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Multilayer Wall System for Protection of Nuclear Facilities Against Airplane Crash and Critical Infrastructure Against Close-in-Explosions

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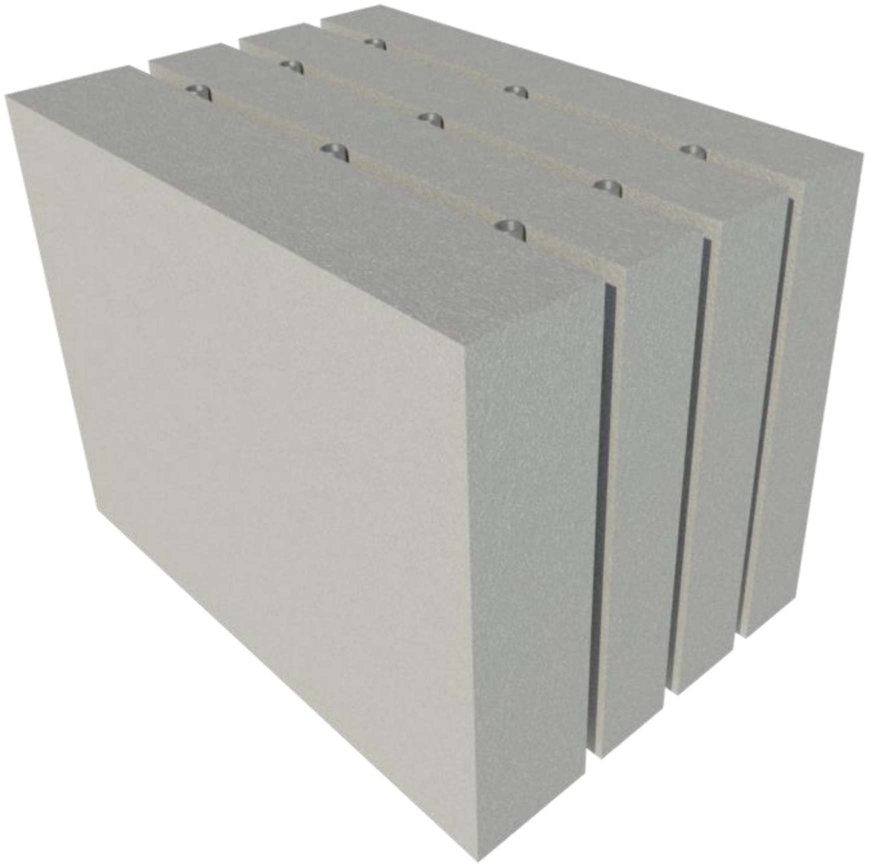
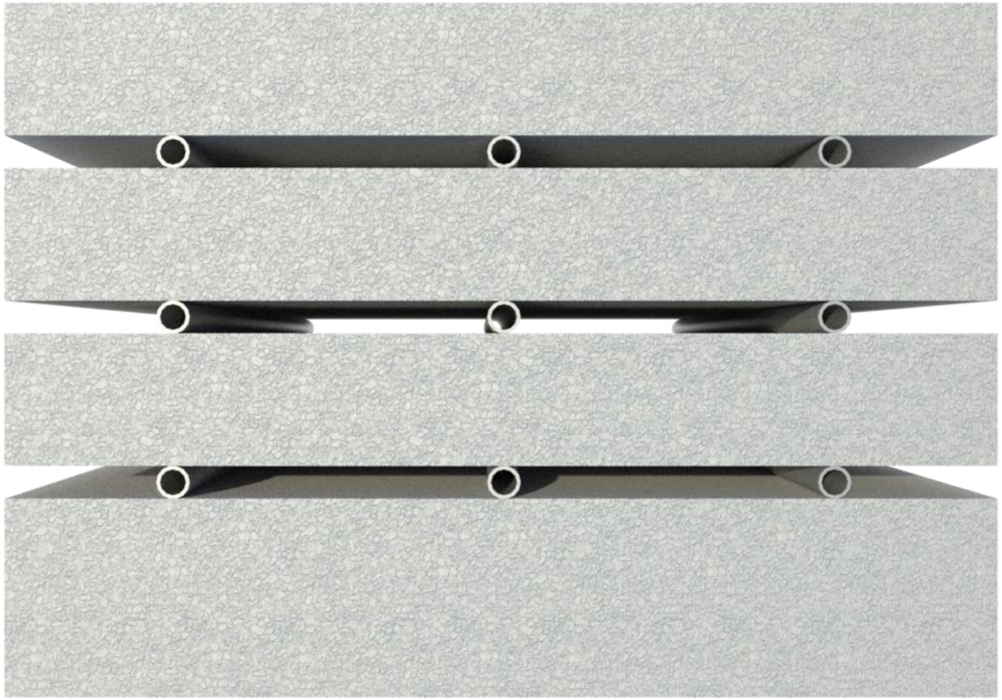
Motivation

- Increased requirements of nuclear facilities resistance against APC impact
- Current standard of 1.80 m wall thickness is not resistant against APC impact for commercial aircraft > A 320.
- Higher massive wall thickness than 1.80 m is technologically problematic.
- Monolithic concrete walls transfer APC induced high frequency vibrations inside the building and exceed the earthquke design spectra in the frequency range above 15 Hz.

Multilayer-Wall-System (MLWS)





- **Concrete elements of 60 cm + 3 x 40 cm**
- **3 Layers with Steel pipes with width d=10 cm**

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Target

Expectations on Multi-Layer Wall System (MLWS):

- Suitable for new build and upgrade of existing structures due to modularity. No limitations on total wall thickness
- Energy absorbtion due to controlled nonlinear deformation
- Reduction of max. deformation at inner side of building structure
- Filter of high frequency APC induced vibrations and reduction of requirements for qualification of components

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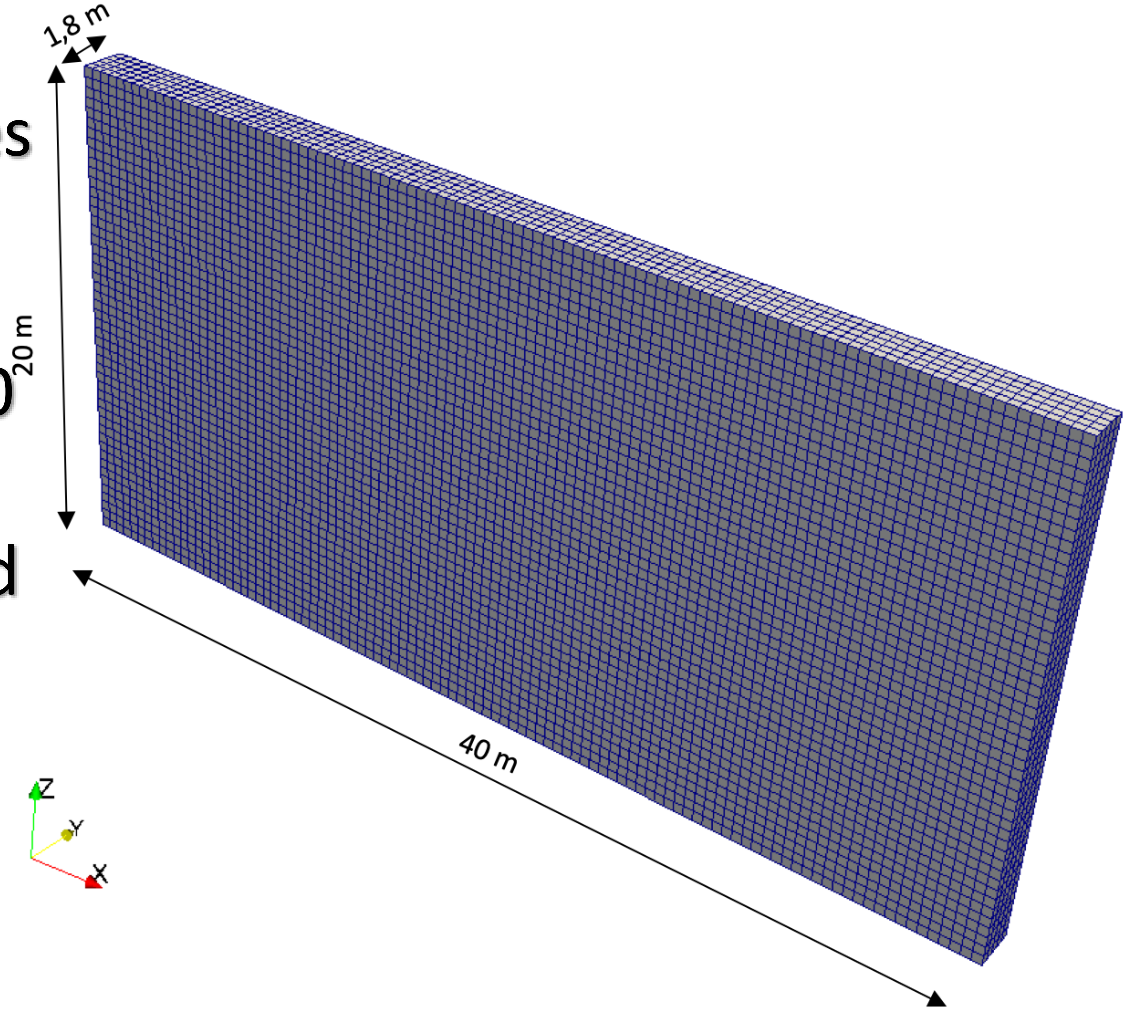
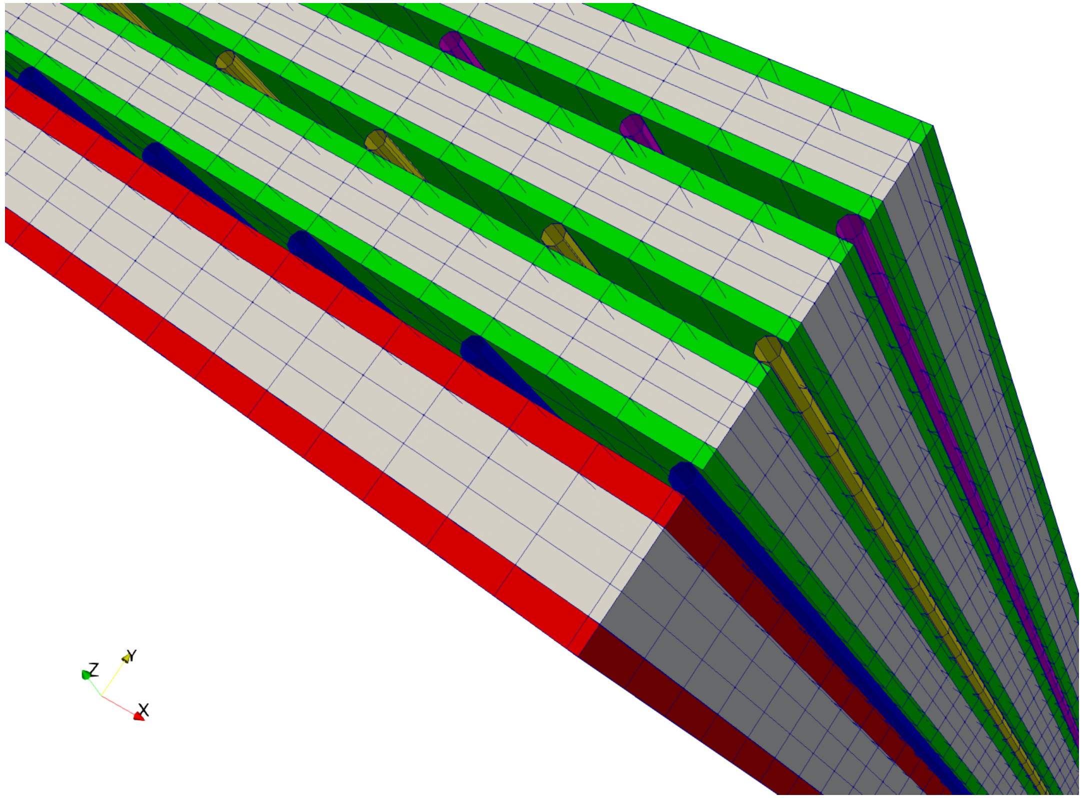
Reference Massive Wall (MV)

