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Division III

MULTI-LAYER WALL SYSTEM FOR PROTECTION AGAINST CLOSE-IN EXPLOSION

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INTRODUCTION

Since the September 11 terrorist attacks, the US NRC has adopted several rules aimed at improving security at existing nuclear power facilities and codified these requirements in a separate rule for all existing and proposed nuclear facilities NRC (2008). In order to fulfill the increased requirements, nuclear facilities that shall sustain the impact of a large commercial aircraft require an external massive wall (MW) thickness of at least 1,80m (NEI, 2011; NRC, 2011; RCC-CW, 2015), which leads to increased efforts and costs for the structural design and construction. In order to allow fulfilling NRC requirements with lower wall thicknesses, Max Aicher GmbH & Co. KG (2021), developed a modular multi-layer wall system (MLWS), which has significant advantages in comparison to the MW for the load case airplane crash (APC) on one side and compatible properties with MW for the load case design basis earthquake (DBE) on the other side (Vlaski and Moersch, 2020).

The favourable dynamic response of the MLWS to APC is the basis for development of a scaled MLWS system for protection of critical structures like dry storage nuclear waste buildings, military and other significant buildings against terrorist attack of close-in explosions. The MLWS is a modular system, consisting of multiple reinforced concrete plates and steel pipes. Due to the modularity, it can be used for new buildings as well as for upgrade of existing buildings, in case an increased resistance against explosions needs to be provided.

Numerical and experimental studies (Fang et al., 2008; Wei et al., 2013) have documented that massive reinforced concrete plates with thickness of 30 cm are not capable to resist close-in explosions of 2 kg TNT.

In the current paper the dynamic response of a MW with 40 cm thickness and of a MLWS with thickness of 26 cm, both exposed to close-in explosion 2 kg PETN, is analysed. The performed comparative studies demonstrate the advantage of the MLWS to provide higher protection against close-in explosions with lower wall thickness than a MW.

NUMERICAL SIMULATIONS

The numerical calculations are performed with the explicit computer code LS-DYNA (2018). The concrete is modelled with the material model *MAT_WINFRITH_CONCRETE and the reinforcement with *MAT_PLASTIC_ KINEMATIC.

Numerical calculations are performed on a MW plate with dimensions 2,0m/2,0m/0,40m and a MLWS with dimensions 2,0m/2,0m/0,26m, exposed to the external load od 2 kg PETN. The explosive, placed on the middle of the front side of each slab is modelled with the LS-DYNA (2018) explosive load function *PARTICLE_BLAST.

Both for the MW and for the MLWS concrete C40/50 and reinforcement BSt 500 is used. Due to the extremely short duration of the excitation, dynamic increase factors of 1.15 for concrete pressure, 1.20 for concrete tension and 1.10 for the reinforcement are applied according to Eibl (1997).

The material model for the concrete, used in the current study, has been calibrated on the basis of experimental results by Fang et al. (2008) of close-in explosion tests of 2 kg TNT applied on a reinforced concrete plate with 30 cm thickness and damage pattern, shown in Figure 1.

Impacted Front Side

Inner Side

Figure 1. Damage Pattern of a 30 cm Massive Wall Exposed to 2 kg TN (Fang et al., 2008)

REFERENCE MASSIVE (MW) PLATE

The massive plate is modelled with dimensions L/H/d 2,0m/2,0m/0,4m, concrete C40/50, reinforcement BSt 500 D12-100 / D12-100 on both sides and fixed boundary conditions. The finite element modelling is performed with volume elements of 2cm / 2cm / 2cm for the concrete and line elements of 2 cm for the reinforcement.

