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

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1. Introduction

The design process of nuclear facilities requires that all possible scenarios of accidents shall be considered and that also in case of an extreme external impact a safe shutdown of the facility without release of radiation shall be performed. For the first two generations of nuclear power plants it was required by some regulatory commissions that the resistance of the structure and components against the impact of military aircraft shall be verified [1].

Since the terrorist attack of September, 11/2001, more and more regulatory commissions require that the load case impact of a commercial aircraft shall be part of the design process. Opposite to the load case impact of military aircraft, there is no standardized load function and no prescribed design procedure, defined in regulations for the load case commercial airpane crash (APC). The load function parameters for the impact of a commercial aircraft is considered as confidential and not published by regulatory commissions. For each new build nuclear facility the regulatory commission in charge prescribes a specific commercial aircraft impact load function and the required APC resistance verification procedure. The requirements for nuclear facilities, currently being built in Europe regarding the load case APC are based on an A320. In calls for new bids, the resistance against an APC of B747 or even A380 is required.

According to RCC-CW [2] and US NRC [3] the resistance of the building structure for the load case APC shall be verified by proving that following strain limits are not exceeded:

ε_s^{pl} = 5 % for the concrete steel
ε_{cu} = -0,5 % for the concrete

The verification of the resistance of a nuclear facility against the impact of a commercial aircraft A320 with "State of the Art" procedures led so far to a monolithic wall with a thickness of 1,80 m. The increase of the requirements to a B747 or A380 would lead to wall thicknesses, whose implementation would be problematic due to technological and economic reasons.

Another significant issue within the dynamic analyses for the load case APC are the induced high frequency vibrations, which do exceed the DBE design spectra in the high frequency range above 20 Hz [4]. Massive concrete walls do not provide any significant capacity for absorption of APC induced high frequency vibrations but do transfer them into the inner structure, which results in huge requirements for the design and qualification of components.

These issues are the basis for the development of a multilayer wall system (MLWS) by Max Aicher GmbH & Co. KG [5], which has significant advantages in comparison to the massive wall (MW) for the load case APC on one side and has compatible properties with a MW for the load case design basis earthquake (DBE) on the other side. For the load case DBE the MLWS shows almost identical response as the MW. The dynamic response of the MLWS for the load case APC is characterized with significantly lower strain at the inner side of the impacted structure in comparison to the dynamic response of a MW, thus reducing the requirements for design and qualification of components.

On the basis of the MLWS for protecion of nuclear facilities against APC, in addition also a scaled-down MLWS for protection of critical infrastructure against close-in explosion has been developed, which is also presented in this paper.

2. Multilayer Wall System for Protection of Nuclear Facilities Against Airplane Crash

In this section the MLWS for protection of nuclear facilities against APC impact is described.

The deformation capacity of the building structures is evaluated in the current paper with the Riera Method [6], [7], [8] according to the recommendations of US NRC [3] and NEI [9]. The calculations are performed with LS-DYNA [10], using the Winfrith concrete model described by L. Schwer [11].

2.1 Massive Wall (MW) Exposed to Commercial Aircraft Impact

A massive wall with dimensions 40 m x 20 m x 1,80 m, shown in Fig. 1, fixed at the boundaries and exposed to the impact of an Airbus A320 is considered as reference.

The maximum compression and tension strain of the reference MW, exposed to the impact of an Airbus A320 is depicted in Fig. 2 and Fig. 3 respectively.

Although the maximum tension of the reinforcement at the MW inner side of 2,99 % is lower than the tension strain limit of 5 % according to RCC-CW [2], there is no capacity to sustain increased requirement like the impact of an Airbus A380, whose impact energy is much higher than the one of an A320.