For evaluation of optimal MLWS properties for earthquake excitation:

- A massive wall (MW), fixed at top and bottom side, with dimensions 40 m x 20 m x 1.8 m is used as reference
- Multi-Layer-Wall-System (MLWS) should have similar dynamic response to earthquake excitation



Parametric Modal Analyses of MLWS 60 cm + 3 x 40 cm



Evaluation of Optimal MLWS Properties

- Target: Similar dynamic properties as MW
- Method: Variation of pipe distance and thickness

Pipe Distance [m]	Pipe Thickness [m]	Eigenv. 1 [Hz]	Pipe Thickness [m]	Eigenw. 1 [Hz]	Pipe Thickness [m]	Eigenw. 1 [Hz]
40,0	0,01	3,639	0,005	3,637	0,0025	3,633
20,0	0,01	4,429	0,005	4,367	0,0025	4,256
8,0	0,01	7,856	0,005	7,171	0,0025	6,269
4,0	0,01	10,513	0,005	9,438	0,0025	8,066
2,0	0,01	12,832	0,005	11,695	0,0025	10,117
1,0	0,01	14,524	0,005	13,600	0,0025	12,158
0,5	0,01	15,613	0,005	14,983	0,0025	13,893

Adopted: Steel pipes with d=10cm, thickness of 1 cm at distance of 1 m

Modal Analysis of MLWS with Pipes thk. 1 cm at distance of 1 m

Eigenvalue	Freq. [Hz]	Mobilized Modal Mass					
		X [kg]	X [%]	Y [kg]	Y [%]	Z [kg]	Z [%]
1	14,524	0,00	0,00	2.182.420,50	66,97	0,00	0,00
2	14,545	0,00	0,00	0,00	0,00	0,00	0,00
3	14,780	0,00	0,00	158.118,80	4,85	0,00	0,00
4	15,415	0,00	0,00	0,00	0,00	0,00	0,00
5	16,636	0,00	0,00	9.558,40	0,29	0,00	0,00
6	18,438	0,00	0,00	0,00	0,00	0,00	0,00
7	20,960	0,00	0,00	1.433,10	0,04	0,00	0,00
8	24,192	0,00	0,00	0,00	0,00	0,00	0,00
9	28,229	0,00	0,00	279,40	0,01	0,00	0,00
10	33,042	0,00	0,00	0,00	0,00	0,00	0,00
11	34,274	0,00	0,00	0,00	0,00	0,00	0,00
12	34,287	0,00	0,00	0,00	0,00	0,00	0,00
13	34,476	0,00	0,00	0,00	0,00	0,00	0,00
14	34,988	0,00	0,00	0,00	0,00	0,00	0,00
15	35,990	0,00	0,00	0,00	0,00	0,00	0,00
16	37,554	0,00	0,00	0,00	0,00	0,00	0,00
17	38,681	0,00	0,00	60,90	0,00	0,00	0,00
18	39,708	0,00	0,00	0,00	0,00	0,00	0,00
19	42,456	0,00	0,00	0,00	0,00	0,00	0,00
20	45,082	0,00	0,00	0,00	0,00	0,00	0,00
21	45,832	0,00	0,00	0,00	0,00	0,00	0,00
22	49,869	0,00	0,00	0,00	0,00	0,00	0,00
23	52,305	0,00	0,00	9,20	0,00	0,00	0,00
24	52,451	2.589.890,60	79,48	0,00	0,00	0,00	0,00
25	54,353	0,00	0,00	0,00	0,00	0,00	0,00
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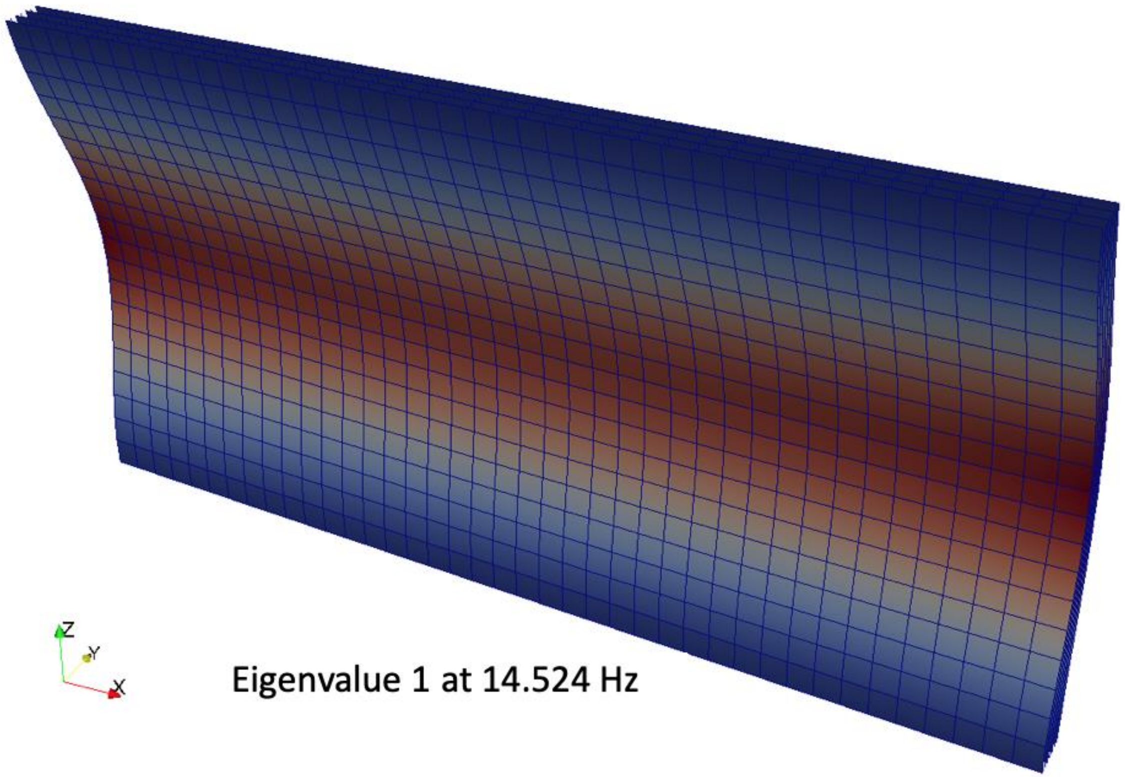
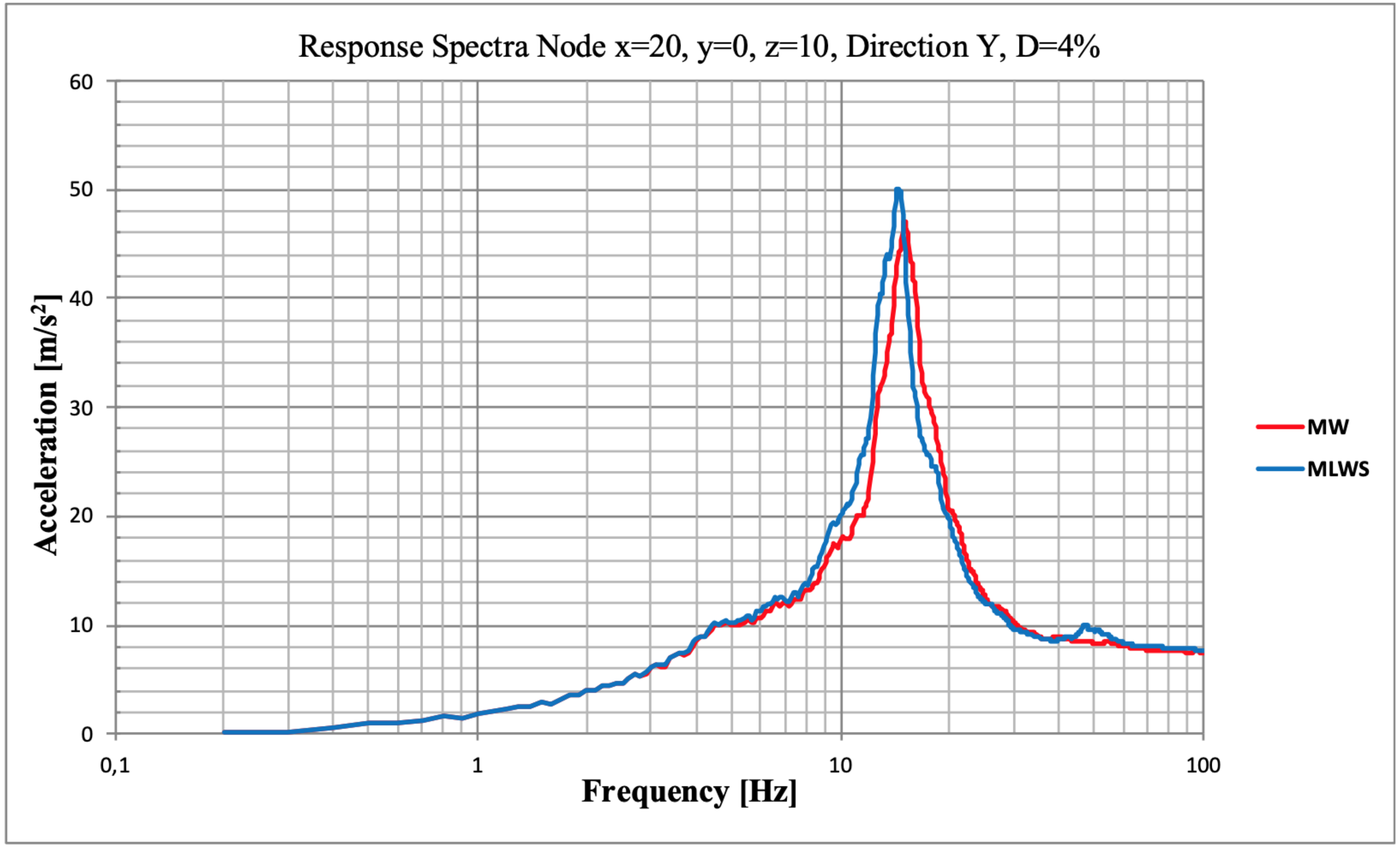


Eigenvalue 1 at 14.524 Hz

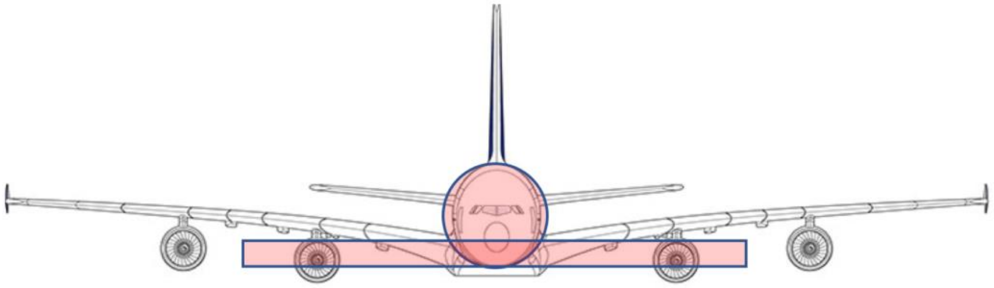
MW and MLWS Dynamic Response to Earthquake Excitation