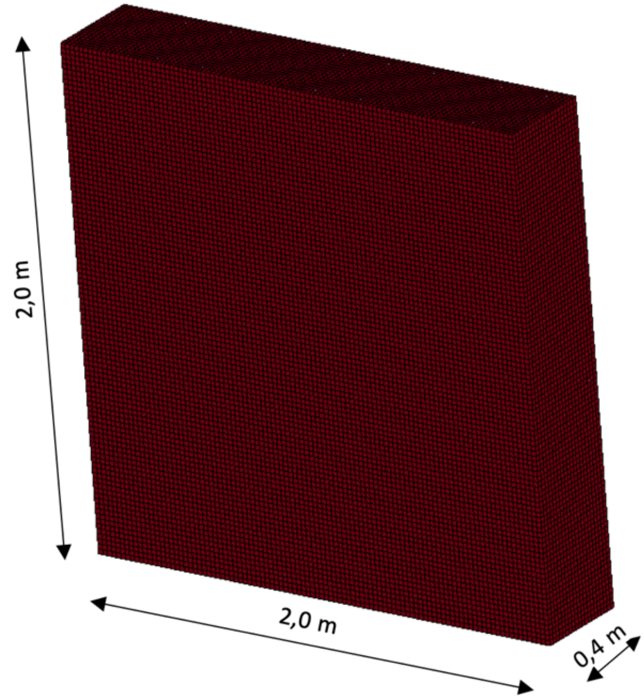

Figure 2. Finite Element Model of MW

MULTI-LAYER WALL SYSTEM (MLWS)

The MLWS analysed in this paper has the same length of 2,0 m and height of 2,0 m as the reference MW plate but instead of 40 cm thickness of the MW, the total thickness of the MLWS is 26 cm. Each plate of the MLWS is reinforced with BSt 500 D6-100 / D6-100 on both sides. The finite element modelling is performed with volume elements of 2cm / 2cm / 2cm for the concrete, shell elements for the steel pipes and line elements of 2 cm for the reinforcement.

For the current study the MLWS consists of the two reinforced concrete plates, each with a thickness of 12 cm and 2 cm space between them as shown in Figure 3. In general, the number of concrete plates forming a MLWS is unlimited and can be chosen on the basis of the external load resistance requirement. The MLWS allows the upgrade of outer MW or MLWS walls of existing structures by additional mounting of pipes and prefabricated concrete elements at selected locations in case of increased requirements.

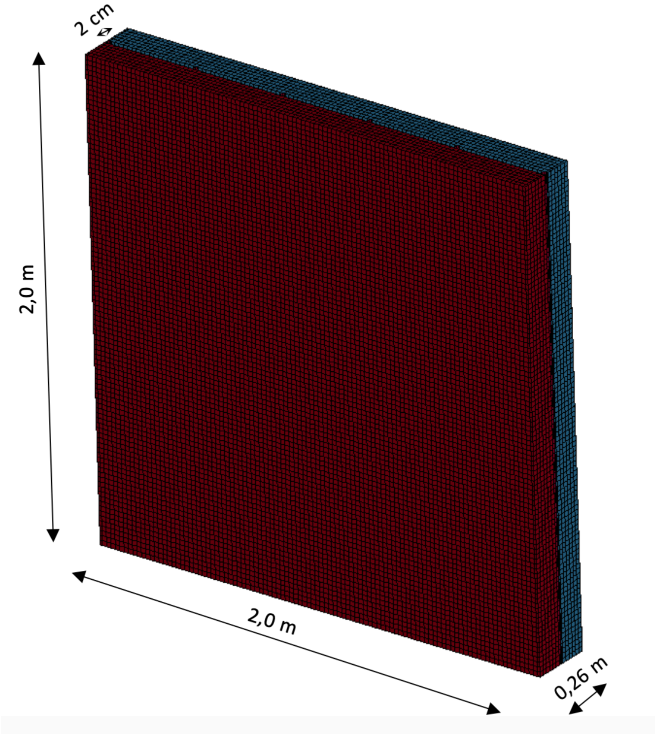

Figure 3. Finite Element Model of MLWS

In the current study steel pipes with diameter of 2 cm, pipe wall thickness 2 mm and yield stress 250 MPa are placed in the space between the two reinforced plates of the MLWS as shown in Figure 4, where one of the two MLWS plates and the steel pipe are depicted. The pipes are with fixed boundary conditions at their ends only and are not connected to the concrete plates, which results in simplified erection of the MLWS. The interaction of the steel pipes and the concrete slabs of the MLWS is modelled in the numerical simulations with contact elements.

When the MLWS is exposed at the outer side to a short duration excitation, the steel pipes between the reinforced concrete plates are deformed, absorbing energy and reducing the forces transmitted to the inner layer of the MLWS.