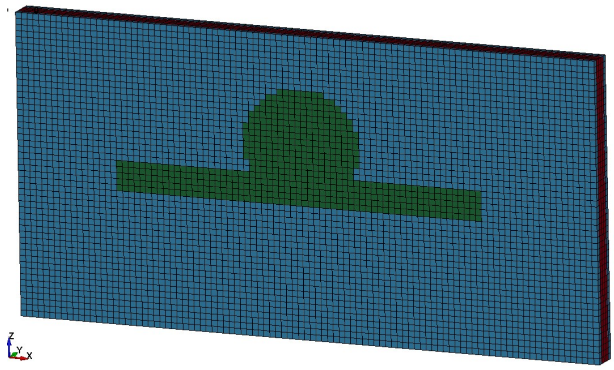


Fig. 1. Reference Massive Wall (MW) 40 m x 20 m x 1,8 m

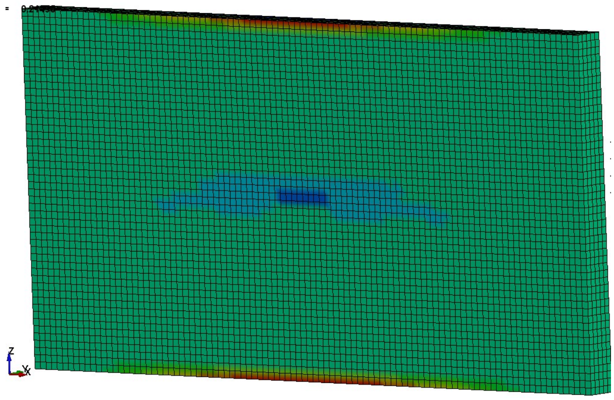


Fig. 2. MW max. Compression Strain on Impact Side: 1,81 %

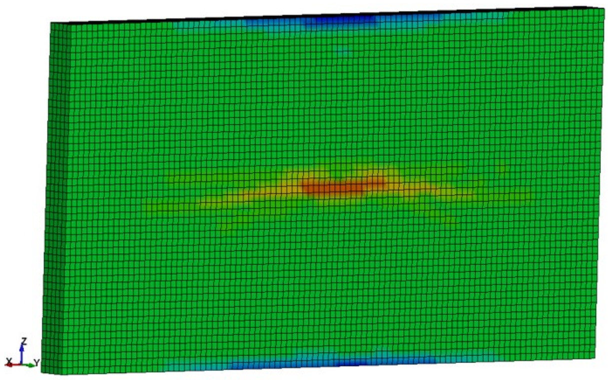


Fig. 3. MW max. Tension Strain on Inner Side: 2.99 %

2.2 Multi-Layer-Wall-System (MLWS) Exposed to Commercial Aircraft Impact

As an alternative to the massive wall, a multilayer wall system (MLWS), depicted in Fig. 4, is introduced.

The MLWS consists of 4 reinforced concrete walls. The outer impacted wall is 60 cm thick, while the thickness of the other 3 walls is 40 cm each. The four walls are separated by 10 cm free space in which steel pipes are mounted. The steel pipes are designed so that in case of DBE they do not deform nonlinear, but are capable to provide sufficient stiffness to the structure. For the load case APC high deformations lead to nonlinear deformations of the steel pipes. Due to the modular construction of MLWS it is possible to vary the number of reinforced walls and free space with steel pipes according to the requirements.

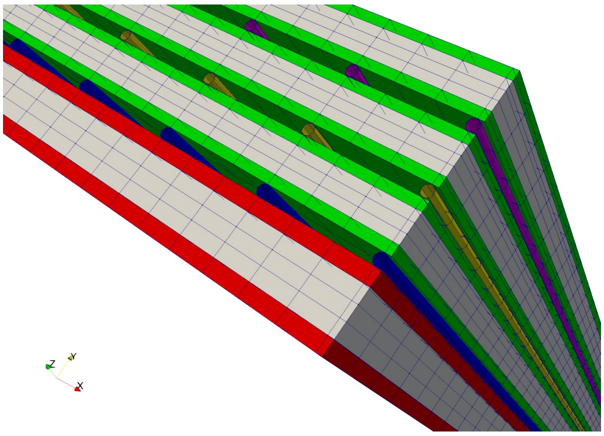


Fig. 4. Multilayer Wall System (MLWS)

The dimensions of the MLWS reinforced concrete walls, of the steel pipes and the distance between the steel pipes are evaluated out of the condition that the dynamic response of the MLWS for the load case DBE shall be compatible with the dynamic response of the reference MW. The first dominant eigenvalue of the reference MW with fixed boundary conditions is at the frequency of 15,748 Hz with modal mass mobilization of 69,46 % in the direction vertical to the MW plane. With a parametric study and variation of the steel pipe distance and thickness, presented in Table 1, a compatible eigenfrequency of the first dominant eigenvalue of the MLWS at 15,613 Hz can be reached for pipe thickness of 10 mm and pipe distance of 0,50m.

