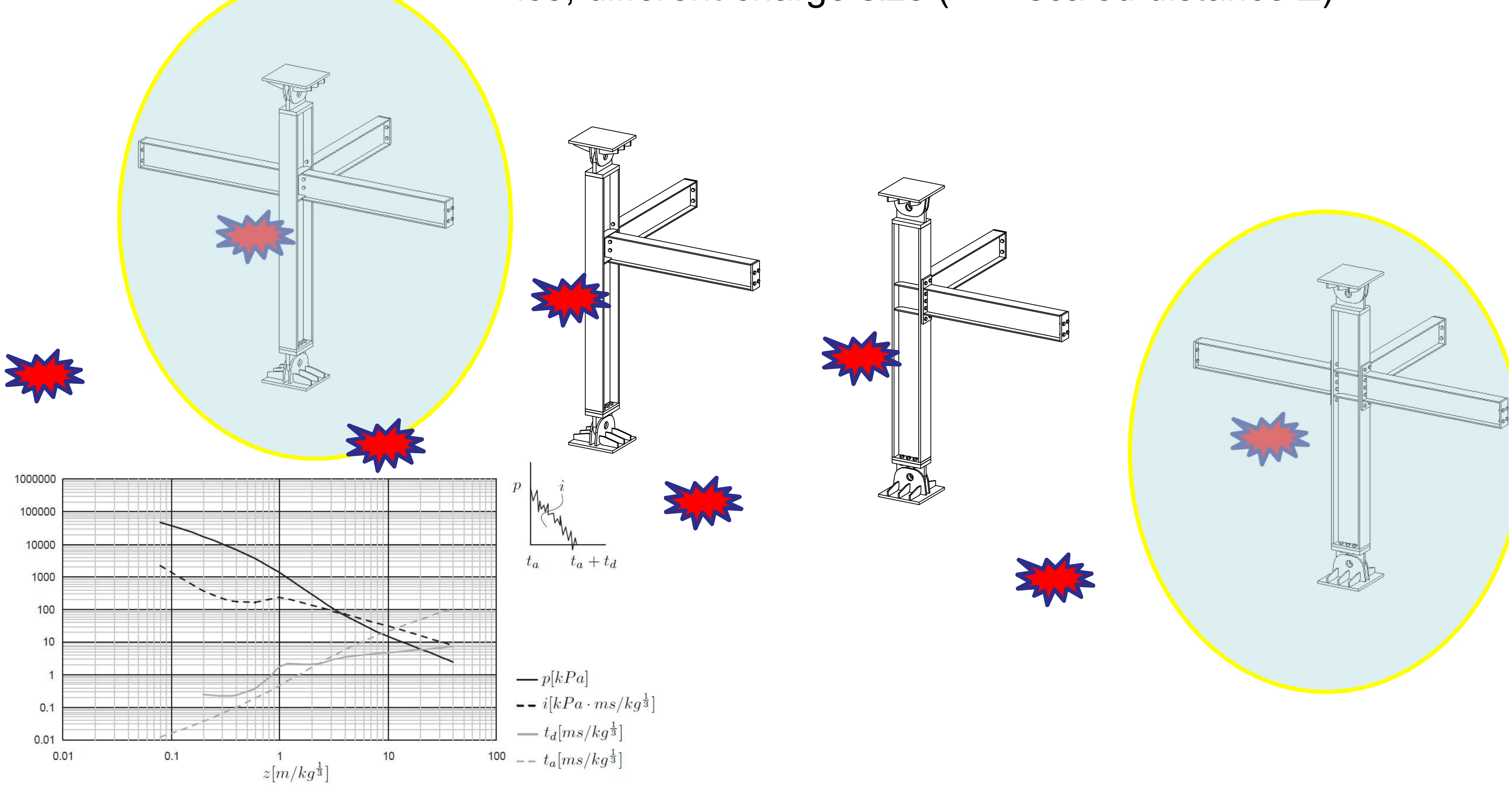


D=0.5 m
W = 100 kg TNT

D=0.5 m
W = 200 kg TNT

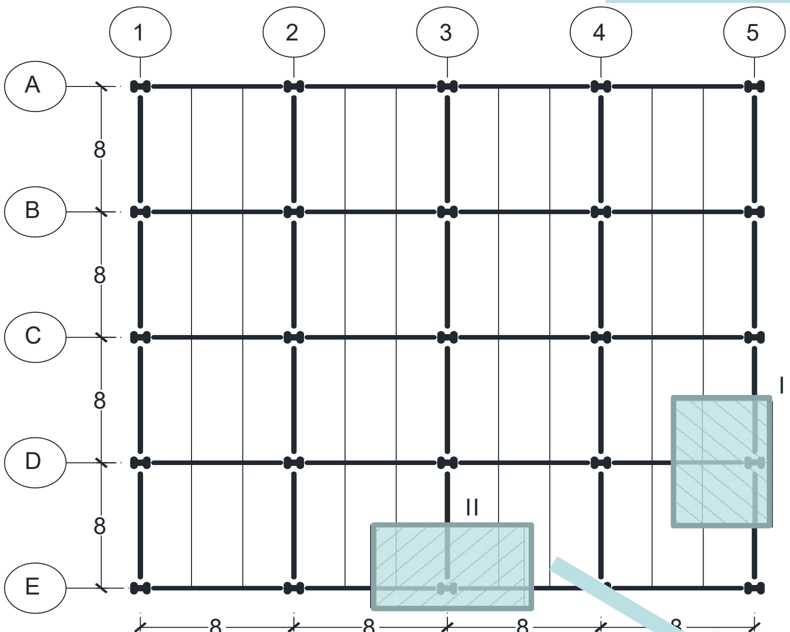


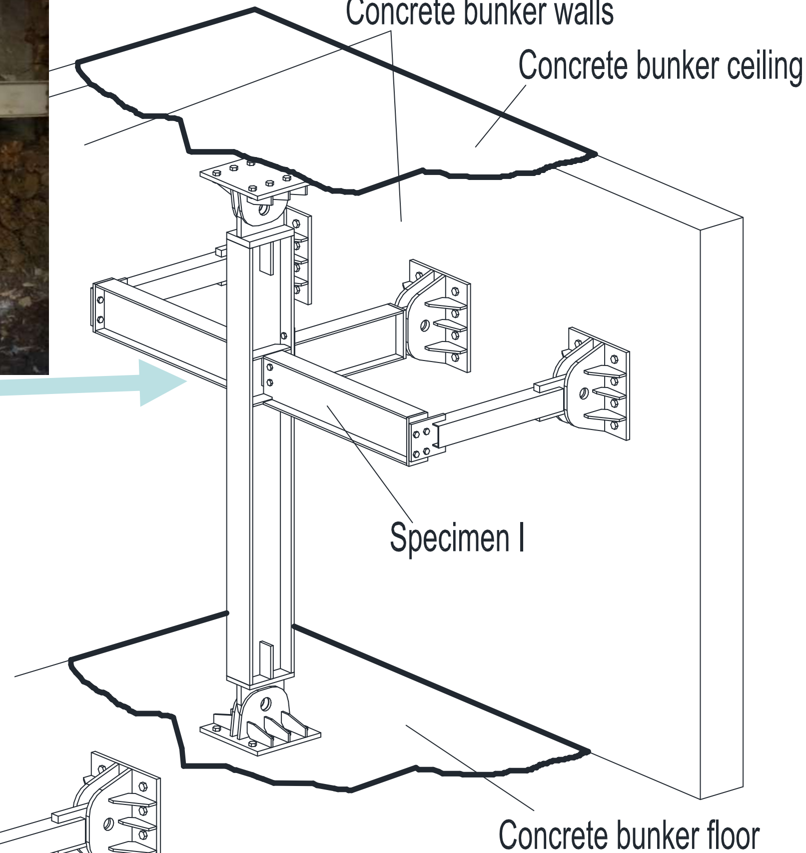
- Perimeter column, corner column
- Strong axis, weak axis
- Different stand off distance, different charge size (==> scaled distance Z)



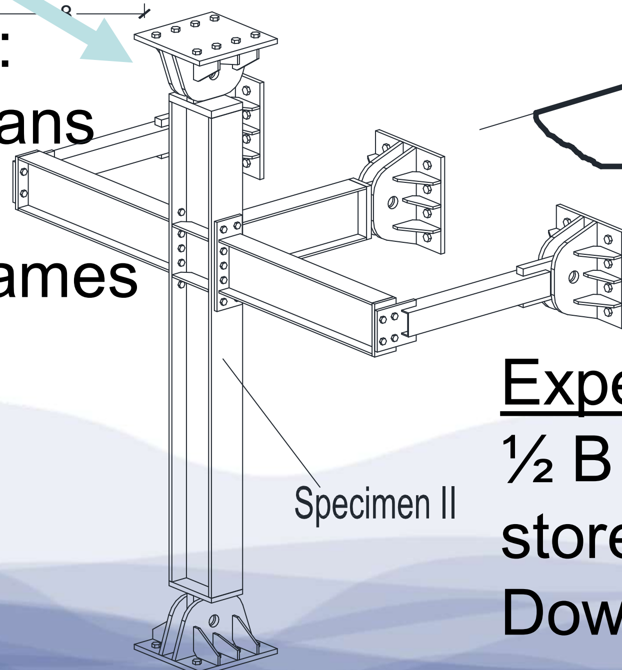
US Army, Navy, and Air Force. Structures to resist the effect of accidental explosions. Technical report, Departments of the US Army, Navy and Air Force, 1990.

Experimental set-up





<u>Case study building</u>:
4 x 8m bays and spans
6 x 4m storey
Moment resisting frames



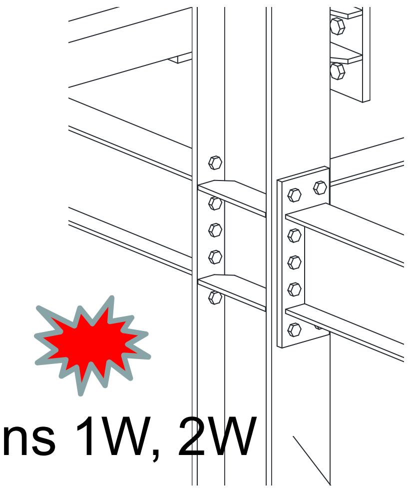
<u>Experimental specimen</u>:
½ B + C + ½ B from first storey of the structure
Downscaled 1 : 2.75

Experimental testing

IPE 220 section for beams

HEB 260 (with flanges reduced to a 160 mm) for columns

Steel material: S275 J0; Bolts grade 10.9



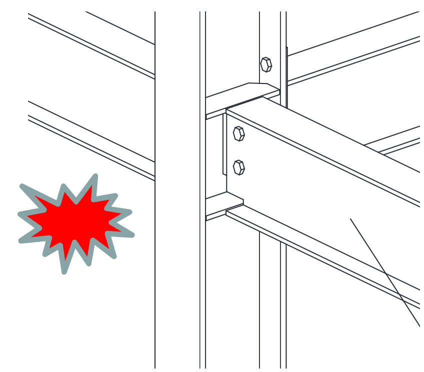
Specimens 1W, 2W

Kiestler pressure sensors

Four blast charges: m1 = 121 g, m2 = 484 g, m3 = 968 g, and m4 = 1815 g, placed at distance D = 50 cm from the column web

One charge m5 = 1815 g, at 20 cm distance from the column web,

One charge m6 = 1815 g, at 0 cm distance from the column flange (specimen 1S)



Specimens 1S, 2S

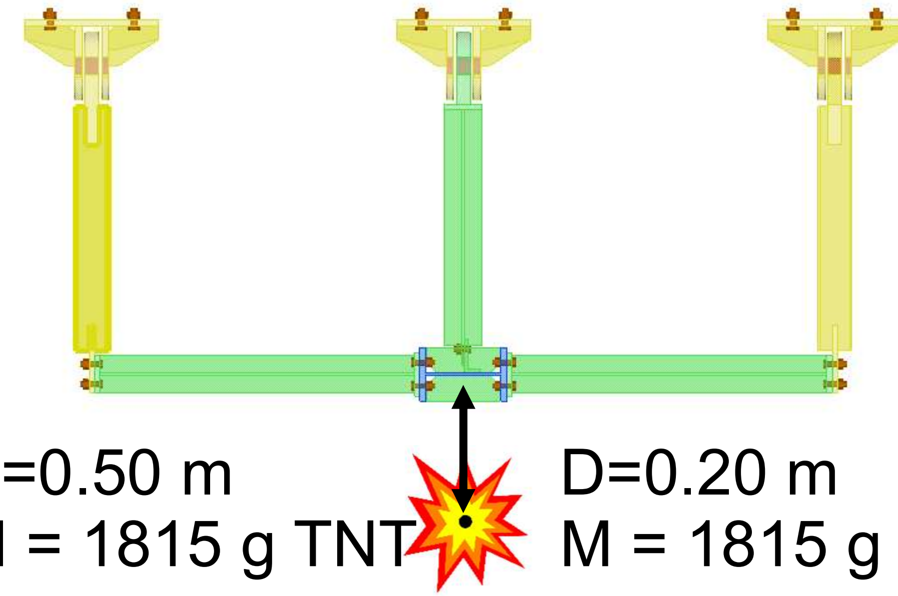
Charges freely suspended from the bunker ceiling