The material properties of the steel pipes and their thickness are evaluated out of parametric studies in order to ensure optimal deformation during the close-in explosion. Too stiff pipes would directly transfer the forces from the impacted outer plate to the inner plate, which will result in local failure of the inner plate in the vicinity of the rigid pipes. On the other side, too soft pipes are not able to absorb sufficient energy by plastic deformation, resulting in contact of the MLWS plates and transfer of a huge amount of energy to the inner plate.

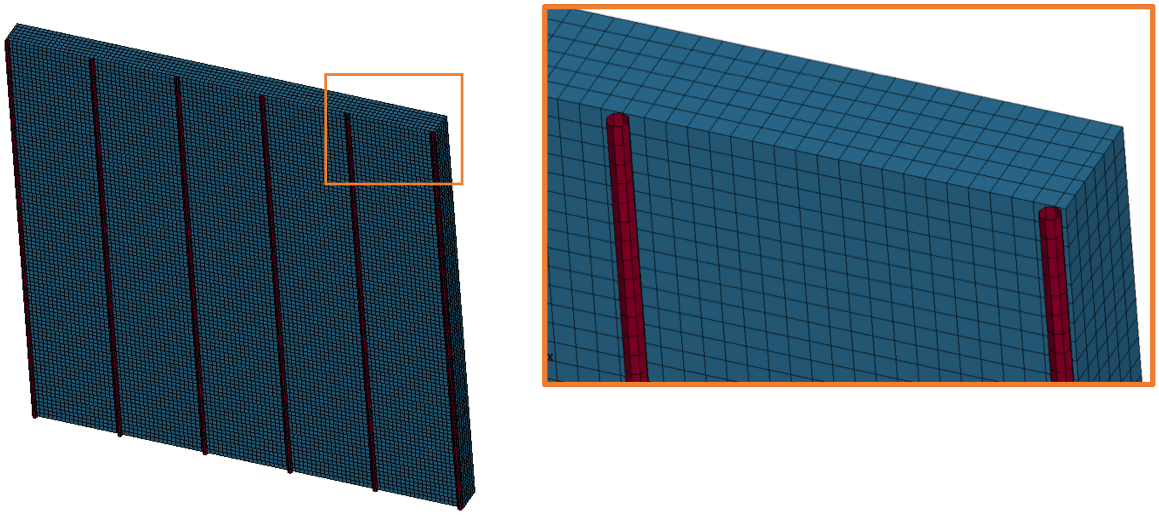

Figure 4. Inner Plate and Pipes of MLWS

DYNAMIC RESPONSE OF MW PLATE EXPOSED TO CLOSE-IN EXPLOSION

The dynamic response of the MW plate, exposed to close-in explosion of 2 kg PETN, is presented for the impacted side in Figure 5 and for the inner side in Figure 6.

The displacement time histories, depicted in Figure 5 (node 9462) and Figure 6 (node 20946) show that high frequency vibrations, result of the extremely short duration of excitation, are induced and transferred from the outer to the inner side of the MW plate.