Comparative calculations of the dynamic response due to the load case earthquake:

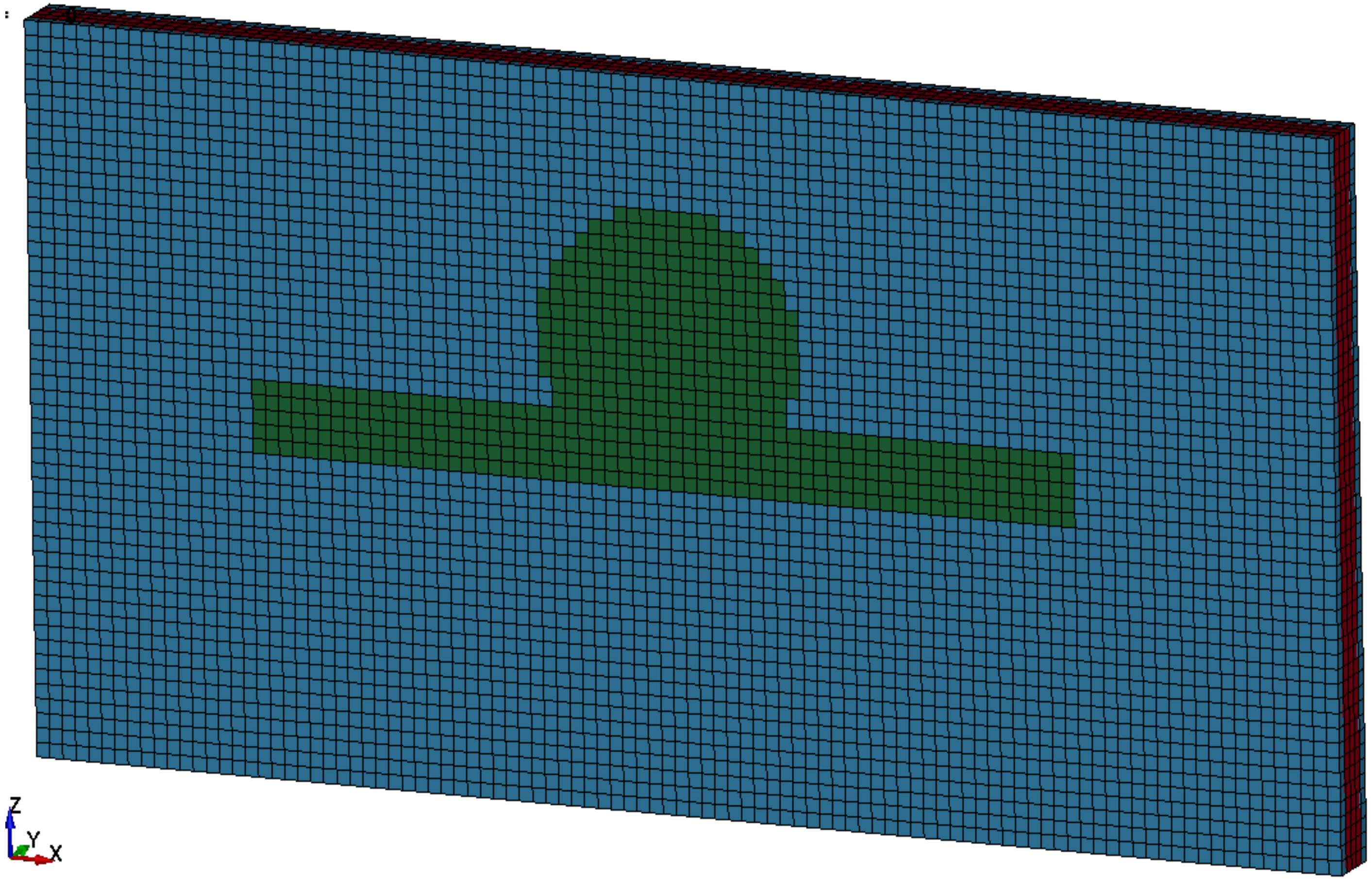
- Excitation based on EUR hard soil spectrum
- Scaled to a PGA of 0.4 g
- Performed for MW and MLWS system



Load Case APC



- Commercial aircraft A320
- Load function evaluated with Riera method
- Nonlinear analyses with LS-Dyna



Nonlinear Dynamic Analyses

- Explicit LS-Dyna
- Material model Winfrith Concrete (LS-DYNA Material 84) with smeared reinforcement
- Concrete C40/50
- Steel BSt 500
- DIF Concr. Press. = 1.15; DIF Concr. Tens. = 1.20, DIF Steel = 1.10
- Failure criteria:
  e_s^{pl} = 5 % for concrete steel
  e_{cu} = -0.5 % for concrete

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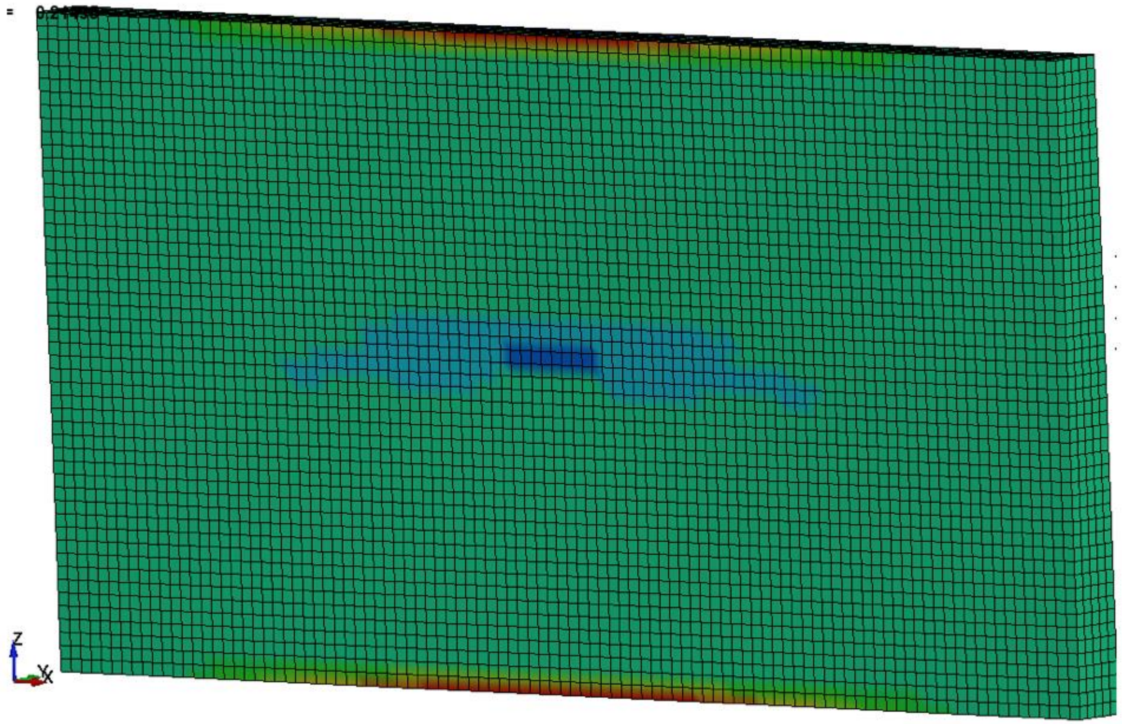
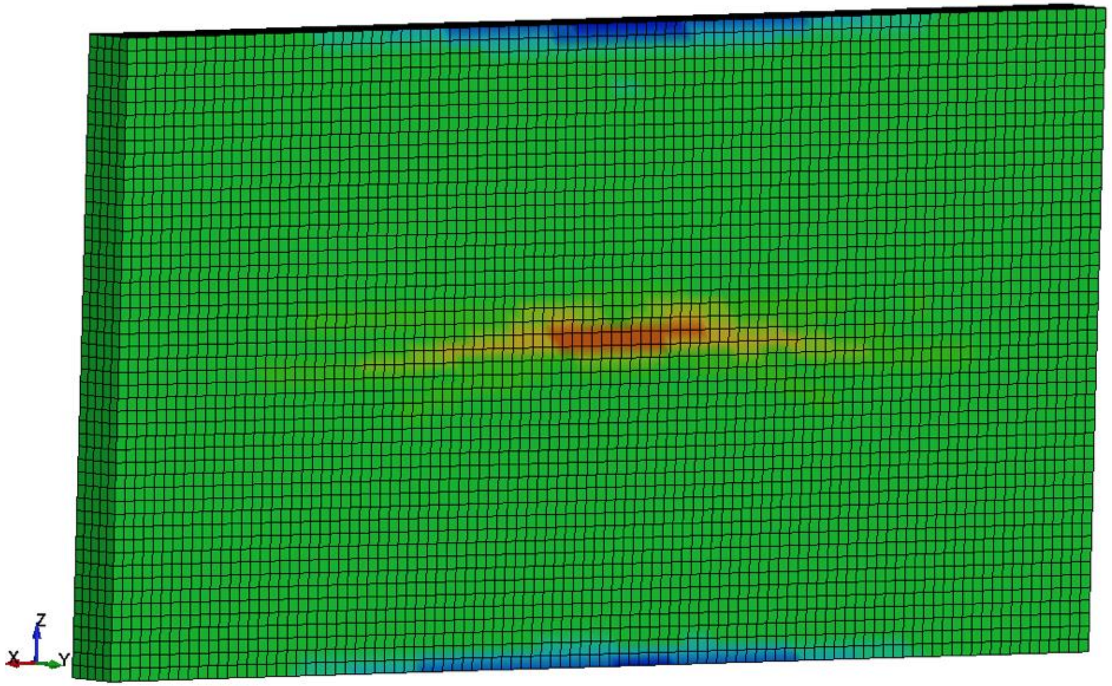
Reference Massive Wall (MW) of d=1.80 m