All charges placed at a height of 1.3 m from the ground and 30 cm beneath the bottom flange of the beam






Specimens W

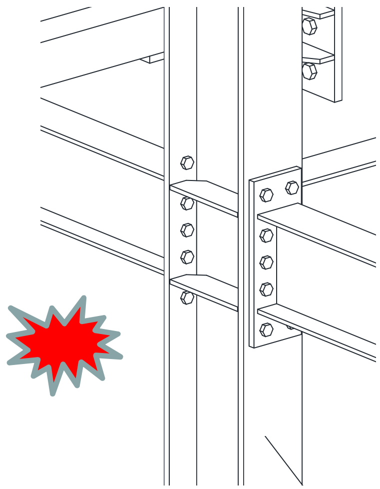


D=0.50 m
M = 1815 g TNT

D=0.20 m
M = 1815 g TNT

Δ_{max}= 22 mm

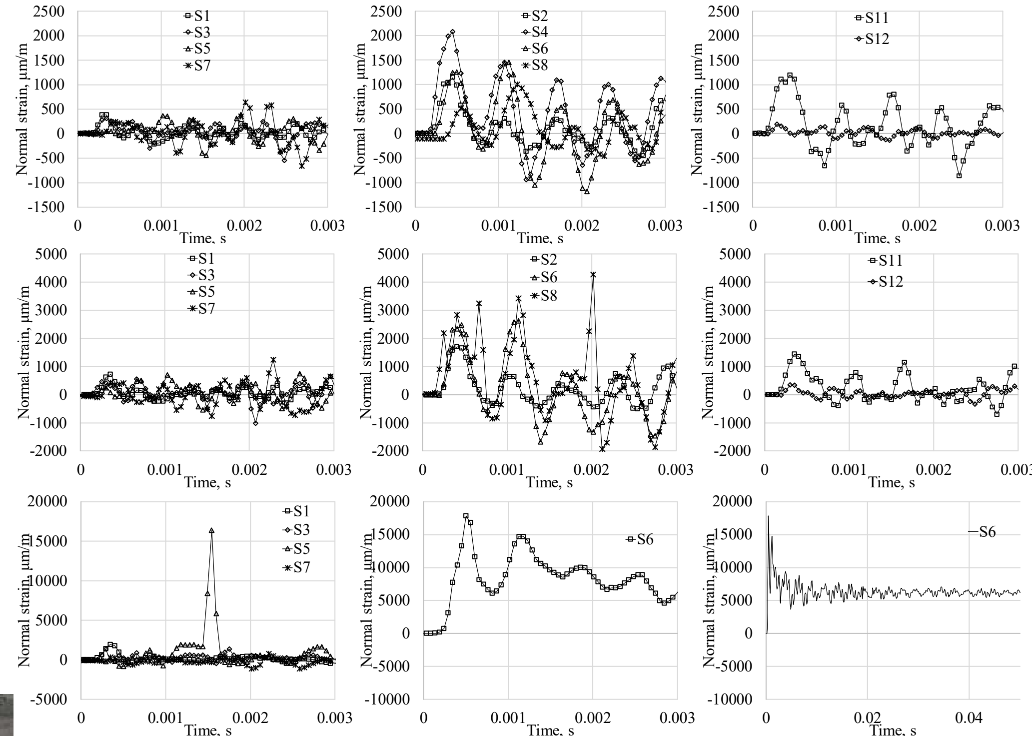
Web removed



Test m_2

Test m_3

Test m_4



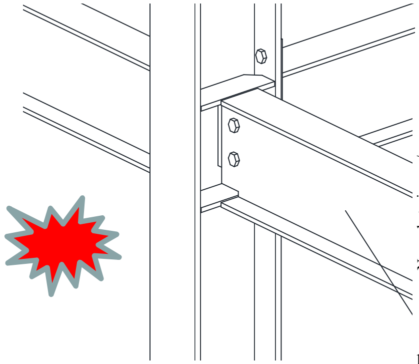
specimen 2W

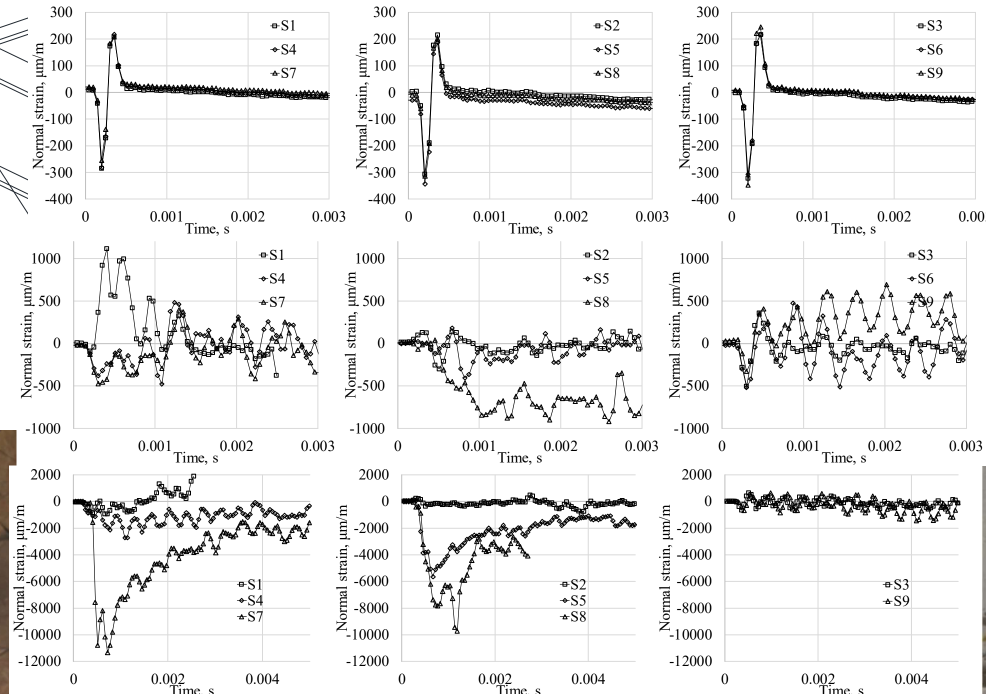
specimen 1W

specimen 1W

Column web fracture, D = 20 cm, W = 1815 g

Specimens S

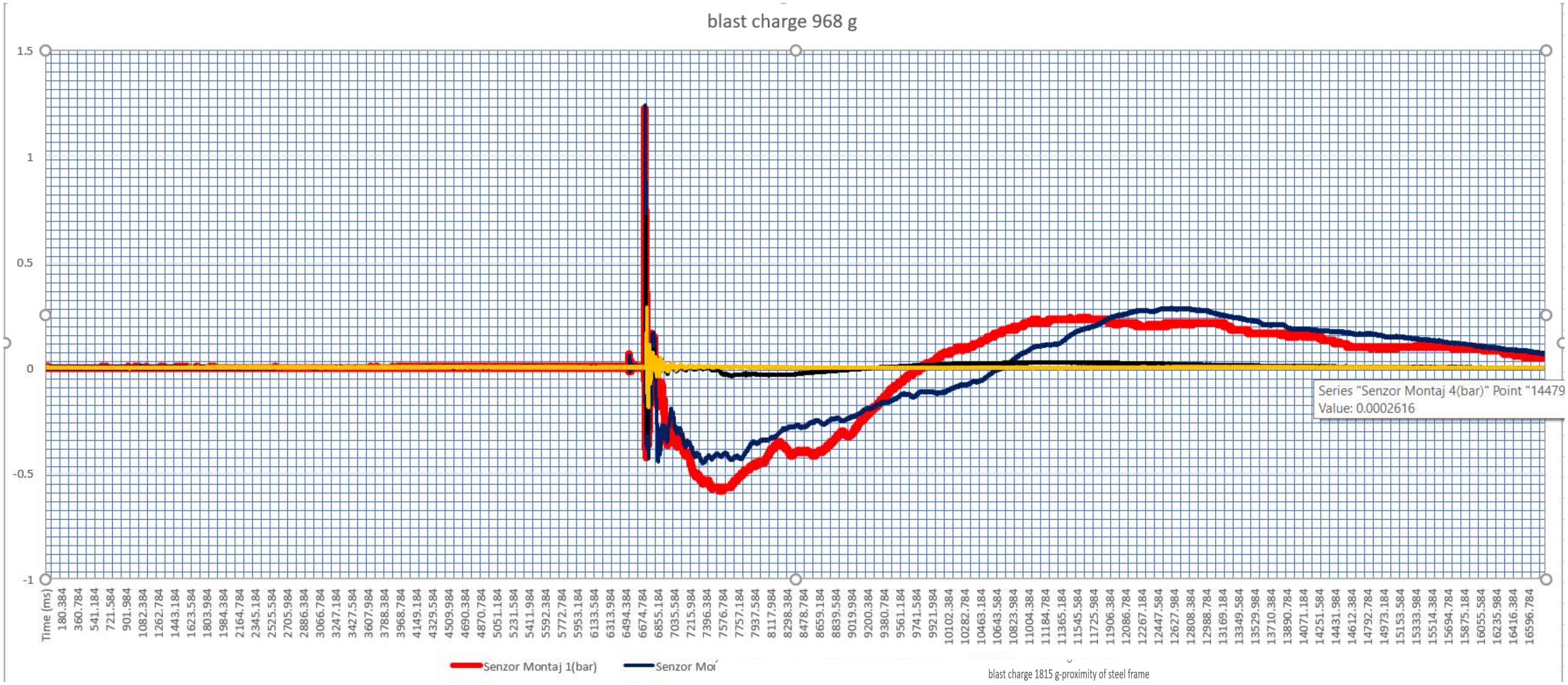


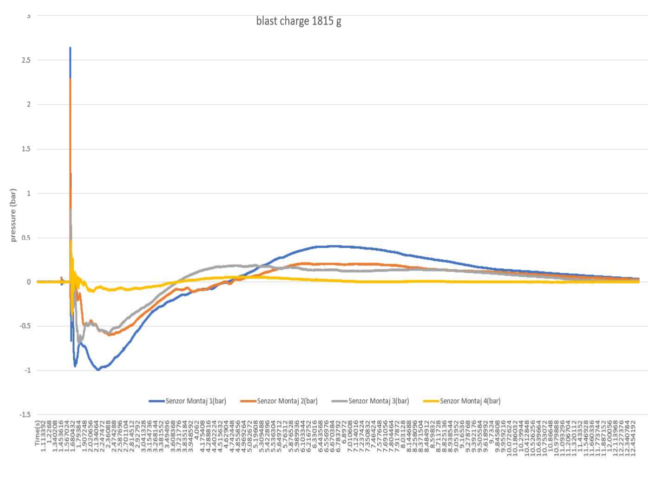


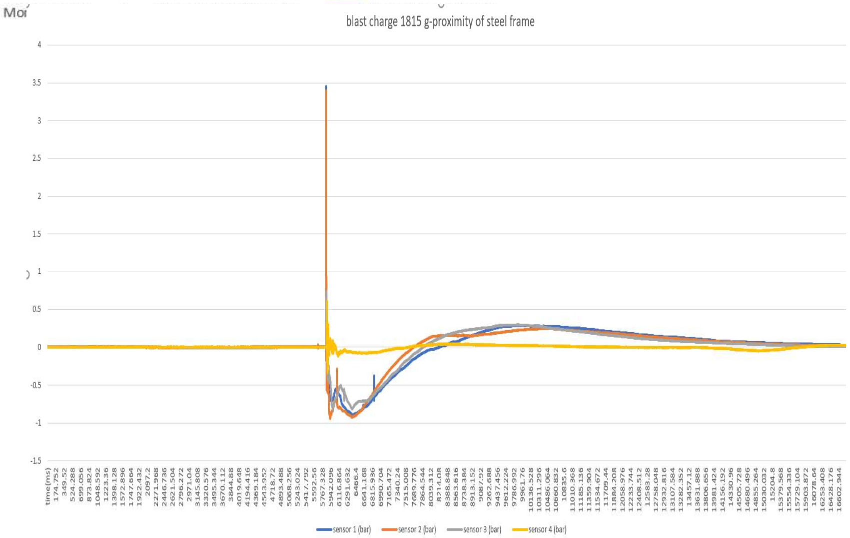
Specimen 1S
Column flange and web fracture,
D = 0 cm, W = 1815 g