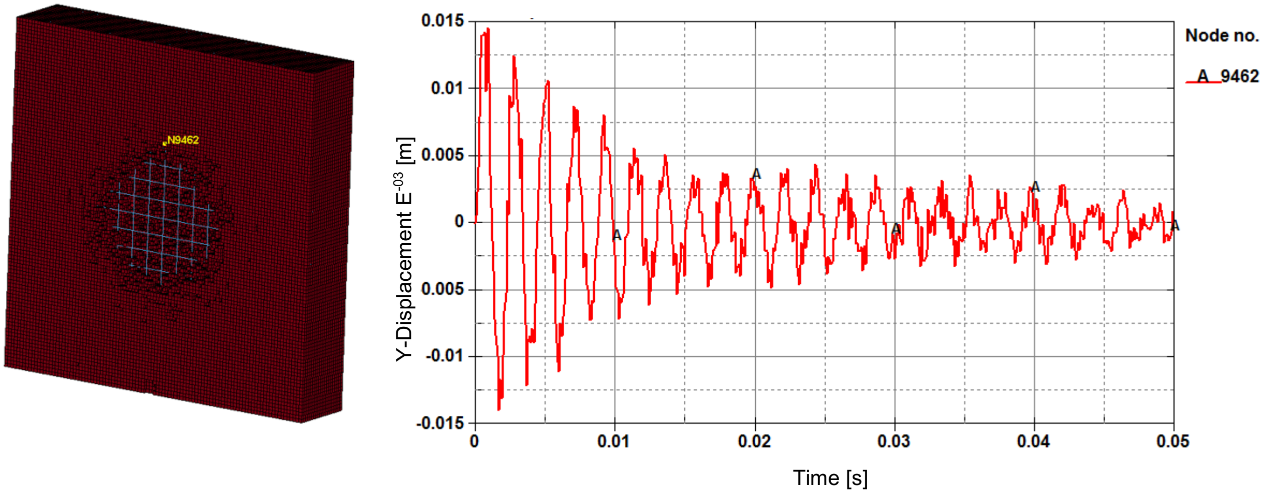

Figure 5. Dynamic Response of the MW at the Impacted Side

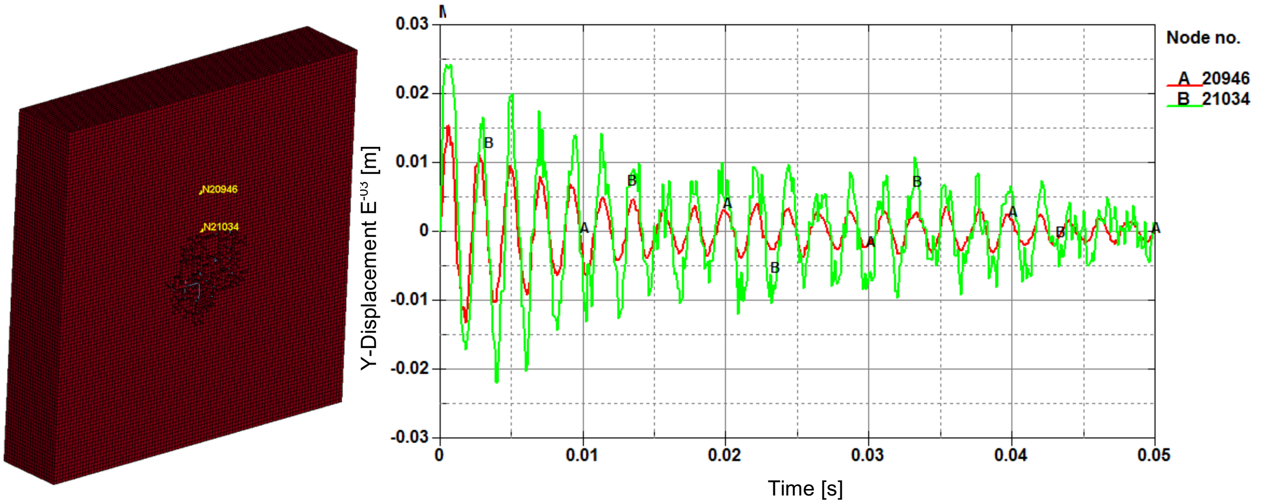

Figure 6. Dynamic Response of the MW at the Inner Side

It is evident out of Figure 7 that the MW is perforated and that a MW with thickness of 40 cm is not suitable to provide protection against the close-in explosion of 2 kg PETN. Variation of the MW reinforcement amount has shown that increased reinforcement does not lead to a significantly more favourable response. In addition to a higher concrete class, better performance of the MW for the load case close-in explosion can preferably be established by increased wall thickness.

It is furthermore evident out of Figure 7 that the MW is not suitable to provide full protection against close-in explosions.