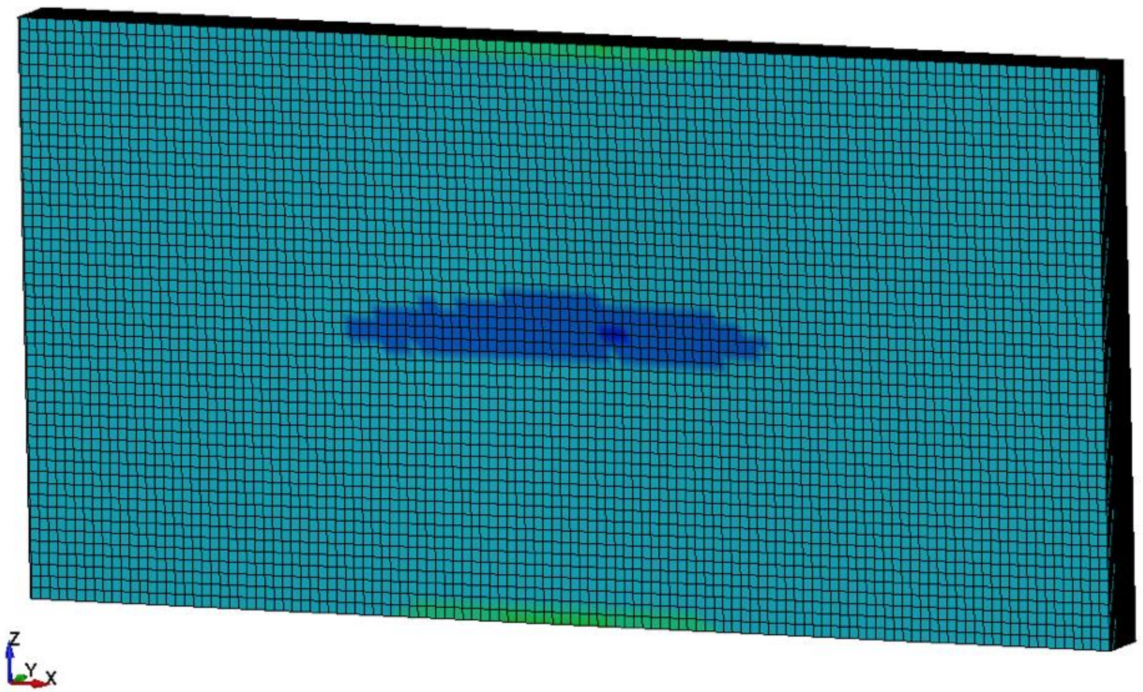


Max. Compression at Impacted Side: 1.81 %

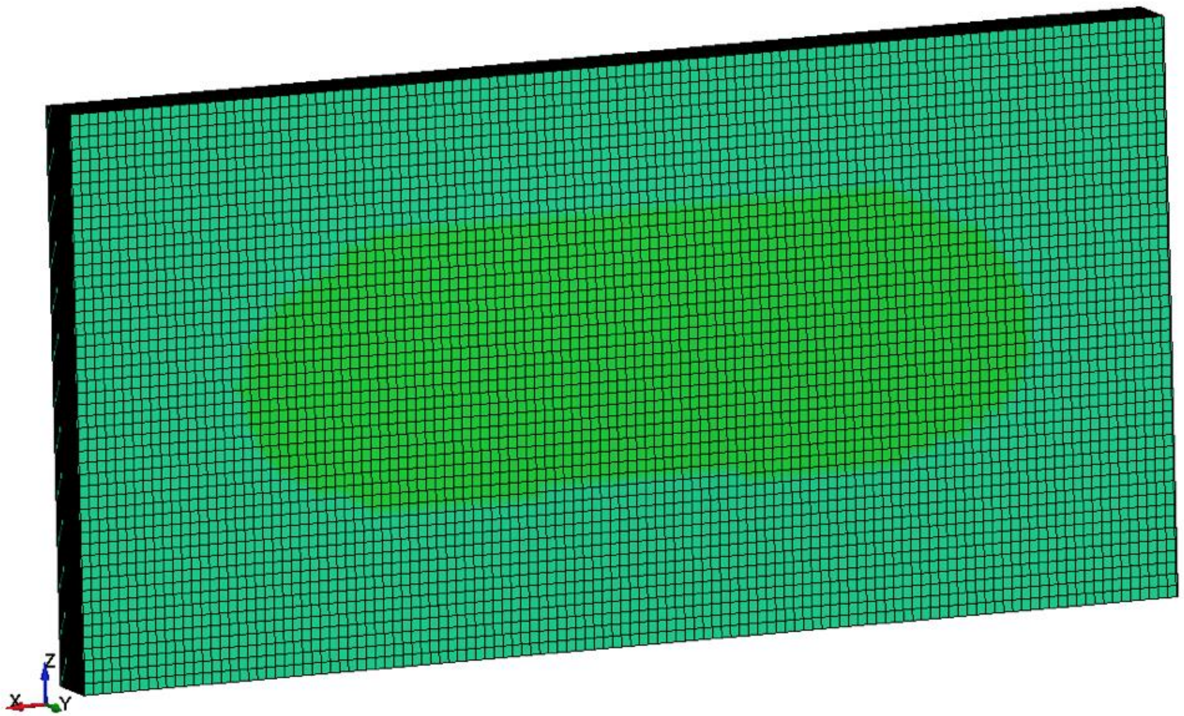


Max. Tension at Inner Side: 2.99 %

Multi-Layer-Wall System (MLWS)
First Layer 60 cm & 3 Layers of 40 cm

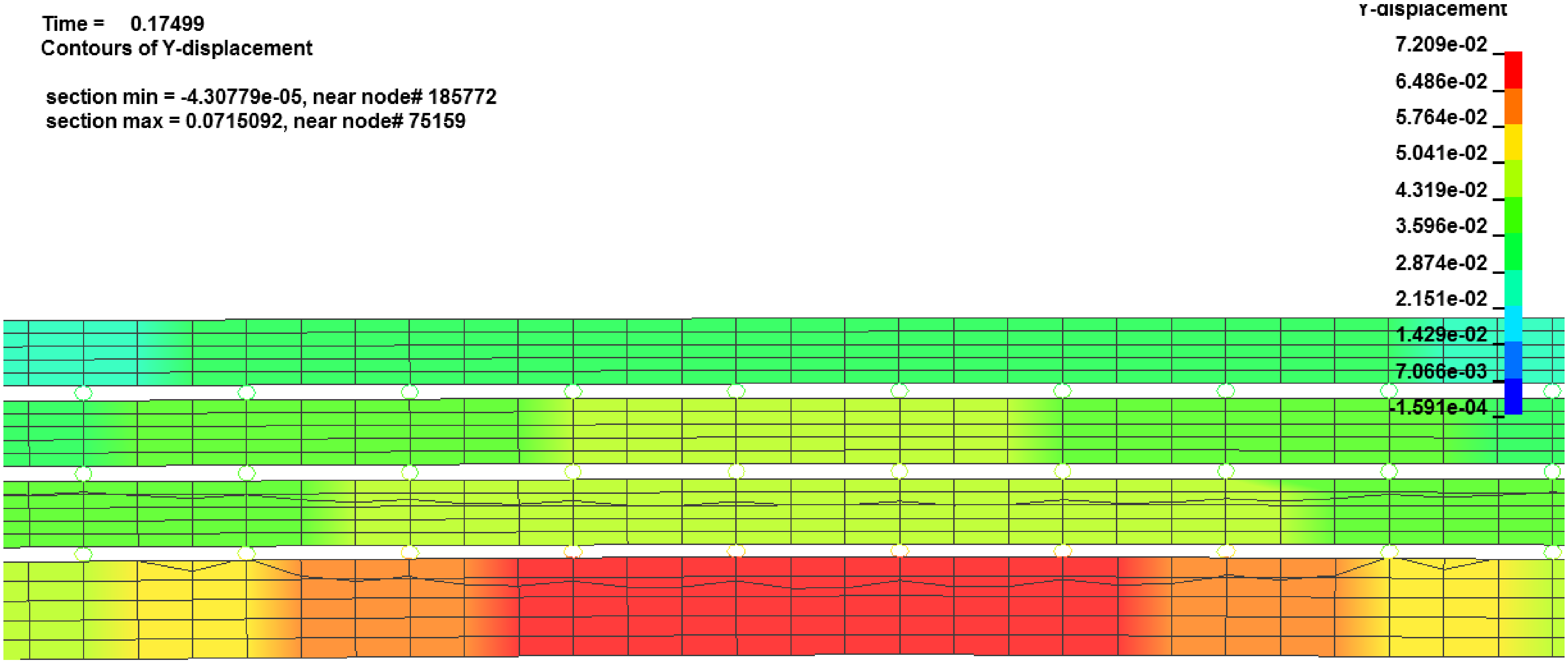


Max. Compression at Impacted Side: 2.10 %

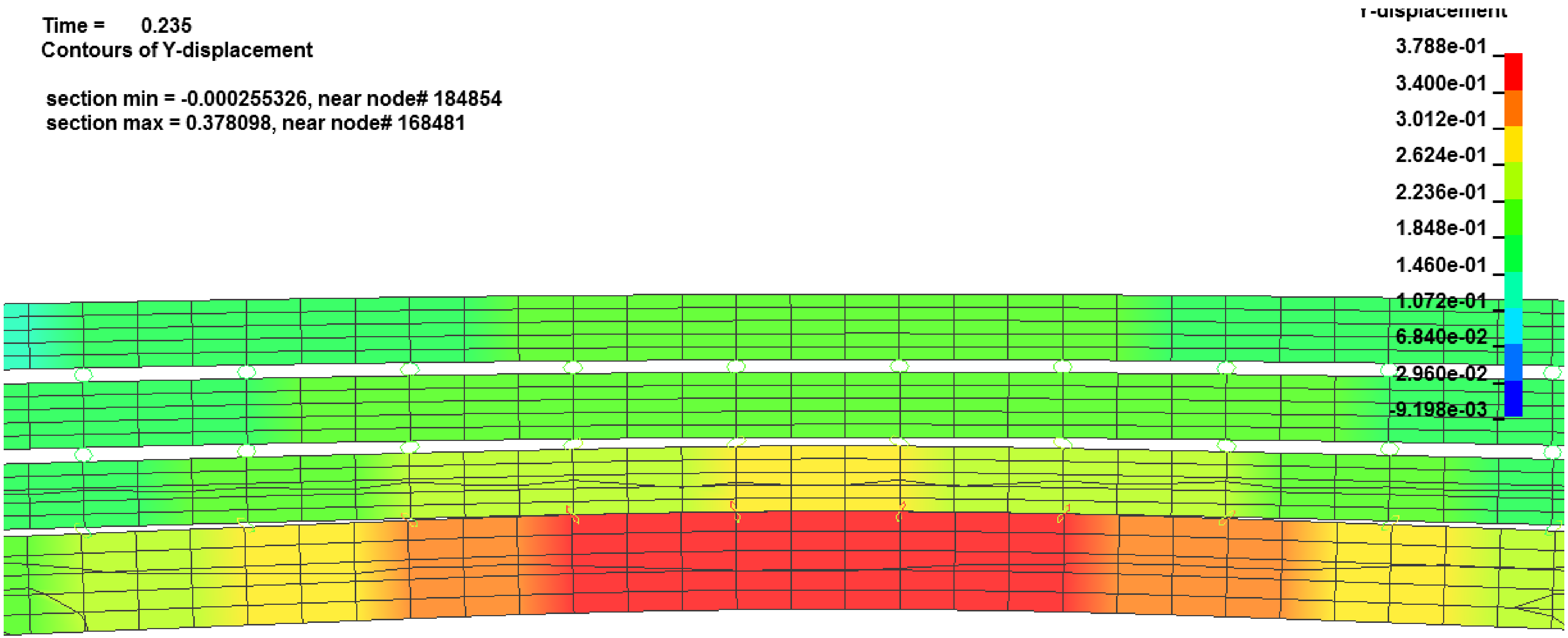


Max. Tension at Inner Side: 0.25 %

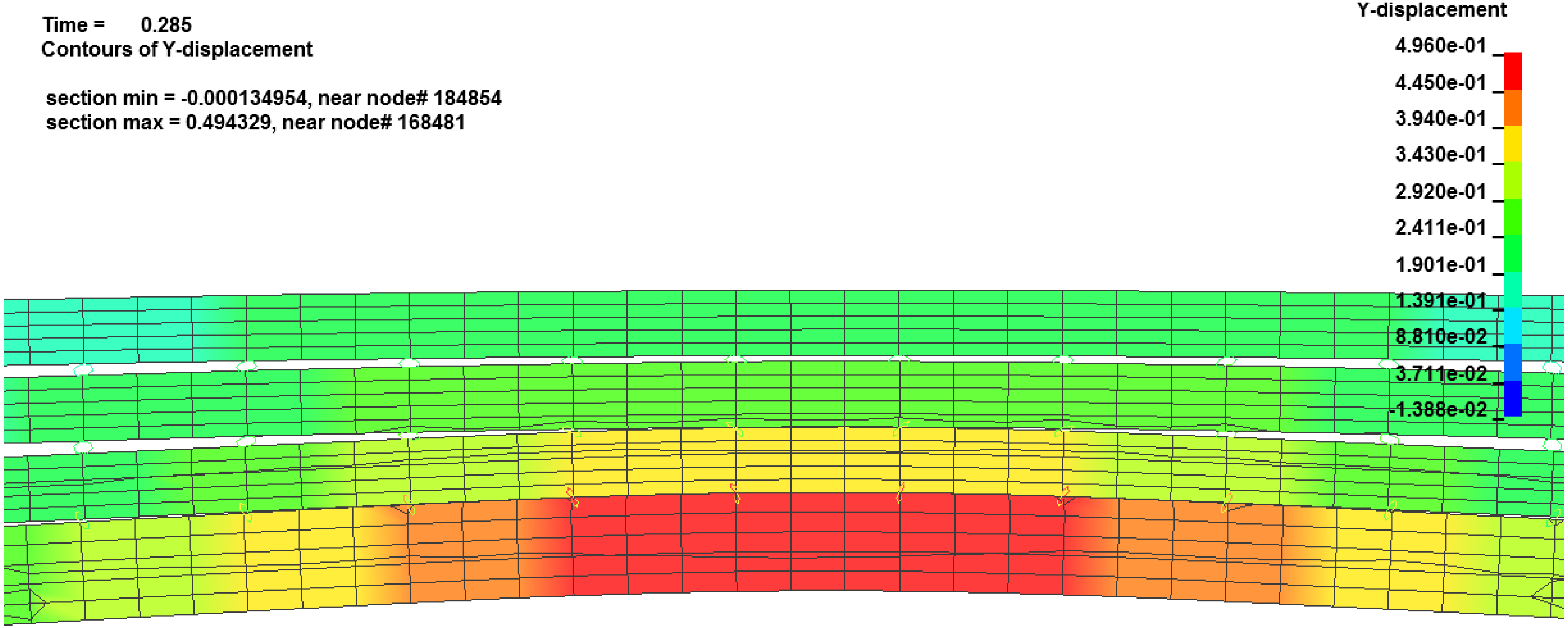
MLWS at 0.175 s



MLWS at 0.235 s



MLWS at 0.285 s



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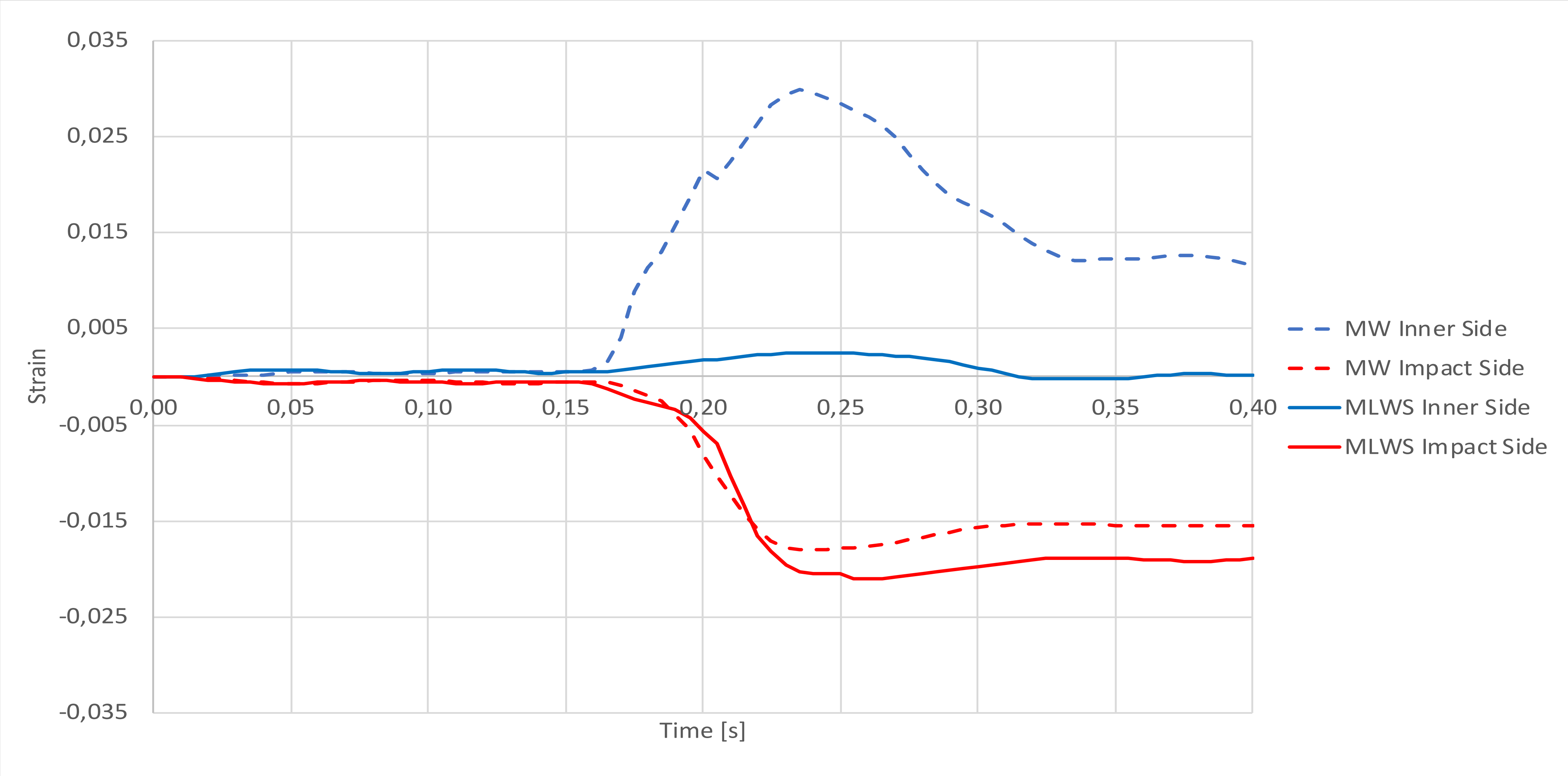
MW and MLWS Strain



Summary MLWS for Protection Against APC

- The compression strains at the impacted side are both for MW and MLWS higher than the limit of -0.5% according to RCC-CW. This exceedance will result for the MW in progressive failure, while for the MLWS just the first wall layer will fail
- The maximum tension strain at the MLWS inner side is distributed over a larger area, while for the MW localized concentration of high tension strain is evident
- The tension strain at the inner side is 2.99 % for the MW and 0.25 % for the MLWS. In case of MW, there is no available capacity to sustain increased demand of APC protection for larger commercial aircraft types than A320 as for example B747 or A380. Due to the modular construction of the MLWS, the number of concrete layers and steel pipes can be varried in order to control the desired reinforcement and concrete strains at the inner side of the impacted structure