Specimen 2S
Column flange bent, fracture at web toe
D = 0 cm, W = 968 g

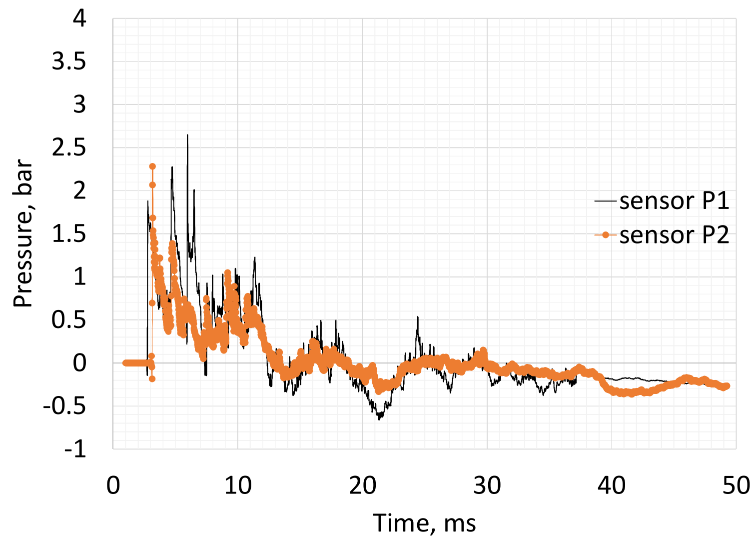
Pressure measurements,



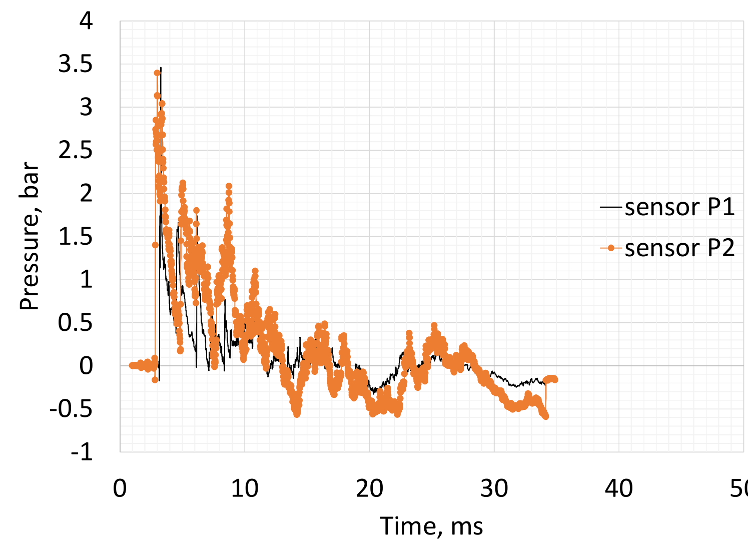




Pressure measurements, 1W



test m4 at D1



test m5 at D2

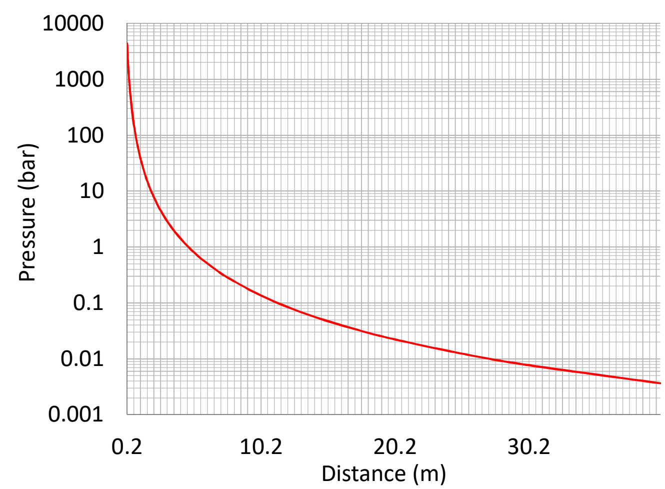
Pressure measurements, 1W

Determination of bunker parameters

$$Z = \frac{R}{W^{1/3}}$$

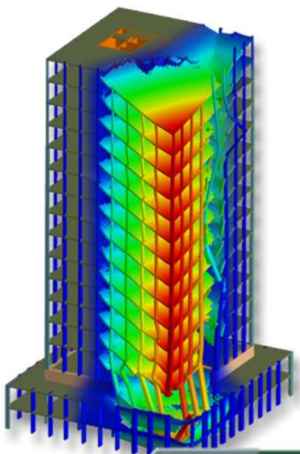
$$P = A \times \left(\frac{D}{(W)^{b}} \right)^{a}$$

A= 3850
a= - 0,73
b=3.87/3=1.29

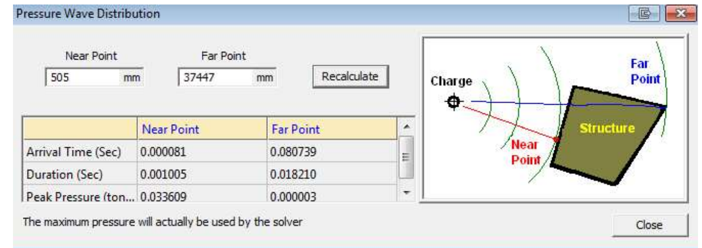


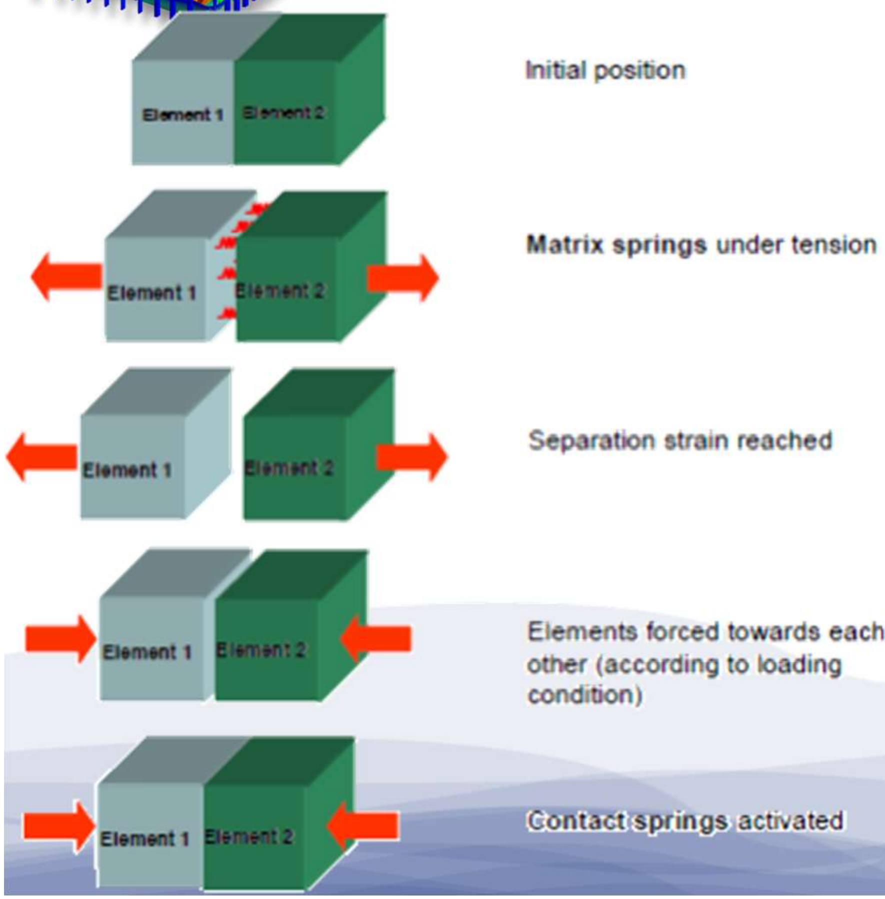
Peak pressure vs. distance between the blast source and the target surface

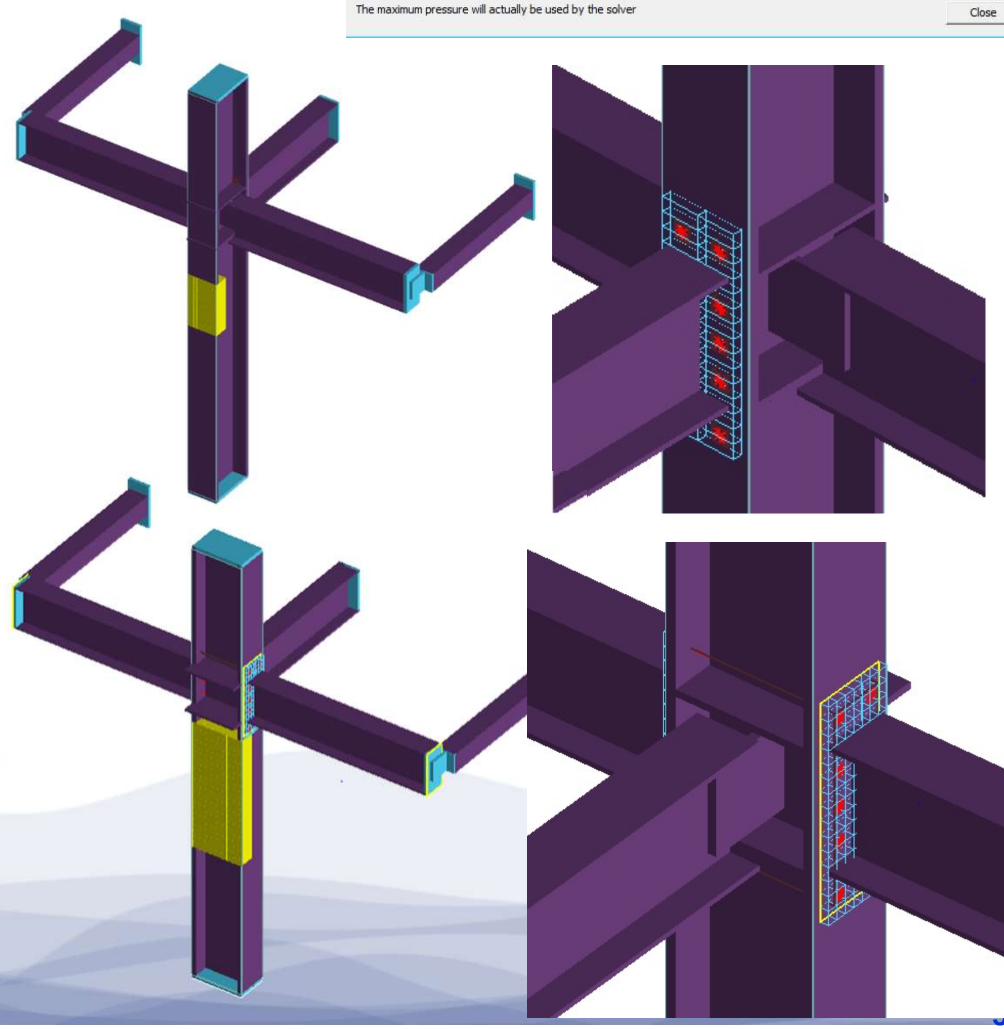
Numerical analysis



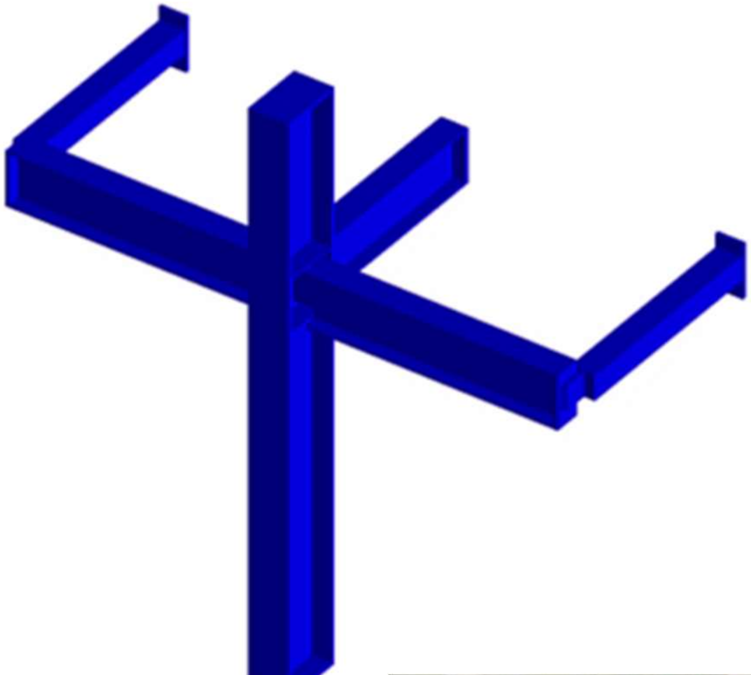
Applied Element Method (ELS)