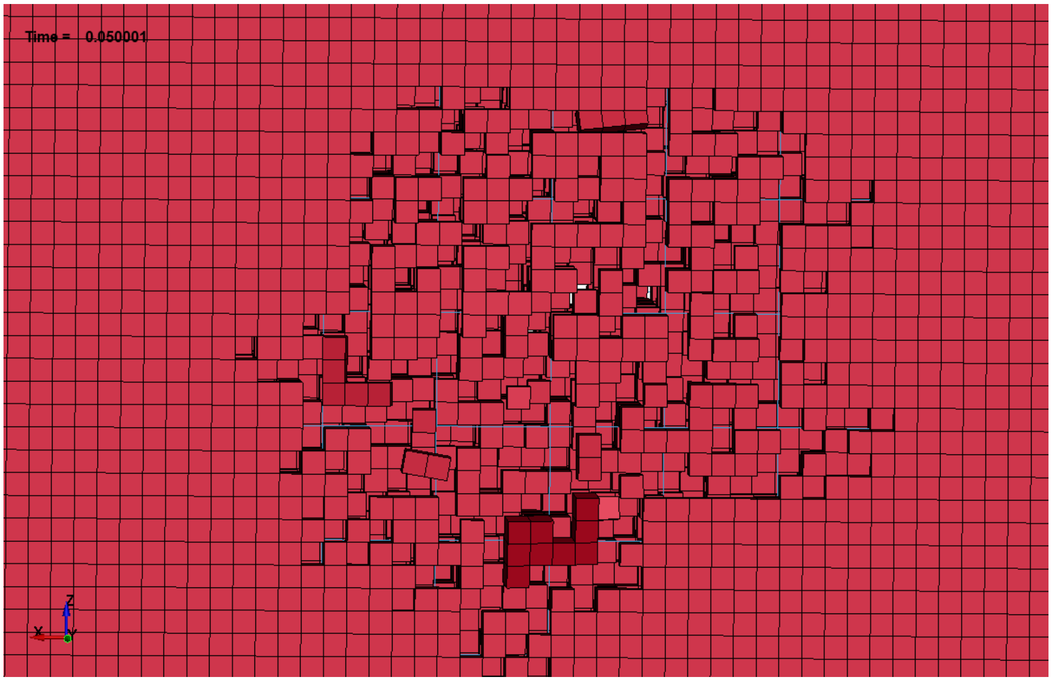

Figure 7. Area of MW Failure at Inner Side

DYNAMIC RESPONSE OF MLWS EXPOSED TO CLOSE-IN EXPLOSION

The dynamic response of the MLWS, exposed to close-in explosion of 2 kg PETN, is presented for the impacted plate in Figure 8 and for the inner plate in Figure 9.

Due to the low thickness of 12 cm, the impacted plate of the MLWS suffers increased damage, as shown in Figure 8, in comparison to the MW, with a thickness of 40 cm with damage pattern, presented in Figure 5. However, the impacted outer MLWS plate is not a relevant criterion as the requirement is that the inner side of the structure has to stay intact in order to provide full protection. The low thickness of the 12 cm impacted MLWS plate results in low stiffness and the positive effect of filtering of the high frequency vibrations, which is evident out of the comparison of the time histories presented in Figure 8 (MLWS) and Figure 5 (MW).

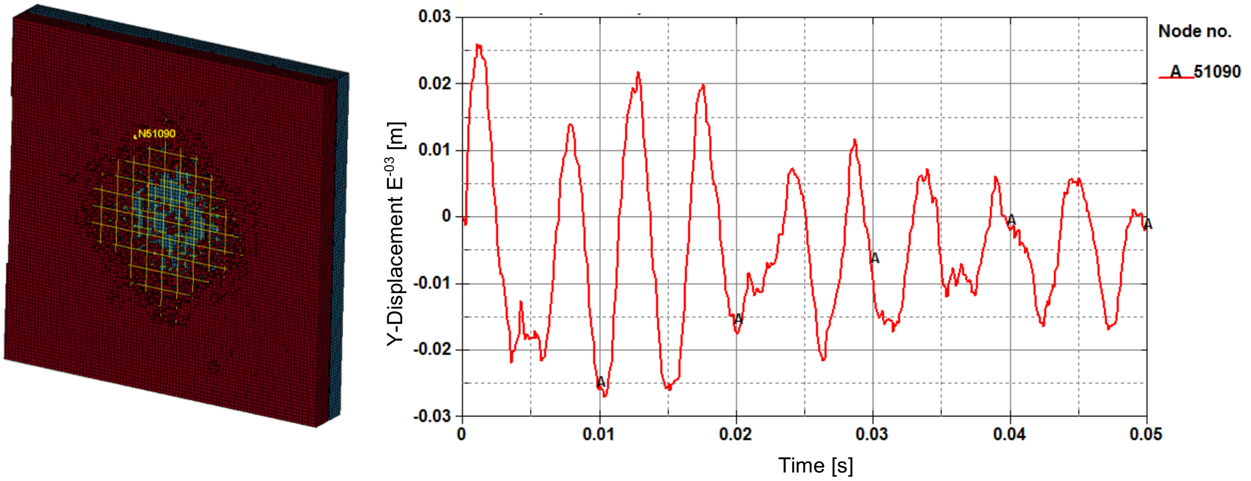

Figure 8. Dynamic Response of the MLWS at the Impacted Side

The inner plate suffers at the impacted side negligible local spalling effects due to the impact of concrete parts from the outer plate, as shown in Figure 0, but the inner plate is not perforated.