- The MV transfers high frequency APC induced vibrations unfiltered into the building structure due to its own huge stiffness. On the other side in case of MLWS due to the nonlinear deformations of the steel pipes filtering of high frequency APC induced vibration occurs, significantly reducing the requirements for design and qualification of components

Scaled MLWS for Protection of Critical Infrastructure

- Experiments performed by Prof. Gebbeken from the „Universität der Bundeswehr“, Neubiberg, have shown:
  - The pressure wave of explosive placed in front of a green hedge is reduced behind the hedge by 60%
  - In case of a combination of a metal chain and water curtain, the reduction of the pressure wave is up to 50%
- A down-scaled MLWS is suitable for protection of critical infrastructure against close-in-explosions:
  - The first layer of the MLWS is sacrified and reduced significantly the pressure wave
  - The metal pipes of the MLWS absorb additional energy by nonlinear deformations and reduce the impact on the inner layers

Experiments of Universität der Bundeswehr

Green Hedge: Reduction of Pressure Wave up to 60%

Chain & Water Curtain: Reduction of Pressure Wave up to 50%

Finite Element Modelling

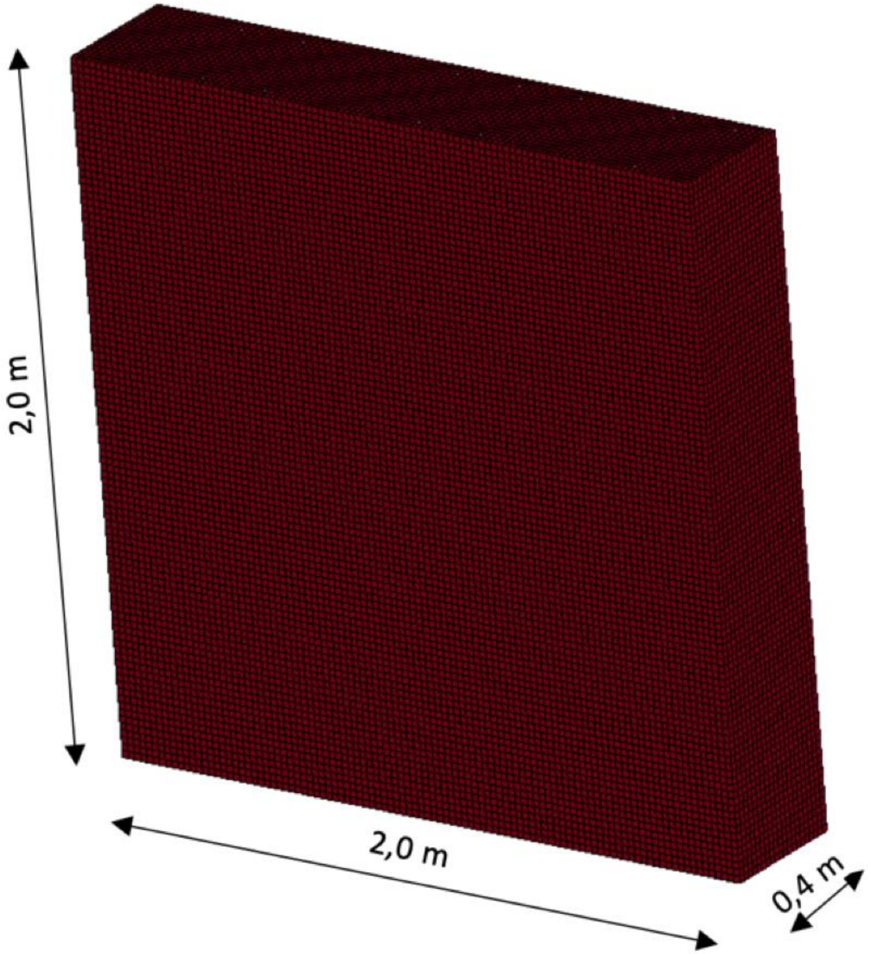
- Calculation performed with LS-DYNA,
- Concrete is modelled with the material model *MAT_WINFRITH_CONCRETE
- Reinforcement is modelled with *MAT_PLASTIC_ KINEMATIC
- Explosive load function *PARTICLE_BLAST used
- Calibration based on experimental studies of Fang et al., 2008; Wei et al., 2013

Impacted Front Side

Inner Side

Reference Massive Wall (MW)

- Dimensions L/H/d 2.0m/2.0m/0.4m
- Concrete C40/50
- Reinforcement BSt 500 D12-100 / D12-100
- Finite element modelling performed with volume elements of 2cm / 2cm / 2cm for the concrete and line elements of 2 cm for the reinforcement