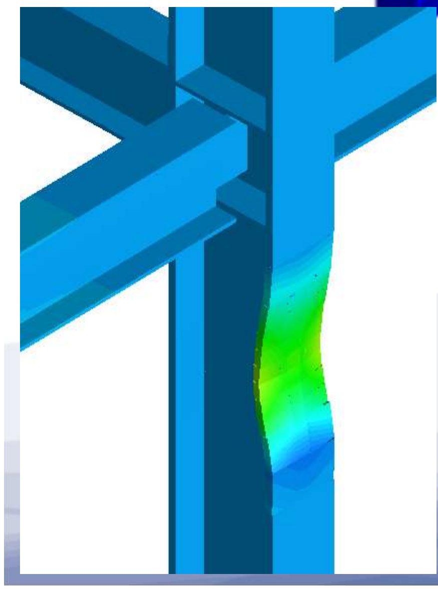


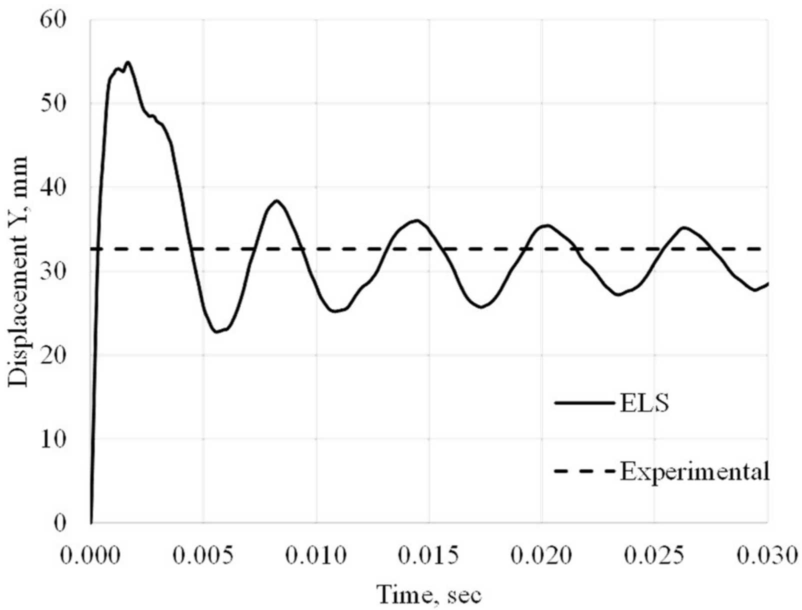




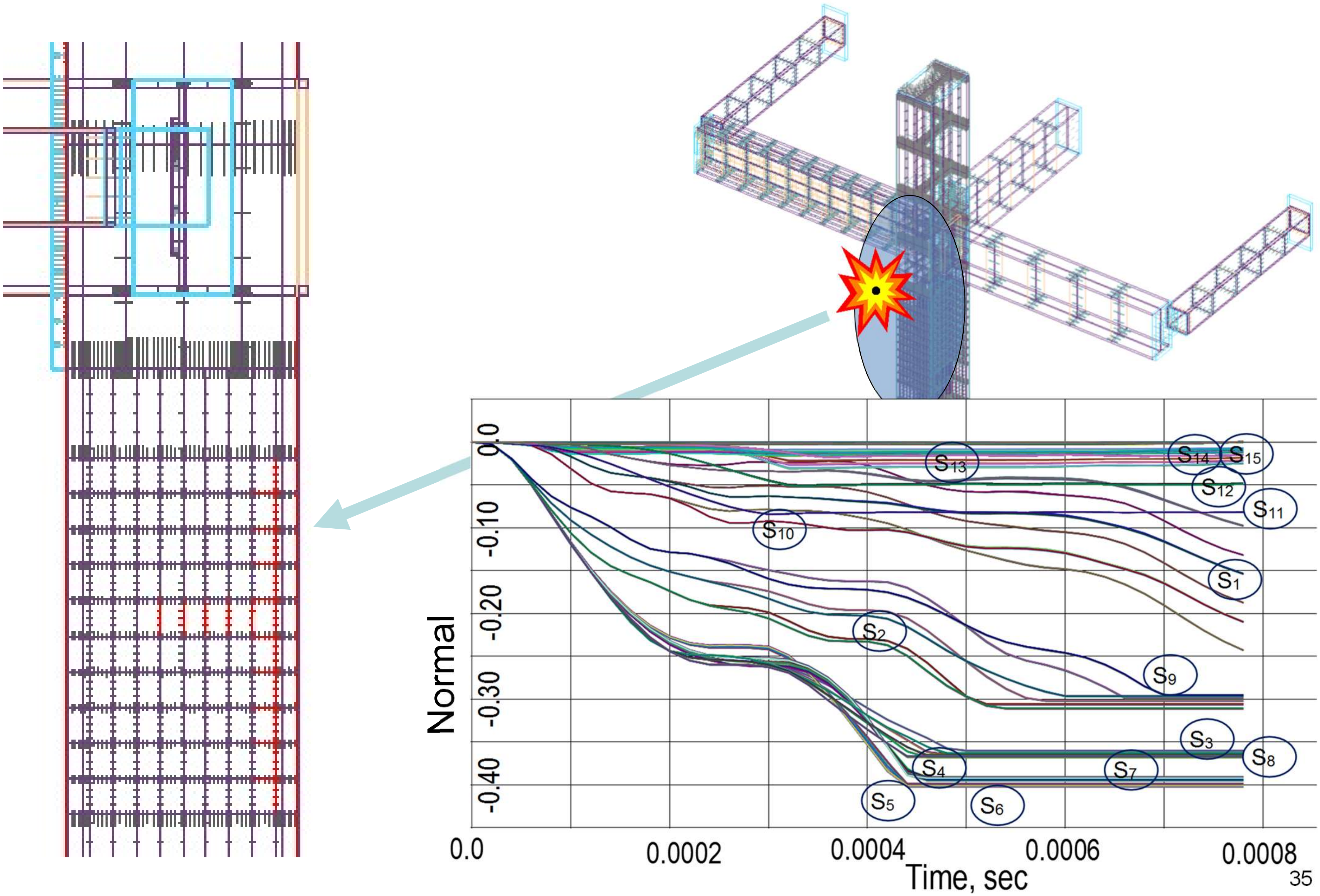
Specimen I



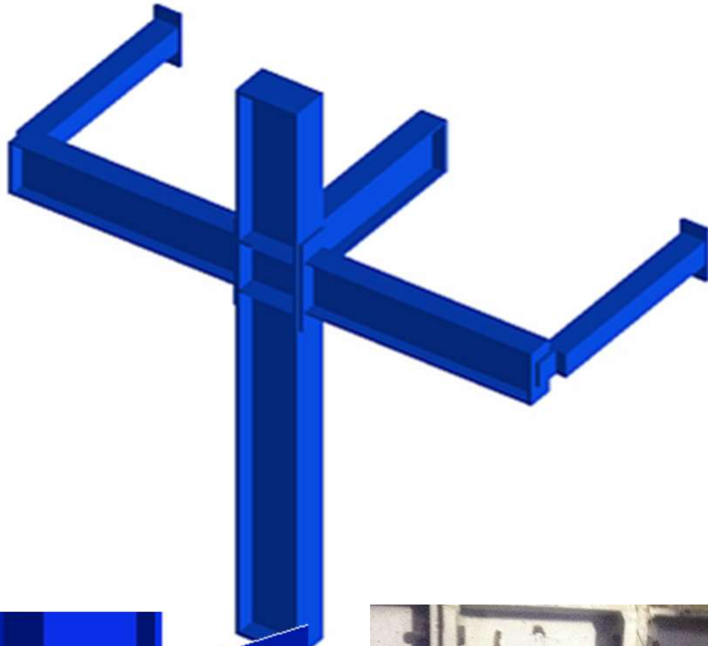


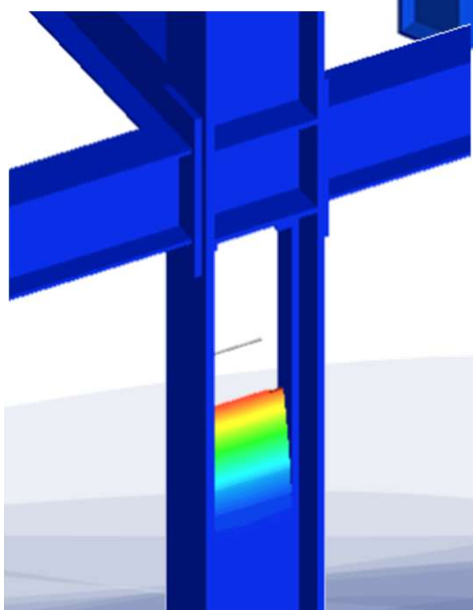


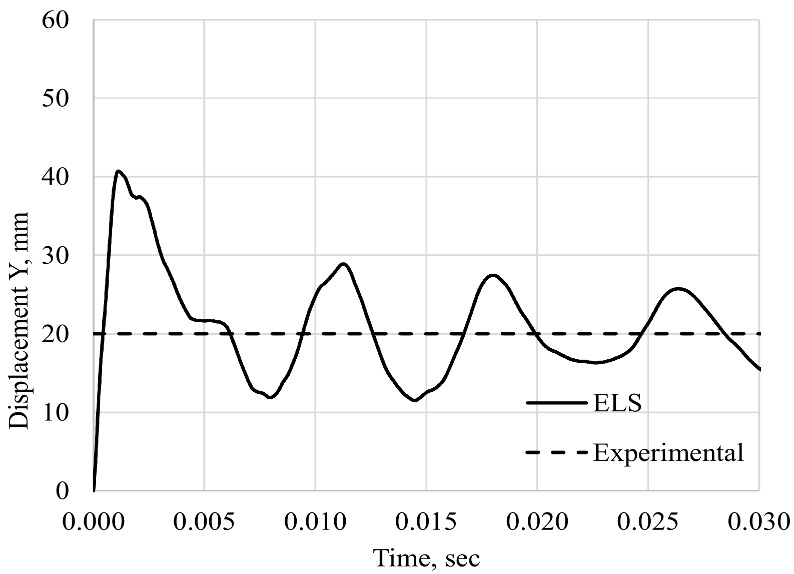
Displacement Y, mm
Time, sec
ELS
Experimental
0
10
20
30
40
50
60
0.000
0.005
0.010
0.015
0.020
0.025
0.030