The pipes (Node 3483 on Figure 9) are exposed to nonlinear deformations, resulting in energy dissipation and filtering of high frequency content of vibrations. As the pipes are not connected to the MLWS plates but interact through contact elements, the vibration of the steel pipes differs from the vibration of the reinforces concrete plate. The concrete on the outer side of the inner MLWS plate (Node 108551 on Figure 9) vibrates in the linear range without high frequency content.

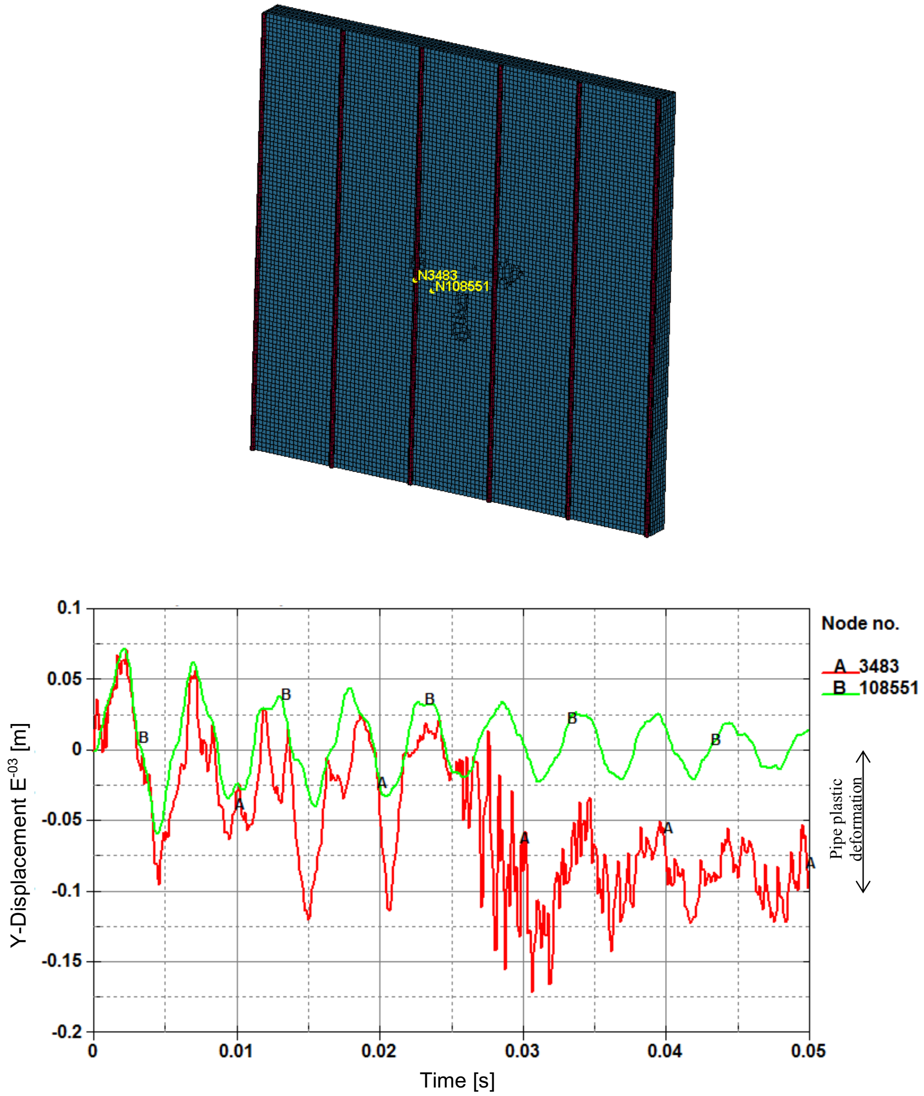

Figure 9. Dynamic Response of the MLWS at the Pipes and Outer Side of the Inner Plate

The inner side of the MLWS is neither damaged nor perforated as evident out of Figure 10.