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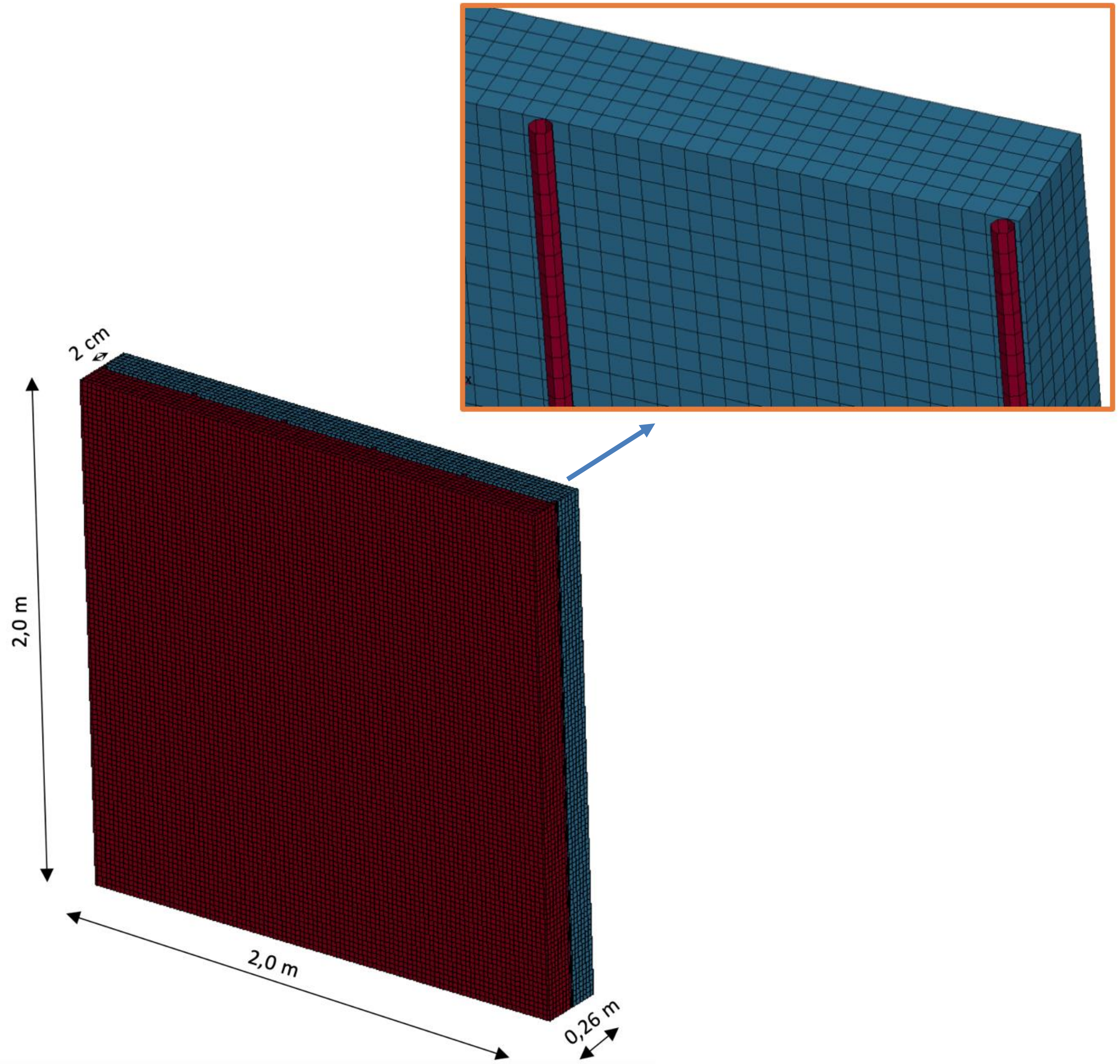
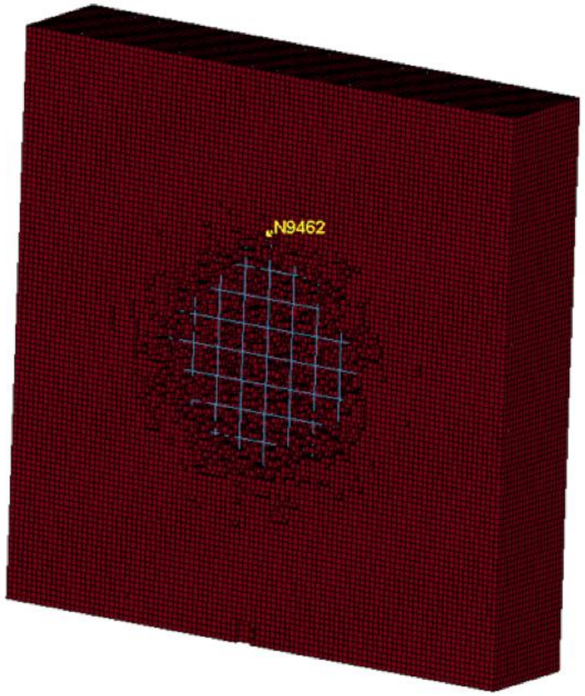
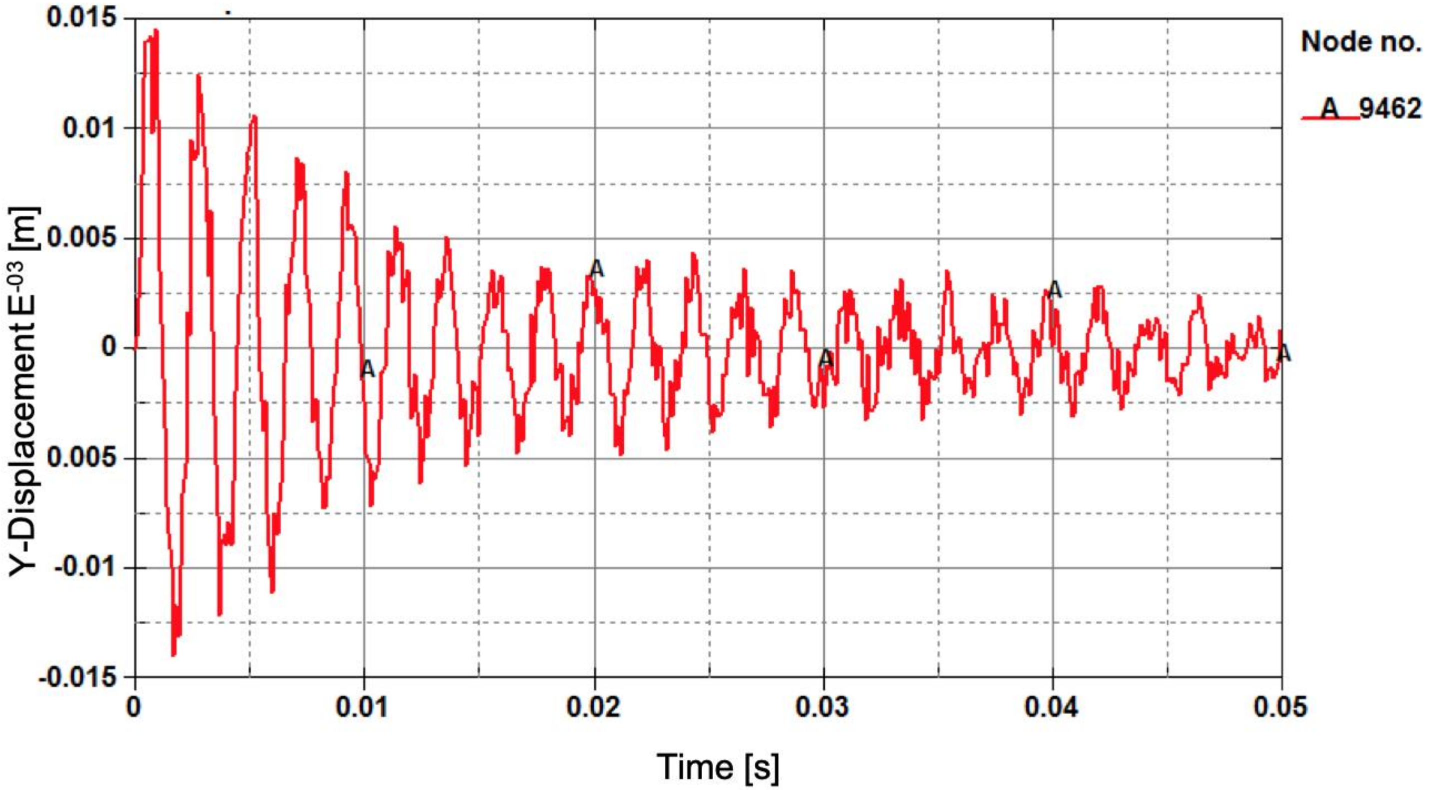
Multi-Layer-Wall-System

- Dimensions L/H/d 2.0m/2.0m/0.26m
- Consists of two concrete elements, each 0,12 m thick, between which pipes with d=2cm are placed
- Concrete C40/50
- Reinforcement BSt 500 D6-100 / D6-100
- 6 steel pipes with t = 2 mm and σ_y = 250 MPa
- Finite element modelling performed with volume elements of 2cm / 2cm / 2cm for the concrete, shell elements for the pipes and line elements of 2 cm for the reinforcement