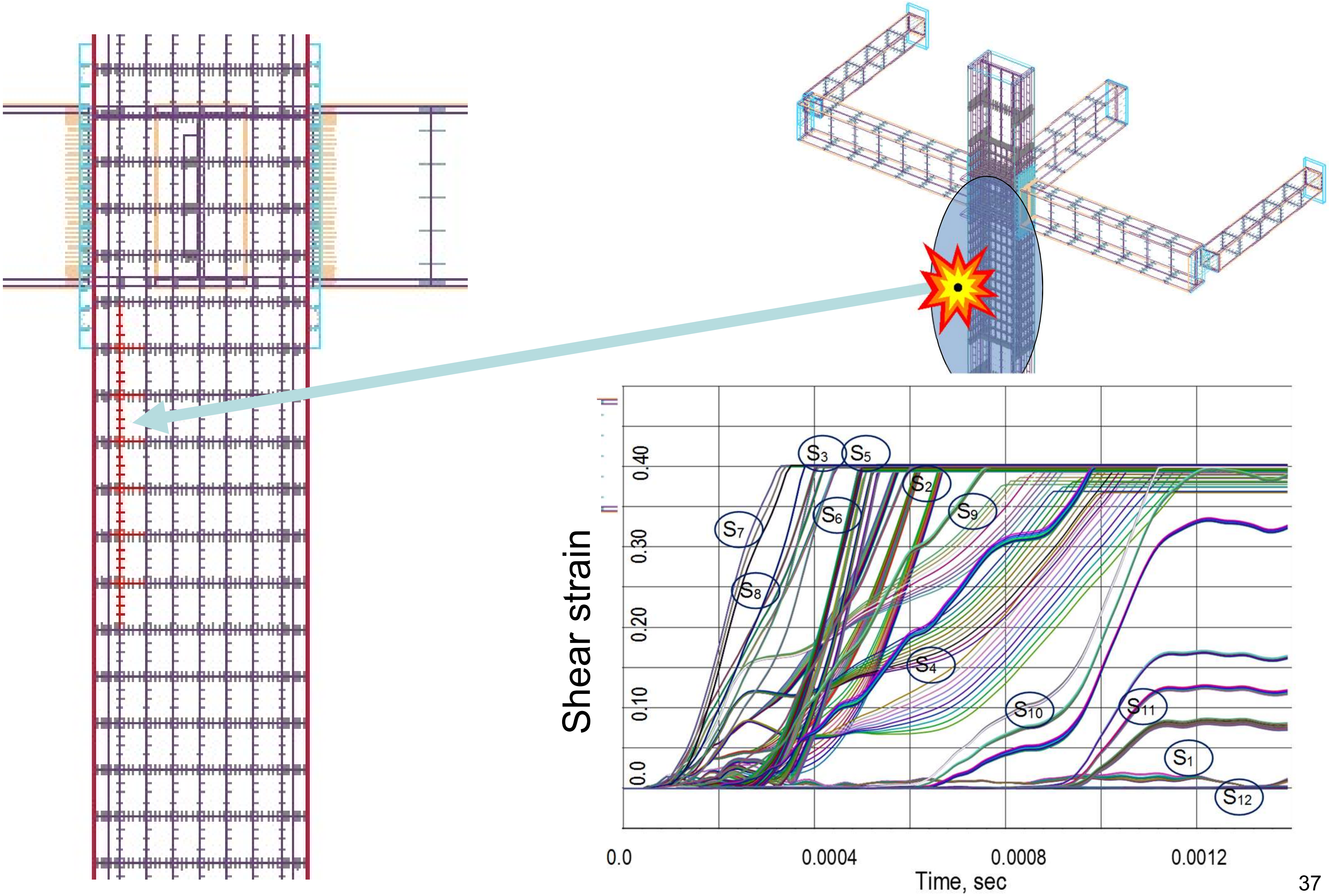

0.0
-0.10
-0.20
-0.30
-0.40
Normal
0.0
0.0002
0.0004
0.0006
0.0008
Time, sec
S13
S14
S15
S12
S11
S10
S1
S2
S9
S3
S8
S4
S7
S5
S6

Specimen II





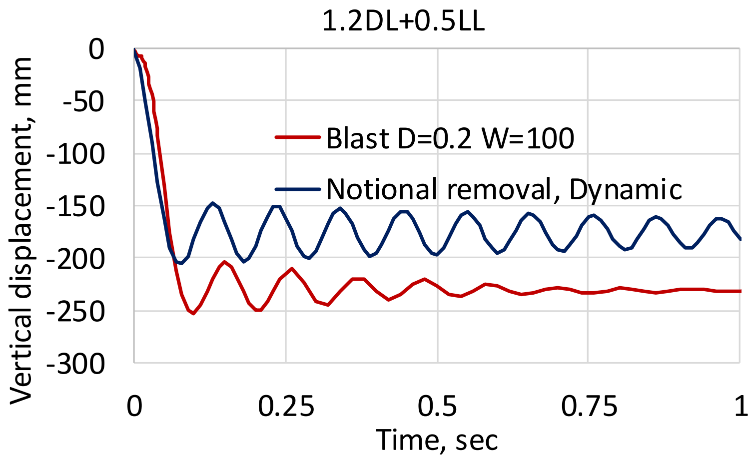

60
50
40
30
20
10
0
0.000
0.005
0.010
0.015
0.020
0.025
0.030
Displacement Y, mm
Time, sec
ELS
Experimental

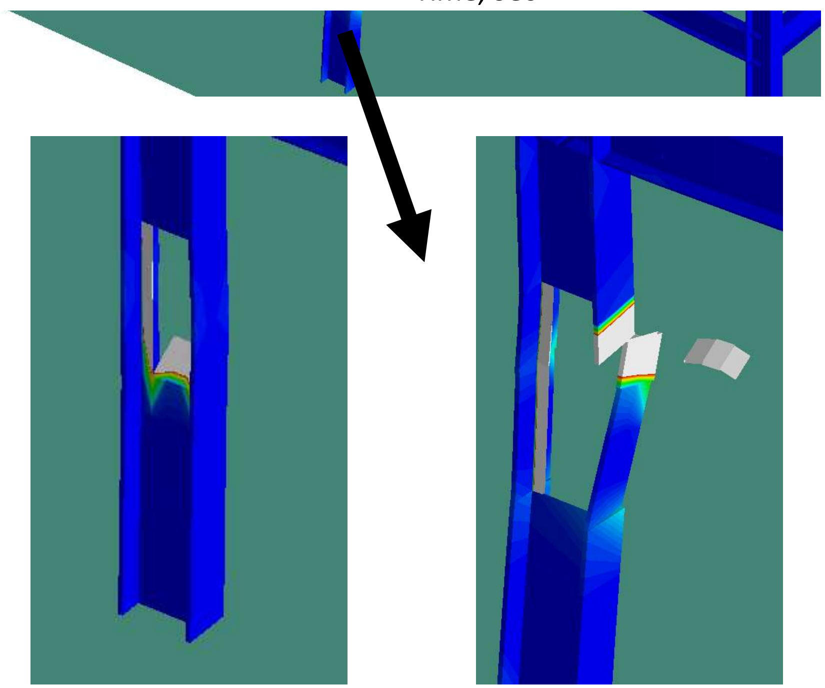

Shear strain
0.0
0.10
0.20
0.30
0.40
0.0
0.0004
0.0008
0.0012
Time, sec
S_3
S_5
S_2
S_9
S_6
S_7
S_8
S_4
S_{10}
S_{11}
S_1
S_{12}

Numerical studies

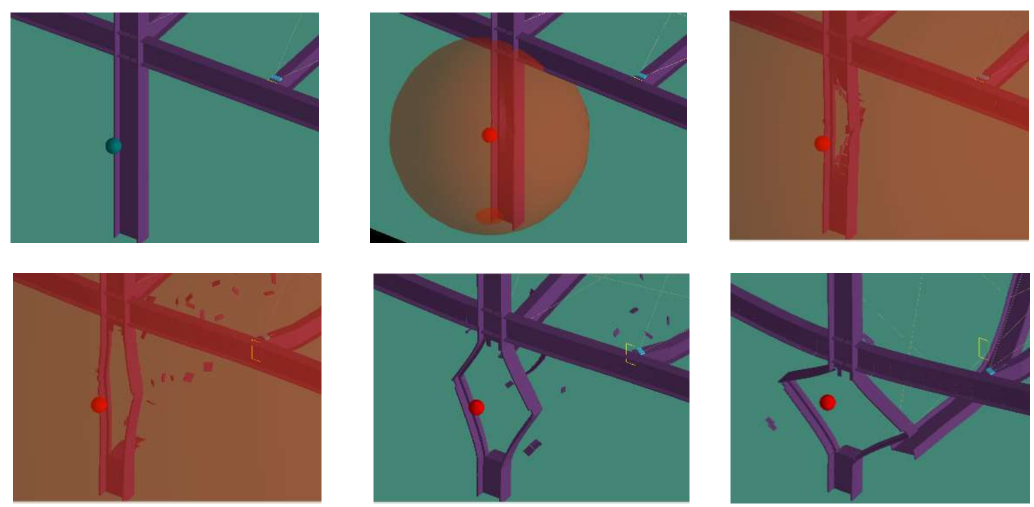
- To evaluate the response of steel moment frames when subjected to different column loss scenarios:
  - Notional removal of a column (static, dynamic) vs. direct blast loading
  - Relation between charge weight, stand off distance, local and global damage to the structure
- 6 stories, 4 spans and 4 bays MRFs, designed for gravity loads and seismic a_g= 0.10g.
- Charge weight W: 20, 50, 100 kg TNT; Stand-off distance D: 0.2, 0.5, 1.0 m
  - ➢ Scaled distance Z varied from 0.043 to 0.368 m/(kg$^{1/3}$)
- Gravity loads from accidental design situation (1.2GL+0.5LL) incremented (by λ) until progressive collapse initiation

Results



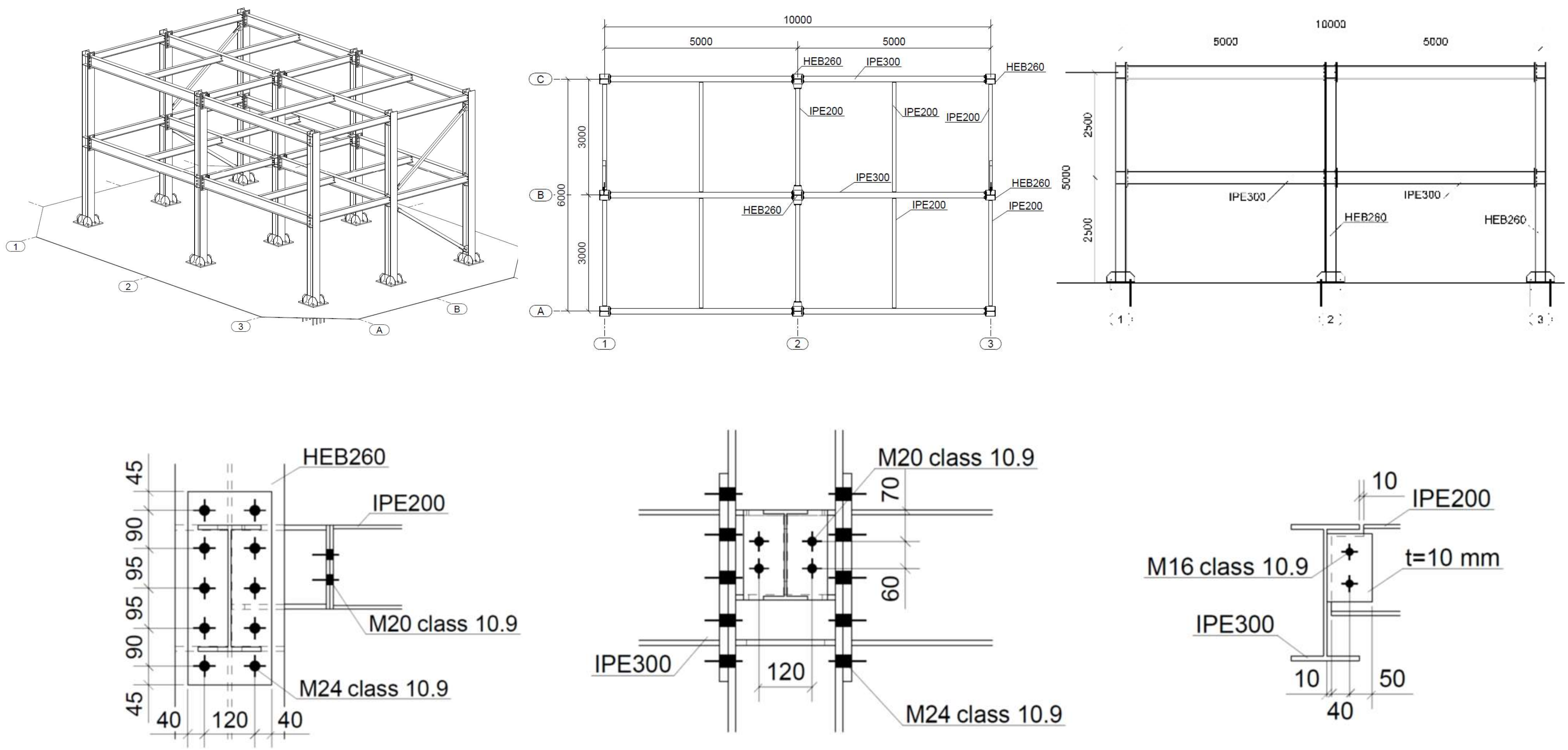


D [m]	W [kg]	Z [m/kg$^{1/3}$]	Column state	λ_u
0.2	20	0.073	Total loss	1.45
0.2	50	0.054	Total loss	1.35
0.2	100	0.043	Total loss	1.35
0.5	20	0.184	Residual capacity (web partially removed)	1.7
0.5	50	0.135	Total loss	1.35
0.5	100	0.107	Total loss	1.05
1.0	20	0.368	Residual capacity (web 5cm out of plane)	-
1.0	50	0.271	Residual capacity (web partially removed)	1.65
1.0	100	0.215	Total loss	1.1
Notional column removal		Static	column removal	**2.25**
		Dynamic	column removal	**1.65**