The comparison of the displacement time histories at the inner side of the MLWS (node 111169, Figure 10) and of the MW (node 21034, Figure 6) shows that high frequency content of the induced vibrations is filtered out by the deformable steel pipes of the MLWS and does not arrive at the inner side of the plate. This is not the case for MW, where high frequency vibrations arrive at the inner side of the plate.

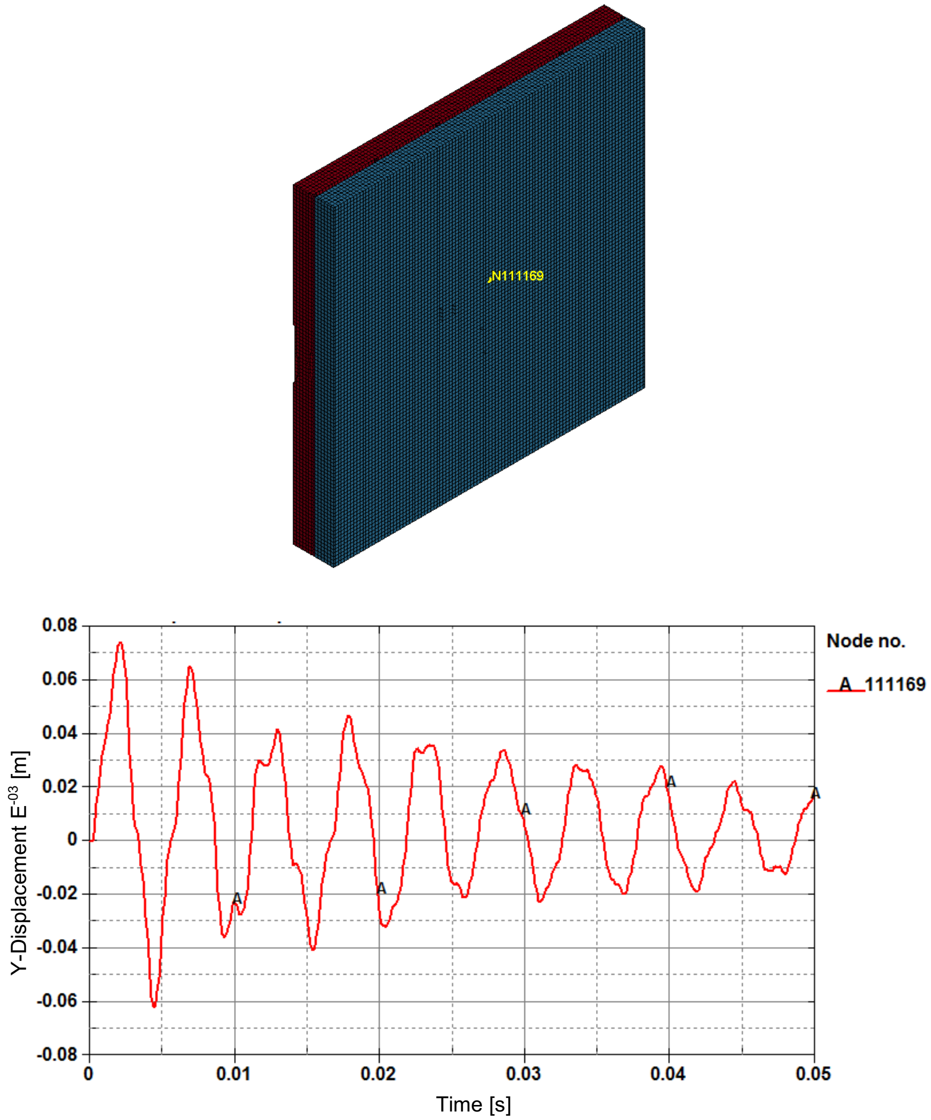

Figure 10. Dynamic Response of the MLWS at the Inner Side

CONCLUSION

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.

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.

A 40 cm thick MW exposed to a 2 kg PETN close-in explosion does not provide the required protection and will be destroyed, while a MLWS provides protection and can be restored in the initial state by replacement of the impacted front plate.

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