MW Exposed to 2 kg PETN





MW Dynamic Response at Impact Side

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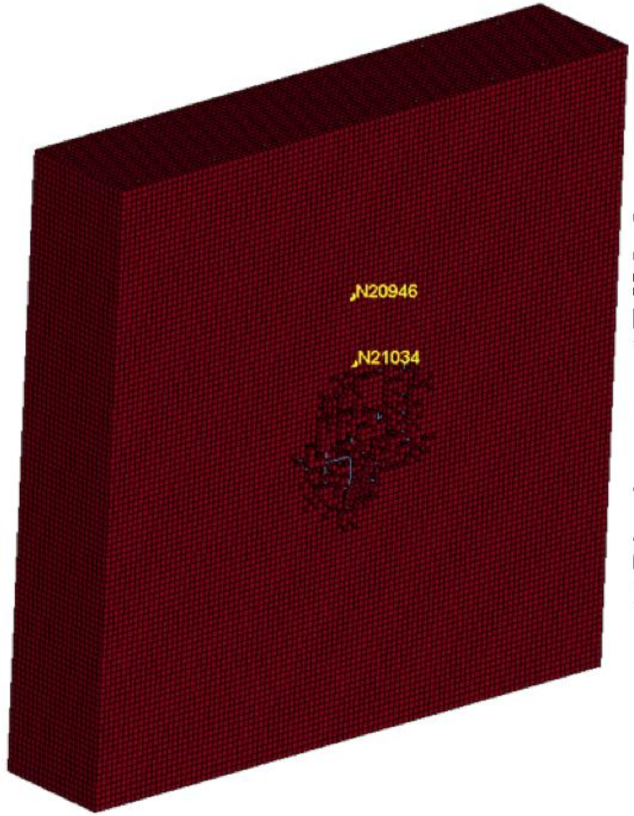
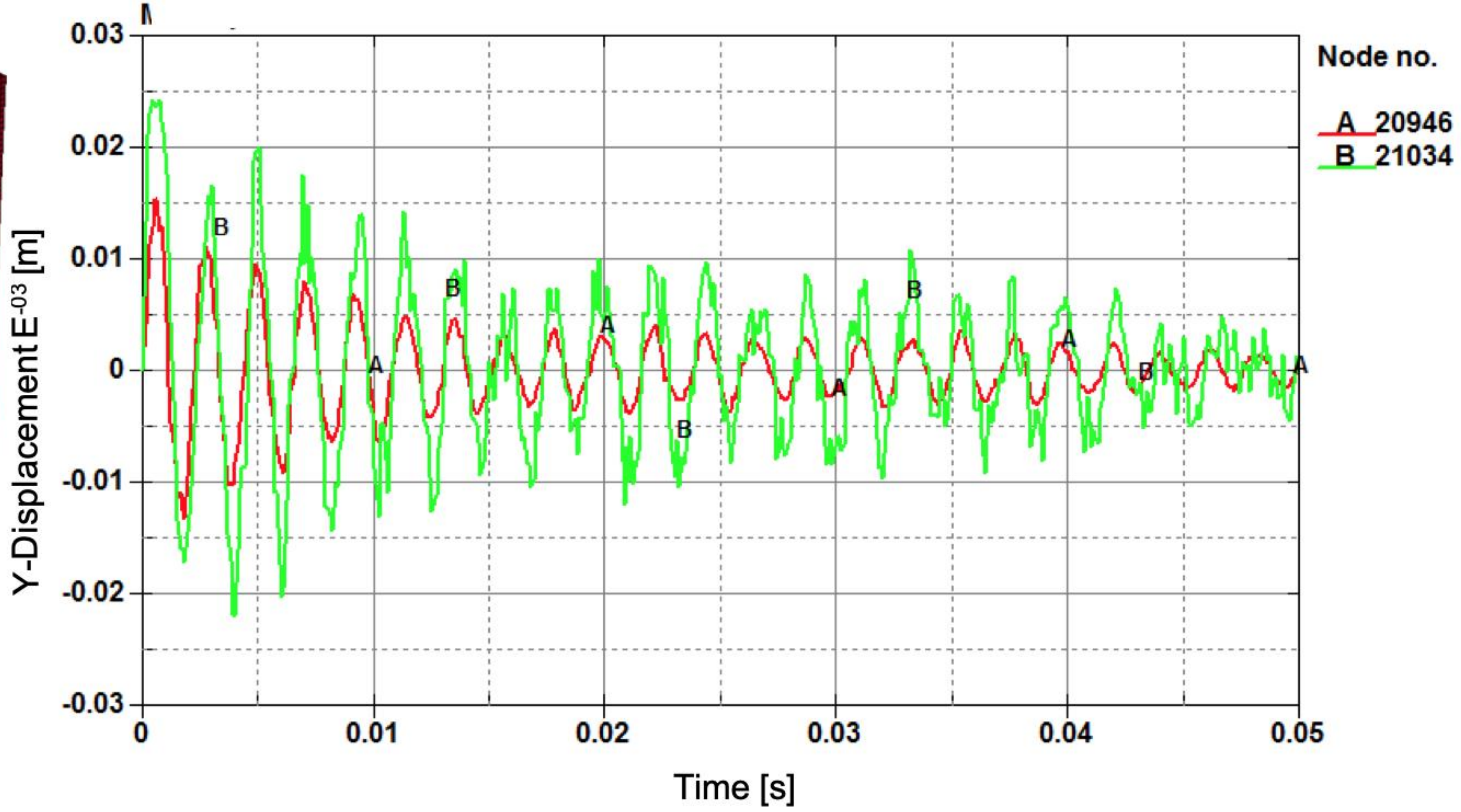
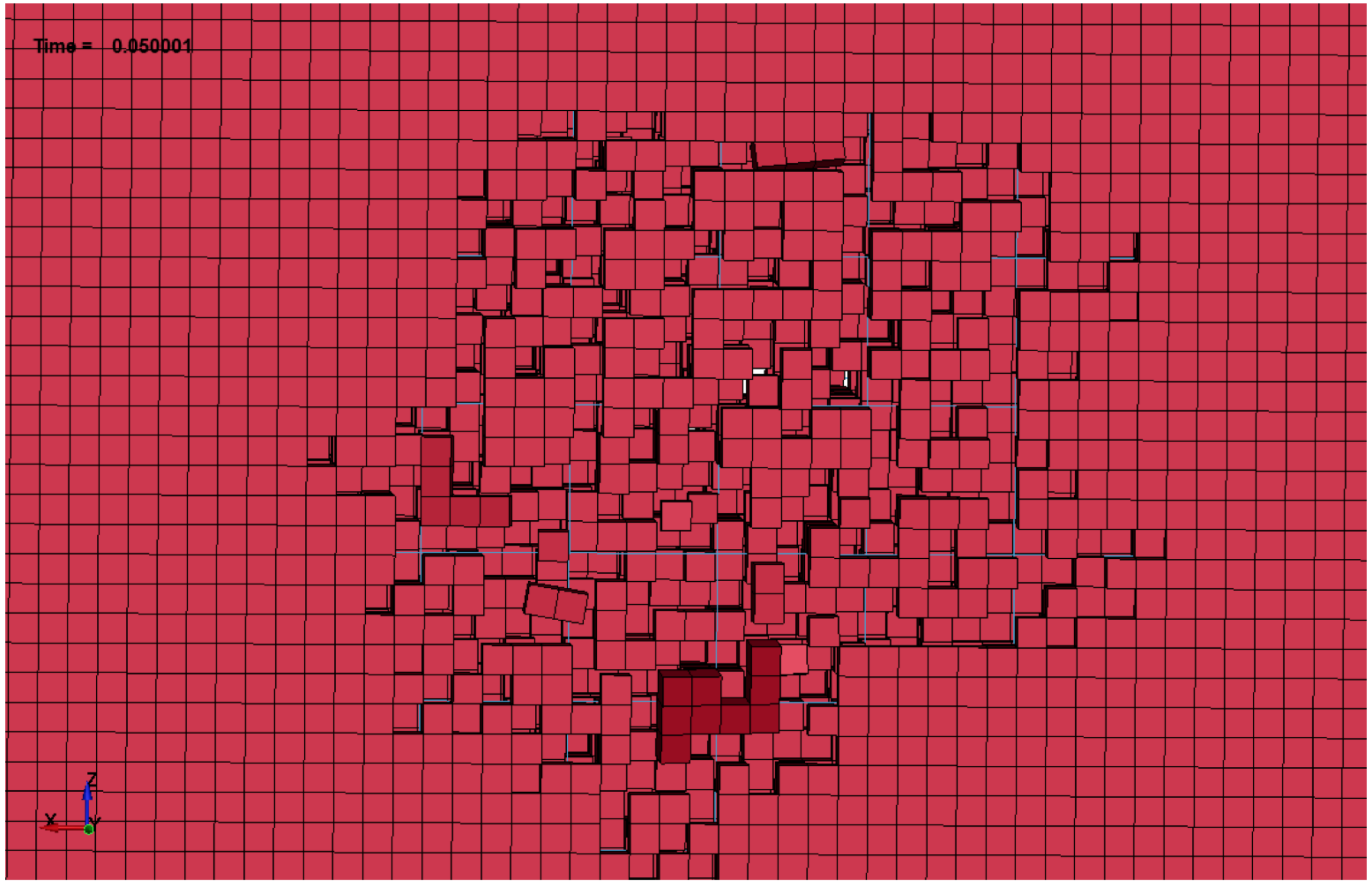
MW Exposed to 2 kg PETN