FRAMEBLAST

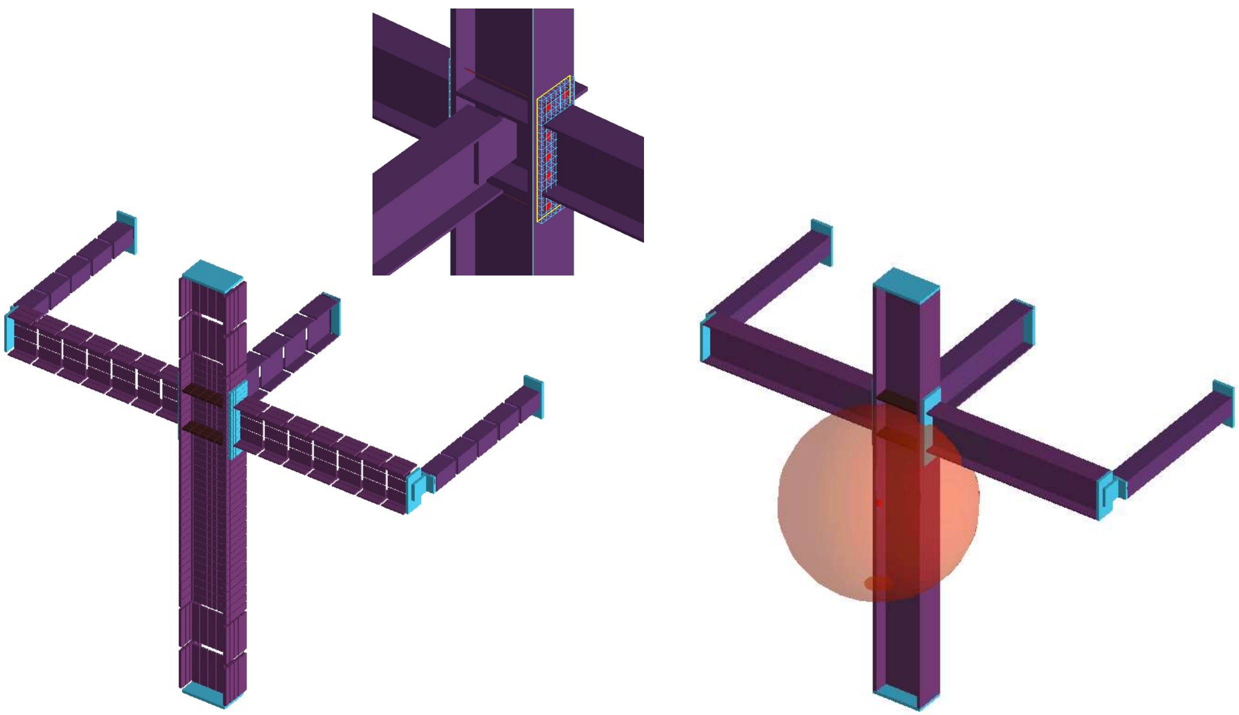
- Building frame system under blast loading conditions in laboratory environment:
  - Full scale tests
  - Numerical model calibration
- Similar steel sections, configurations, and steel grade with CODEC
- Existing blast test results (CODEC) used for design and preliminary blast simulations



Views and details of the full-scale building model

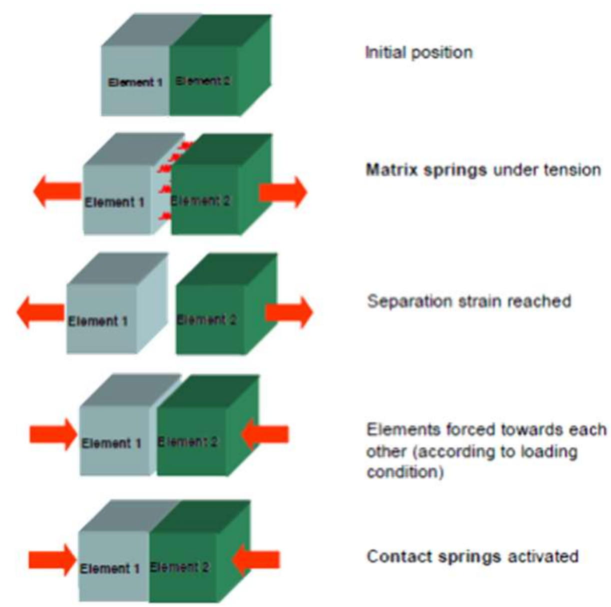
Preliminary calibration of the numerical model

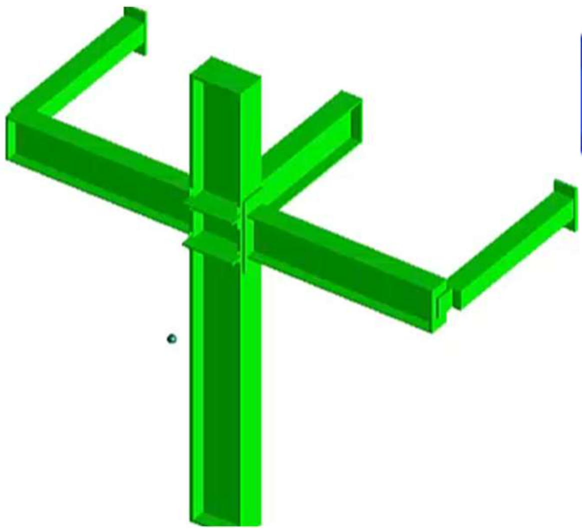
- Extreme loading for structures ELS (2017)
- Numerical models for sub-assemblies calibrated against tests (CODEC)

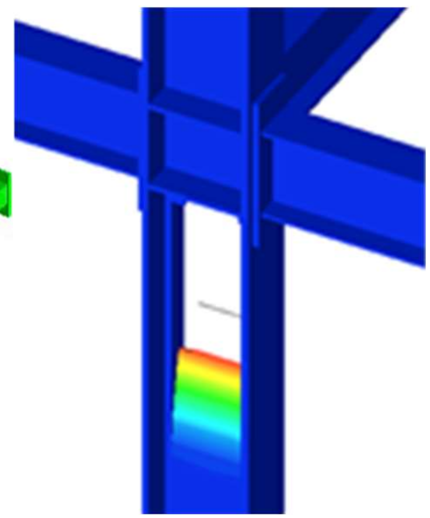


Numerical model: a) mesh discretization of components; b) radially expanding shock wave; c) experimental vs numerical

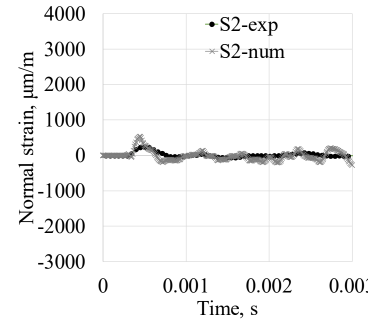
ELS



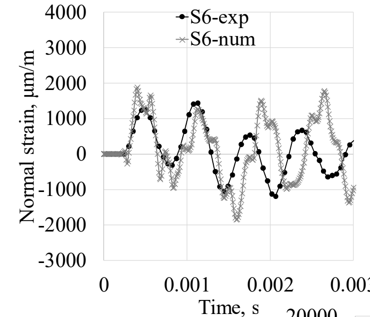




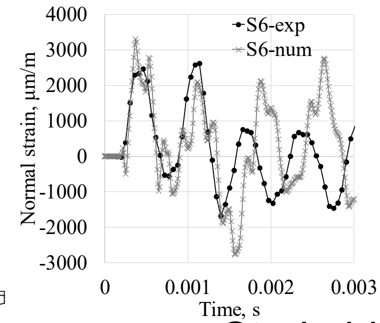
test m_1



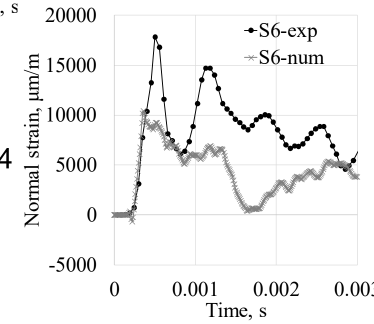
test m_2



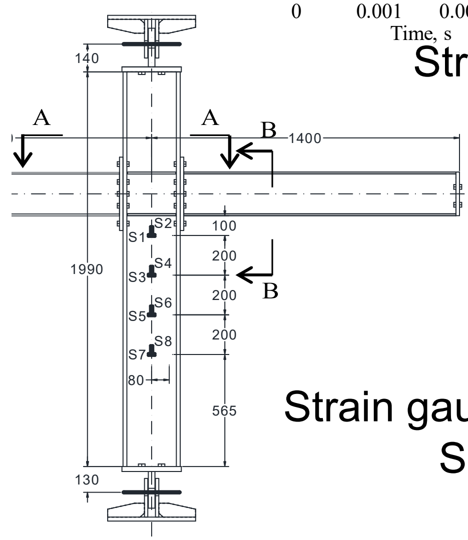
test m_3



test m_4



Strain history, experimental vs. numerical, specimen 2

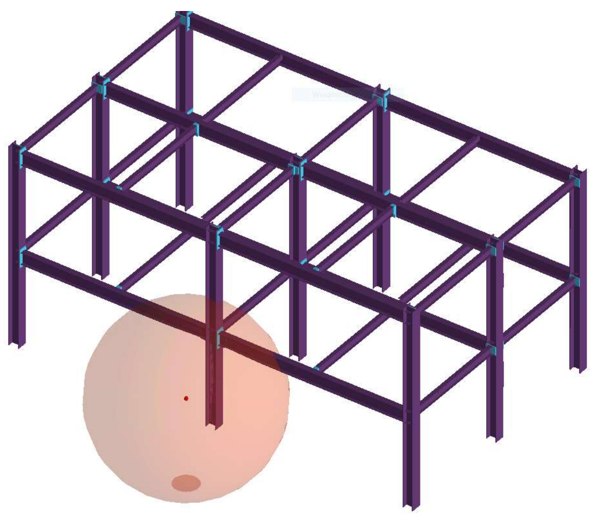


Strain gauges (S1 ÷ S8)

Parametric study

- Numerical model calibrated against test data used to study the behaviour of the full-scale building model subjected to external blast loading
- Parameters:
  - the level of gravity load on the floors, G
  - the standoff distance from the building, R
  - and the charge weight, W
- Dead load D, live load L: 4 kN/m^2
- Load combination:

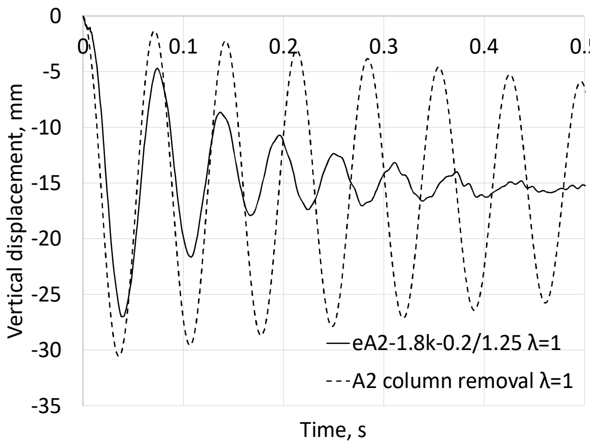
$$G_{ND} = 1.2\,D + 0.5\,L$$



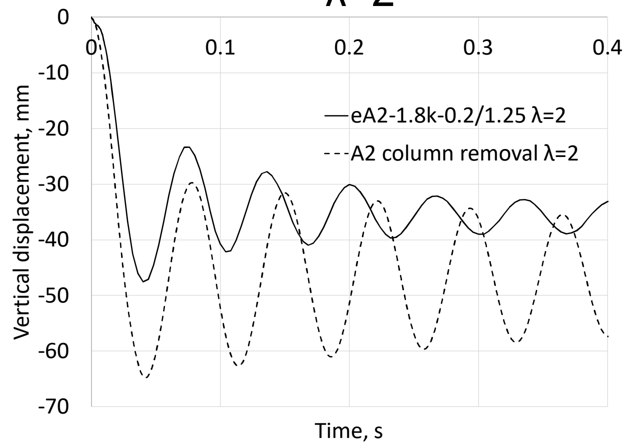
Results

Vertical displacement for eA2-1.8k-0.2/1.25

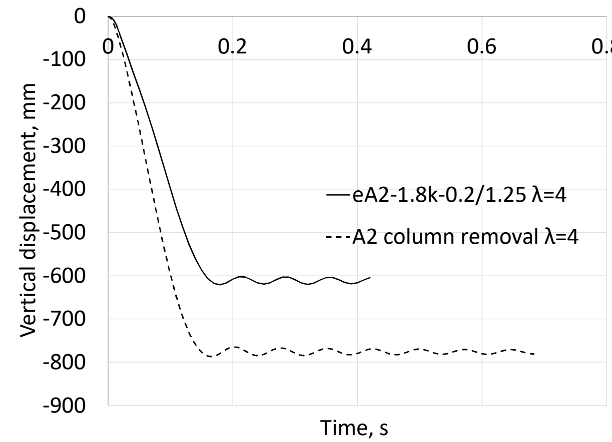
λ=1



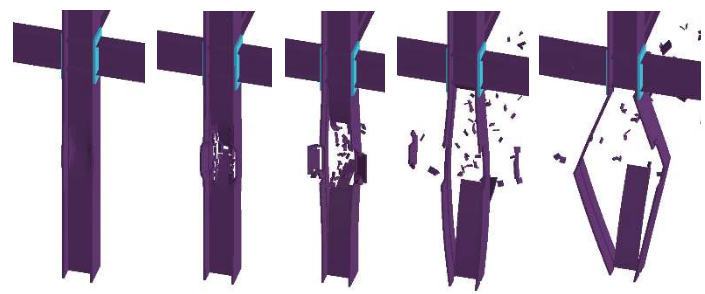
λ=2

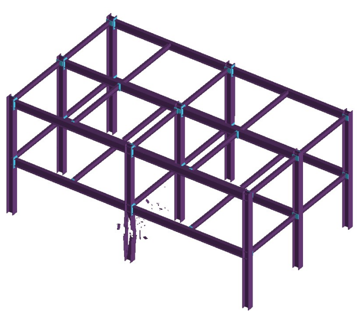


λ=4

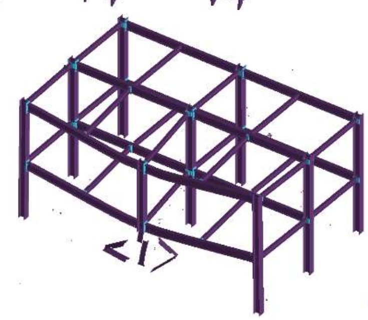


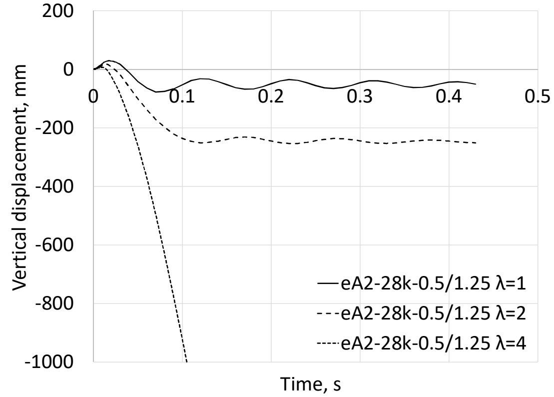
Blast damage in column at different moments in time





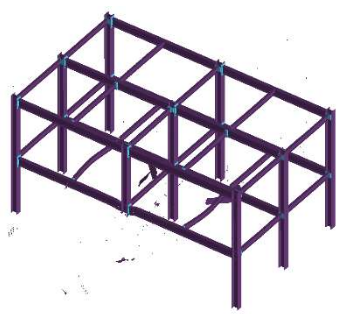
Deformed shape



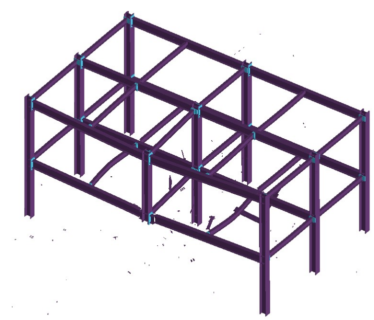


History of vertical displacement for scenario 28k-0.5

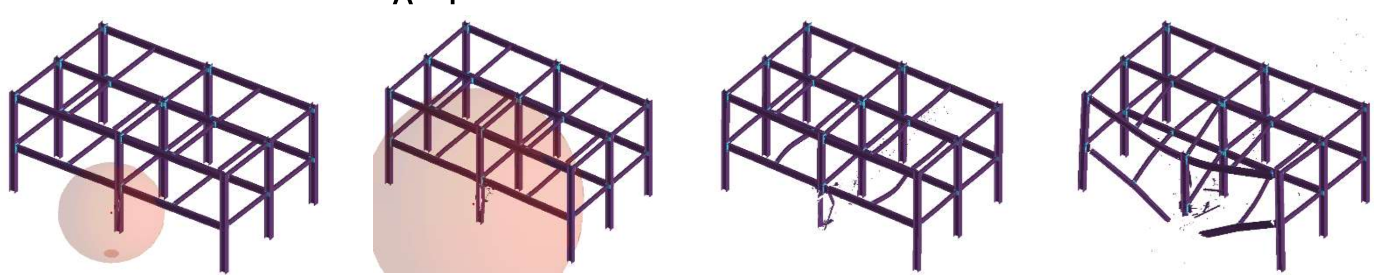
Results for blast scenario eA2-28k-0.5/1.25



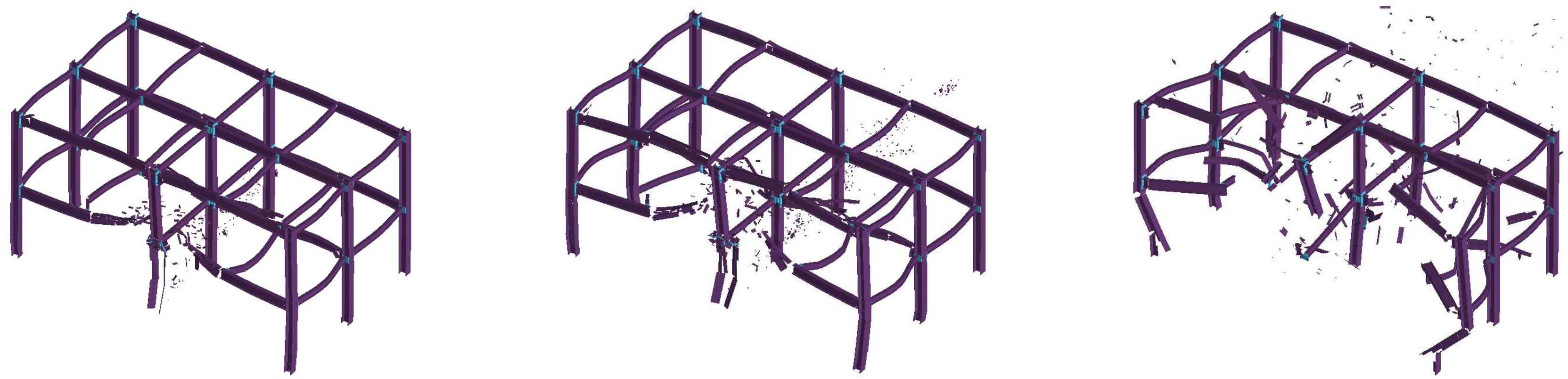
Deformed shape, λ=1



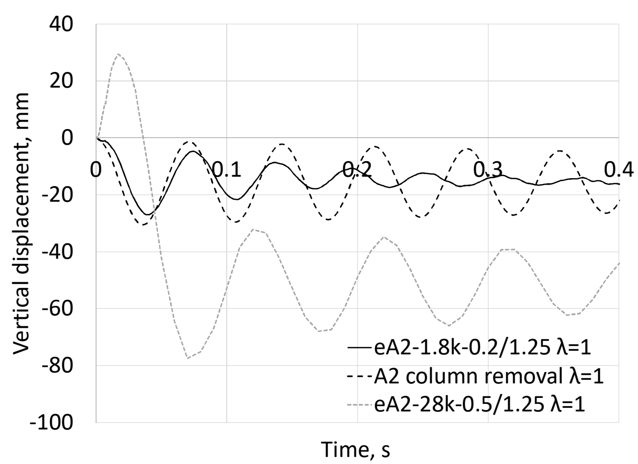
Deformed shape, λ=2



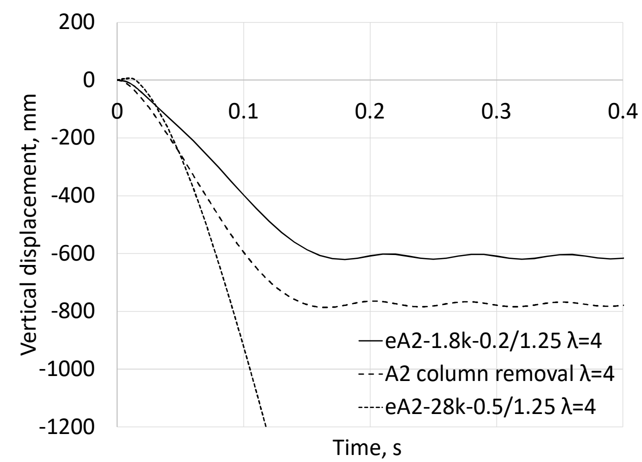
Deformed shape at different moments in time, λ=4



Deformed shape at different moments in time for blast scenario eA2-277k-1/1.25, λ=1