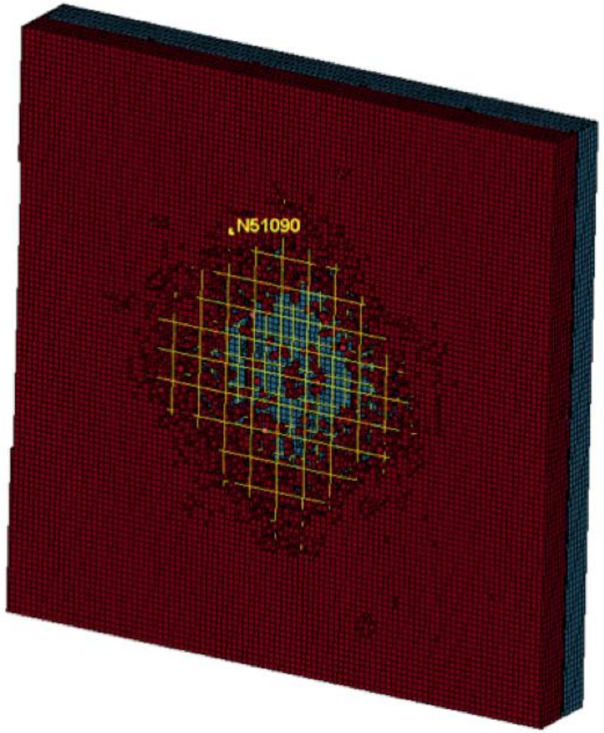
MW Dynamic Response at Inner Side

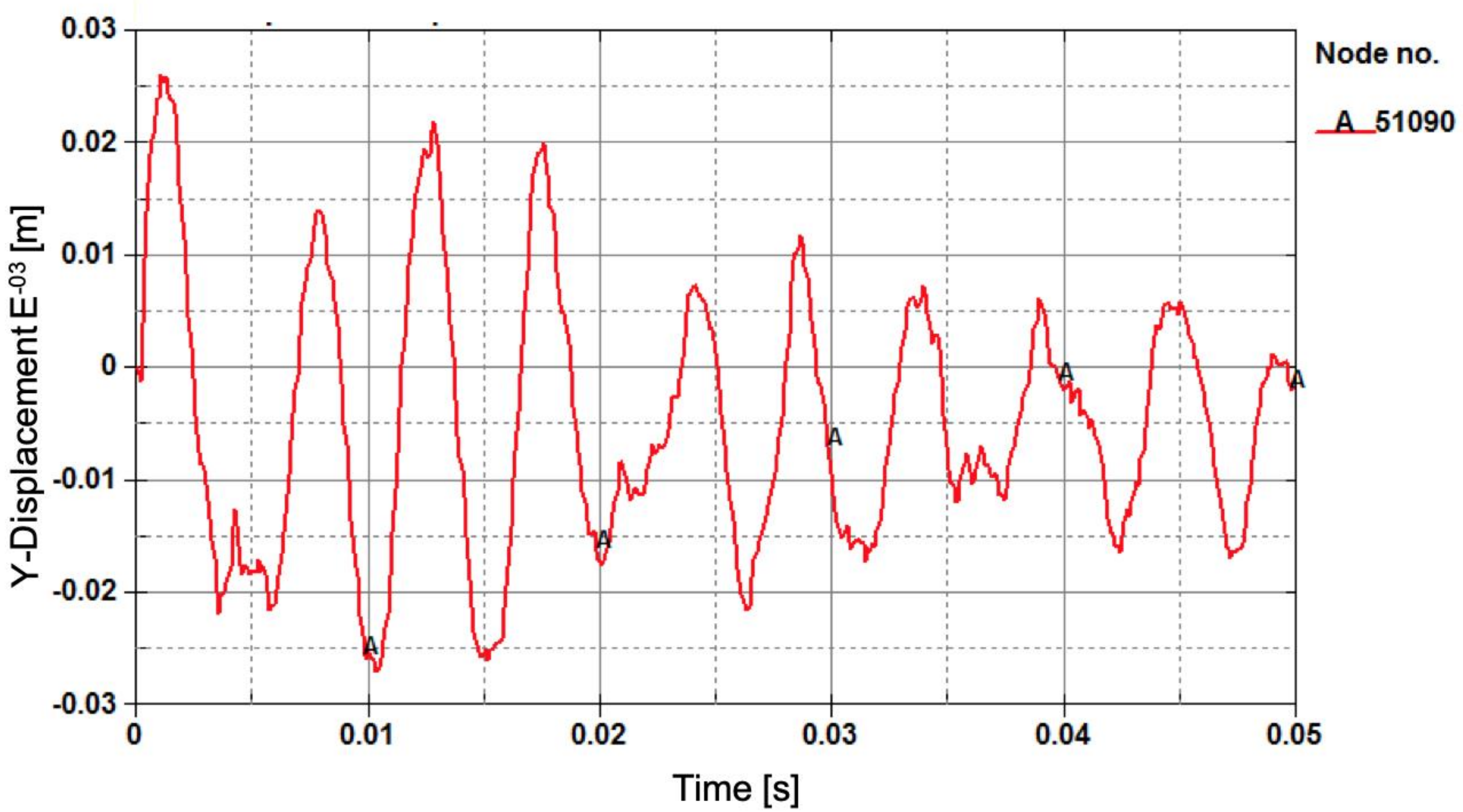
MW Exposed to 2 kg PETN



MW Damage Pattern - Failure at Inner Side

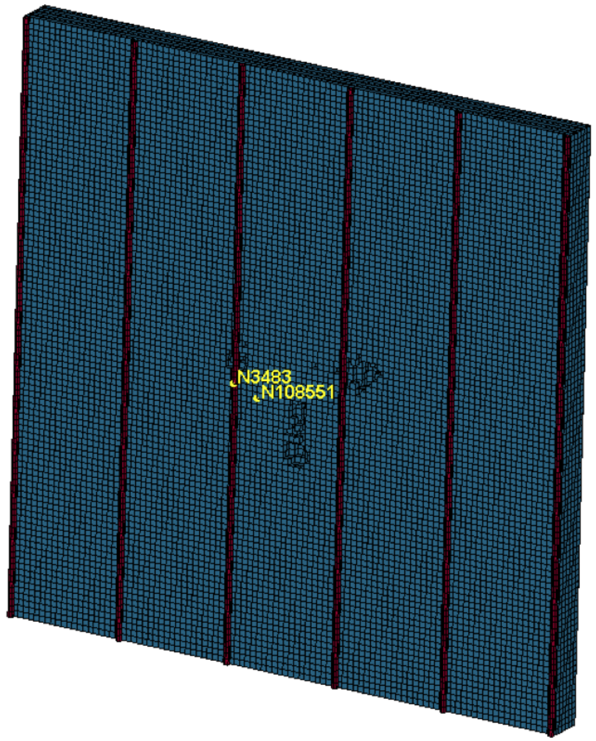
MLWS Exposed to 2 kg PETN

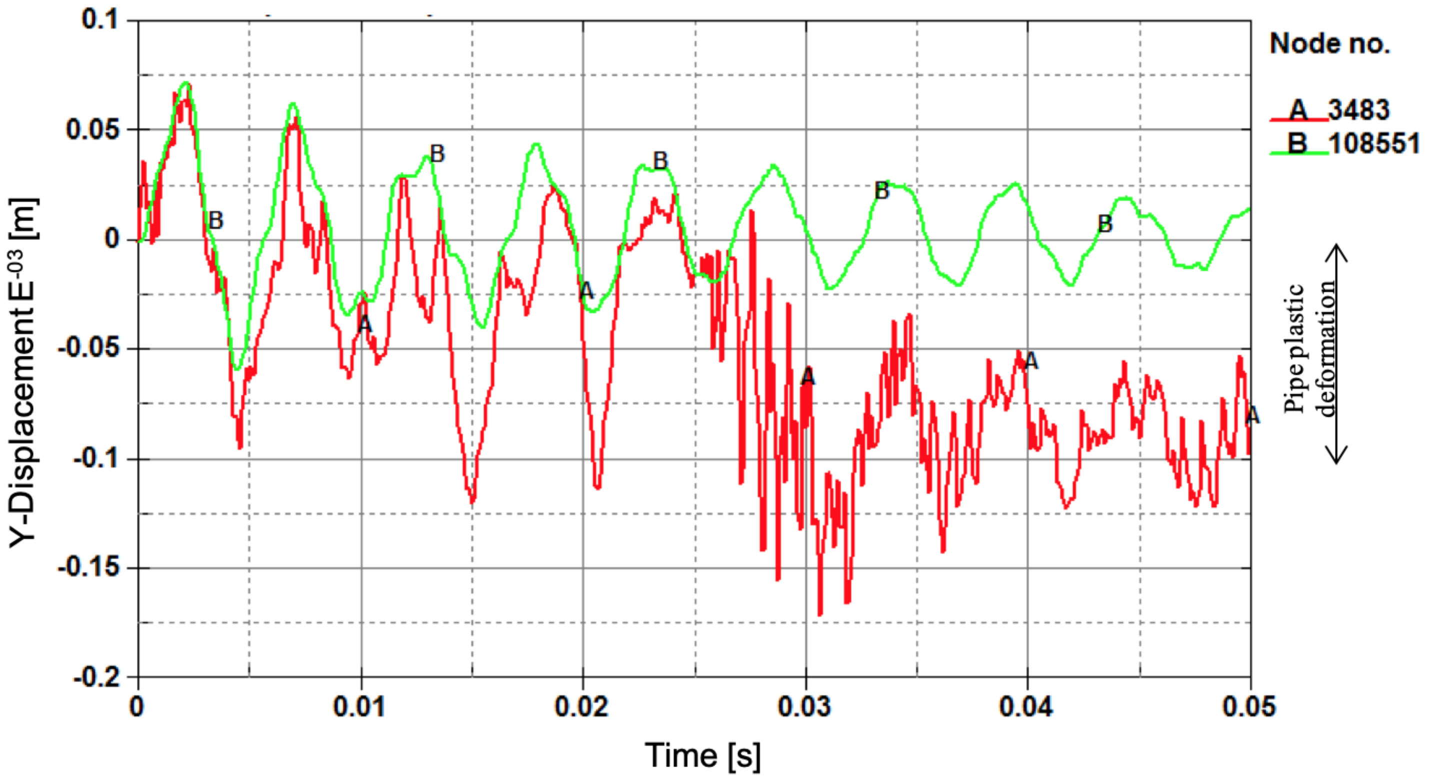




MLWS Dynamic Response at Impact Side

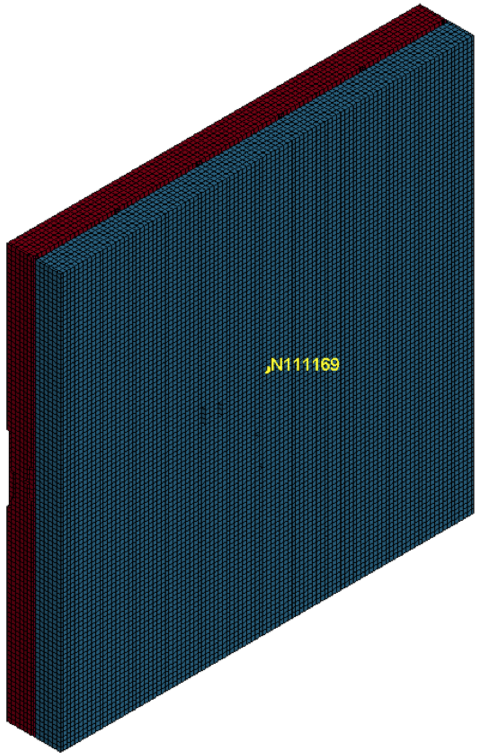
MLWS Exposed to 2 kg PETN

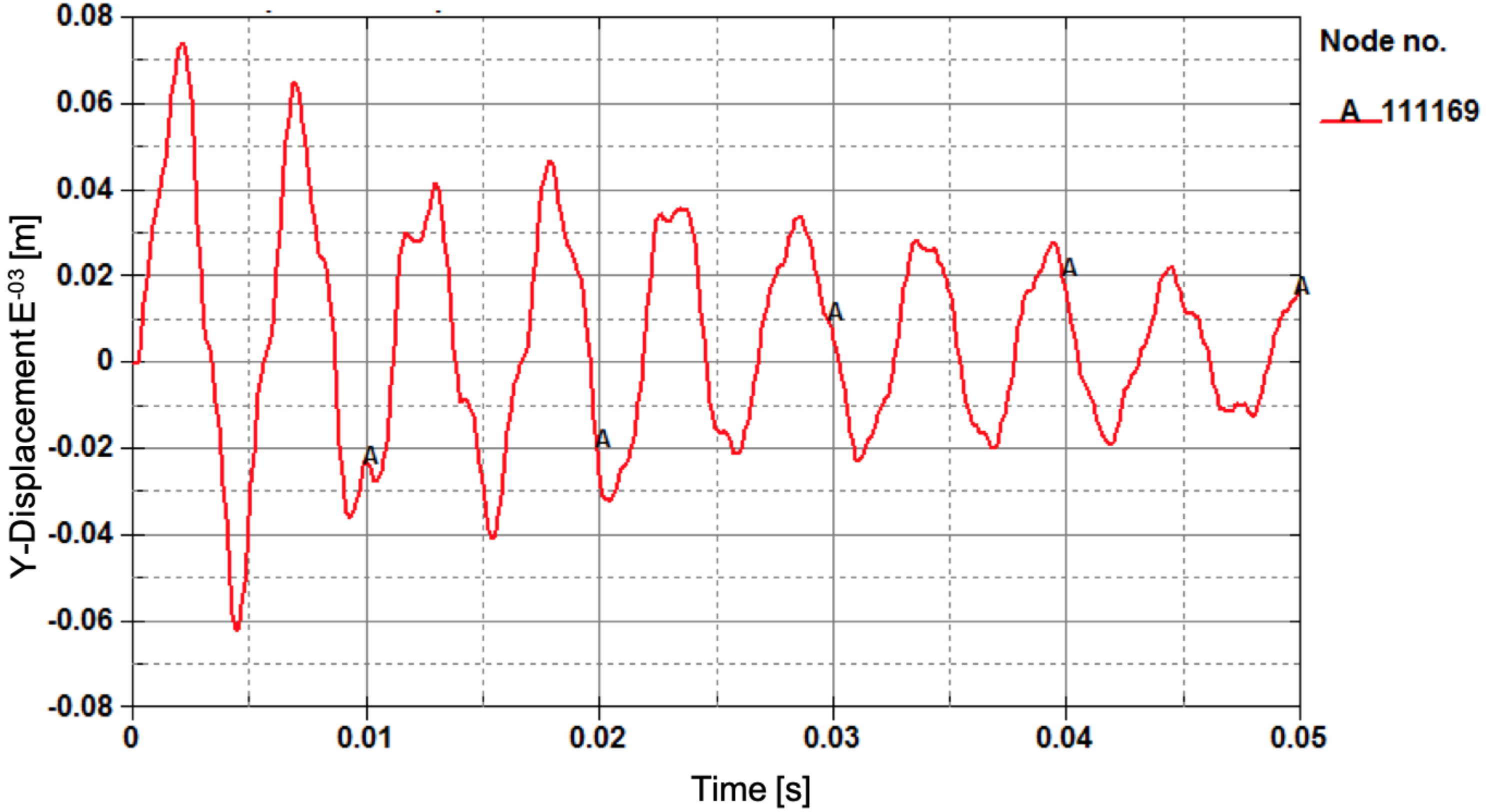




MLWS Dynamic Response at Impact Side of Inner Layer

MLWS Exposed to 2 kg PETN





MLWS Dynamic Response at Inner Side of Inner Layer

Summary MLWS for Protection Against Close-In-Explosion

- Dynamic analyses are performed for a 2m x 2m massive wall (MW) plate with thickness of 40 cm and for a 2m x 2m multi-layer wall system (MLWS) plate with thickness of 26 cm, both exposed to close-in explosion of 2 kg PETN
- Out of the performed analyses it is evident that in case of close-in explosion of 2 kg PETN, the 40 cm thick MW is perforated, suffers significant damage on the inner side, is destroyed and does not provide full protection. The 26 cm thick MLWS, exposed to the same external load is not perforated and provides full protection for the considered load case although the total thickness of the MLWS is significantly lower than the thickness of the MW
- In the case of the MLWS, energy is absorbed and high frequency content is dissipated by nonlinear deformation of the steel pipes, reducing the load which arrives at the inner plate. Energy dissipation does not take place during the short duration of close-in explosions and high frequency vibrations are induced to the inner side of the MV plate. The increase of reinforcement amount does not significantly lead to better resistance of the MW as the concrete class is the relevant parameter for resistance of the MW exposed to the load case explosion

Cont. Summary MLWS for Protection Against Close-In-Explosion

- In addition to the higher resistance against close-in explosions in comparison to a massive reinforced concrete wall, the huge advantage of the MLWS is the modularity. In case of increased requirements for resistance of a MW against close-in explosion, there is no simple solution for upgrading of a MW. On the other side, a MLWS can be upgraded by mounting of any desired number of additional steel pipes and prefabricated concrete elements. The MLWS upgrade can also be performed on existing MW

Thank you for your attention

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