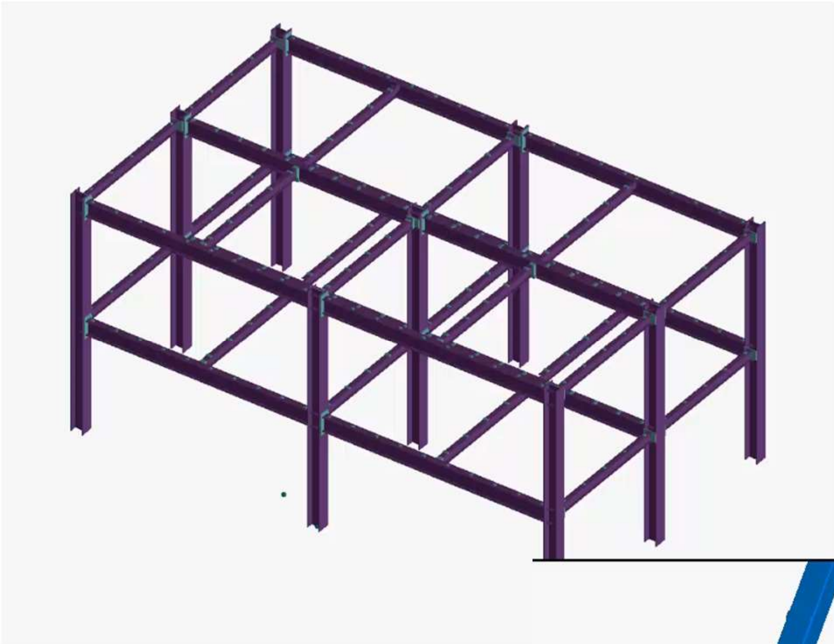
λ=1

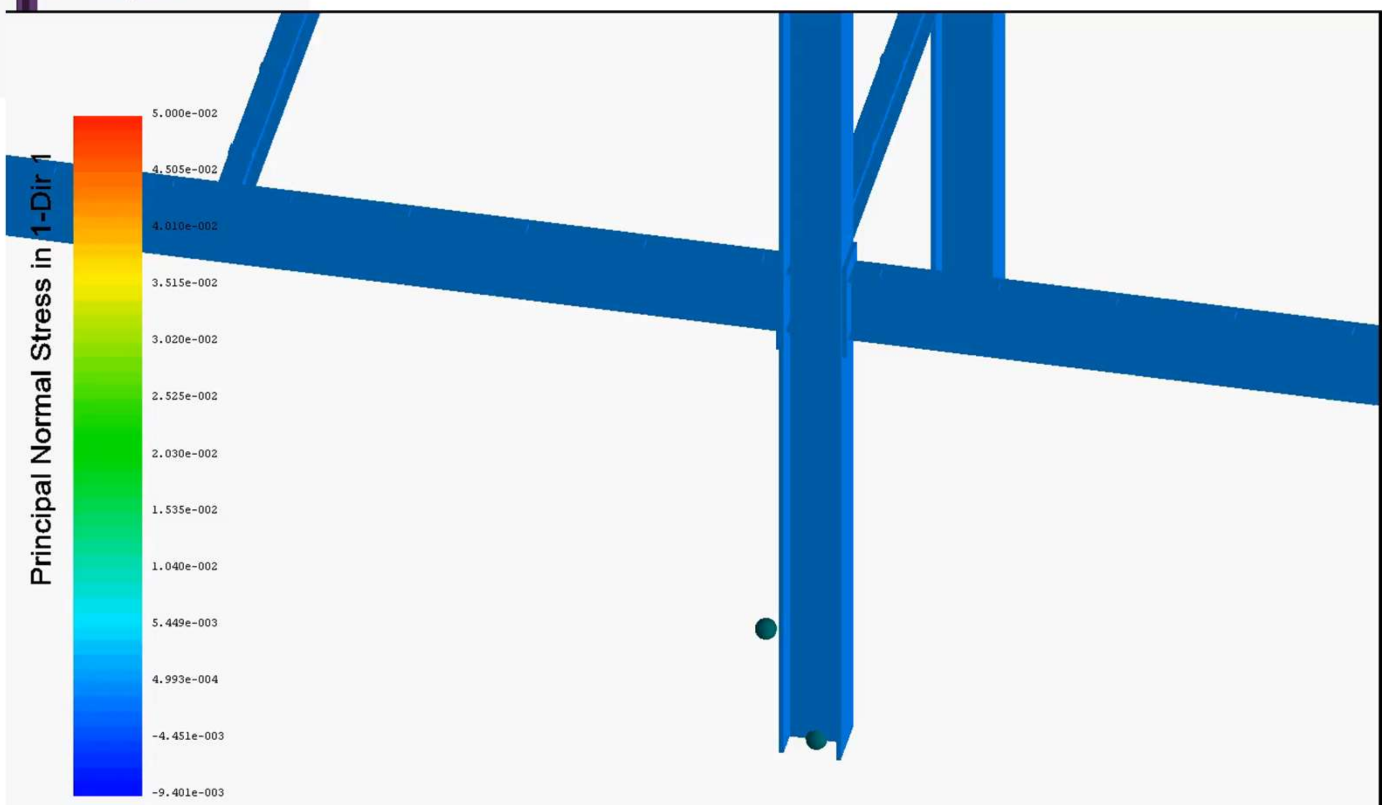


λ=4

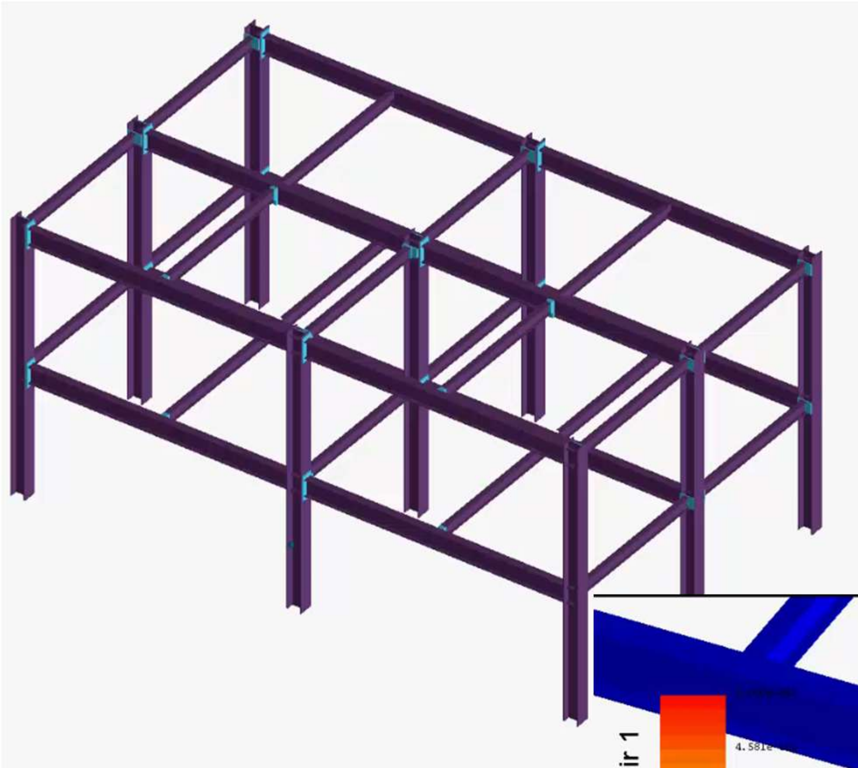
History of vertical displacement for scenarios 1.8k-05 and 28k-0.5 vs. notional column removal

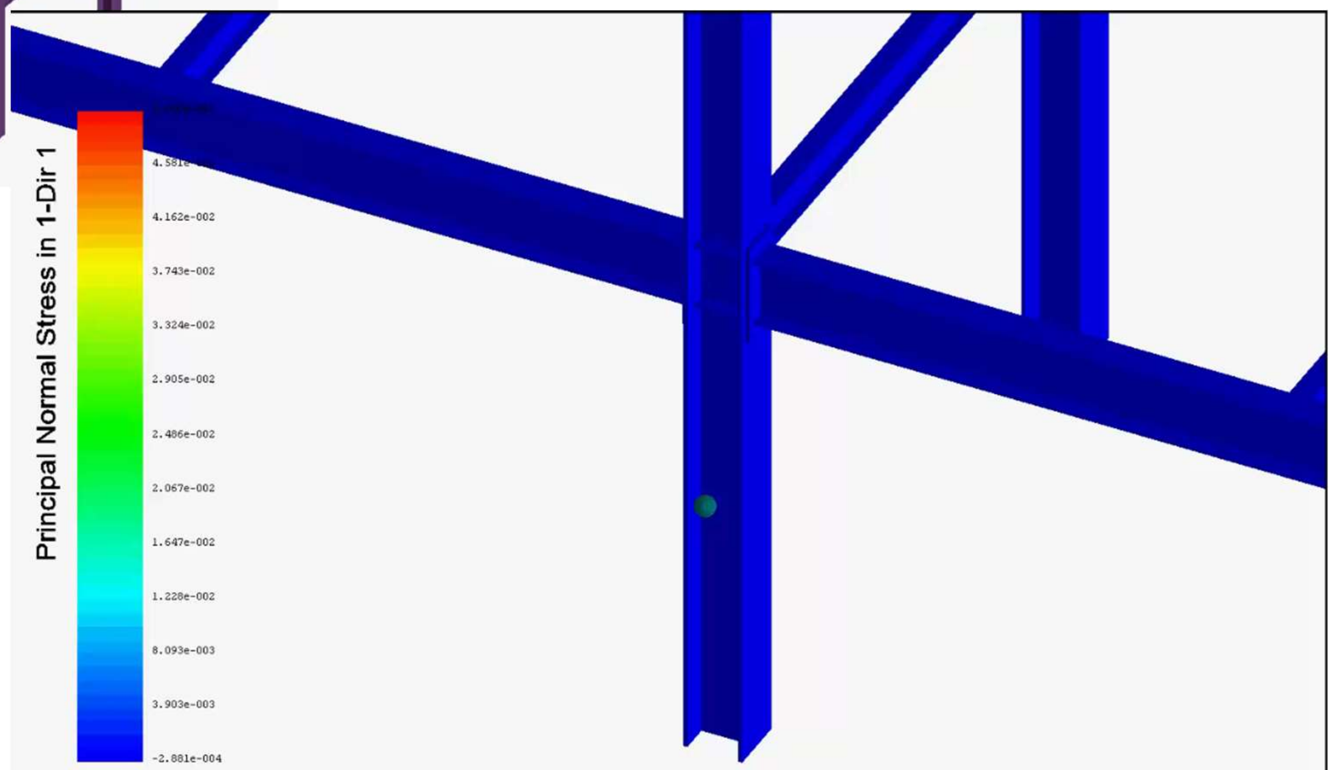
eA2-277k-1/1.25, λ=1

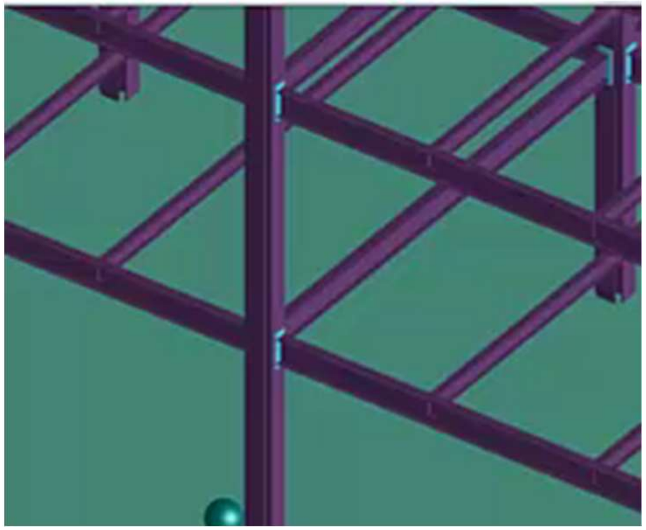


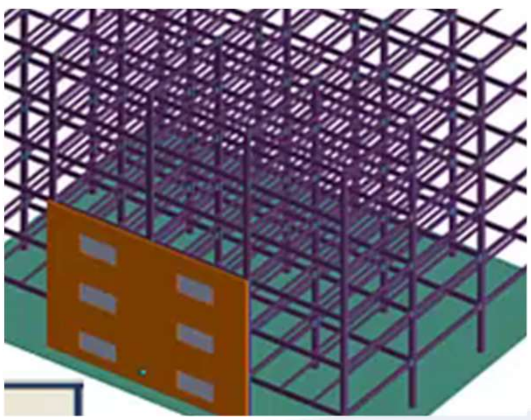


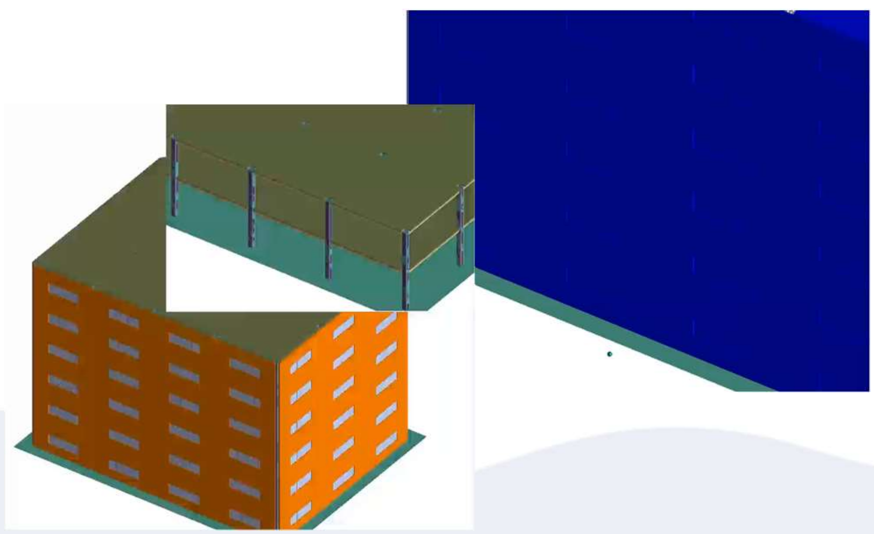
eA2-2k-0.2/1.25, λ=4

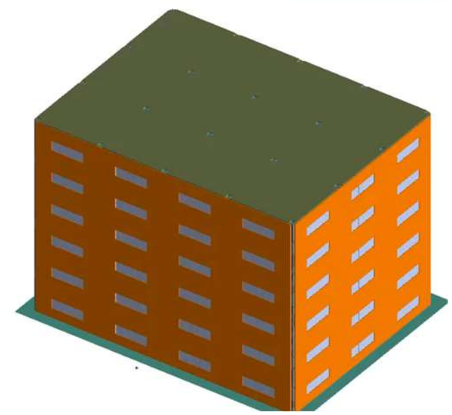












http://www.ct.upt.ro/centre/cemsig/codec.htm

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