Table I. Dominant MLWS eigenfrequencies as a function of pipe distance and pipe thickness

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

Comparative calculations of the dynamic response due to the load case DBE, with excitation based on EUR hard soil spectrum of EUR [12] scaled to a PGA of 0,4 g have been performed for MW and MLWS system. The dynamic response of both, MW and MLWS, are compatible as shown in Fig. 5.

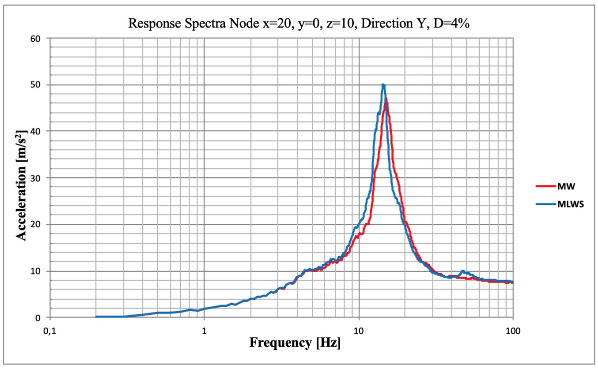


Fig. 5. Response spectra MW and MLWS

In case of commercial APC, the deformations of the impacted wall are transferred through the pipes to the neighboring walls. The maximal compression strain at the impacted side of the MLWS is 2,10 %, while the maximum tension strain at the inner side of the MLWS is 0,25 %, as presented in Fig. 6 and Fig. 7. respectively.

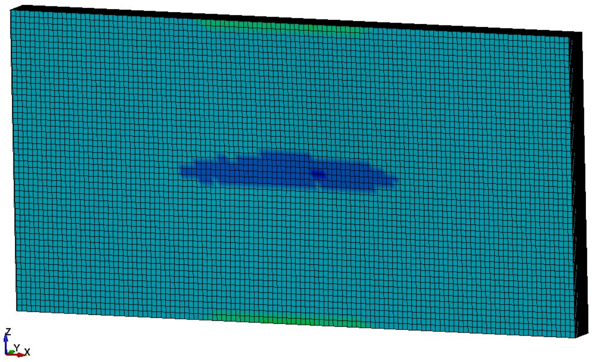


Fig. 6. MLWS max. Compression Strain on Impacted Side 2,10 %

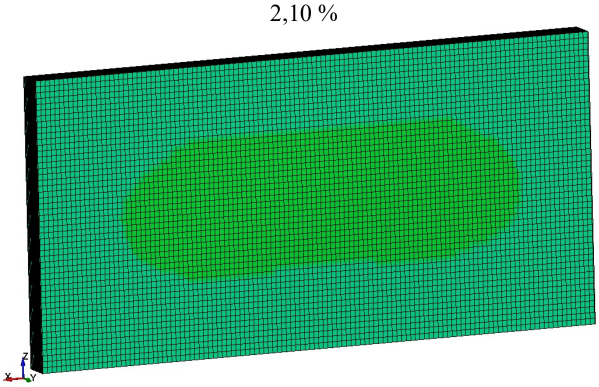


Fig. 7. MLWS max. Tension Strain on Inner Side 0,25 %

The deformation states of the MLWS due to APC of an Airbus A320 at selected times are depicted in Fig. 8. At time of 0,175 sec. the deformation of the impacted wall is so huge that the first row of pipes starts with nonlinear deformation. At 0,235 sec. the nonlinear deformation of the first row of pipes is completed, the first two walls segments have established contact and the nonlinear deformation of the next row of pipes starts. After 0,285 sec. significant transfer of deformation to the inner wall segment starts.

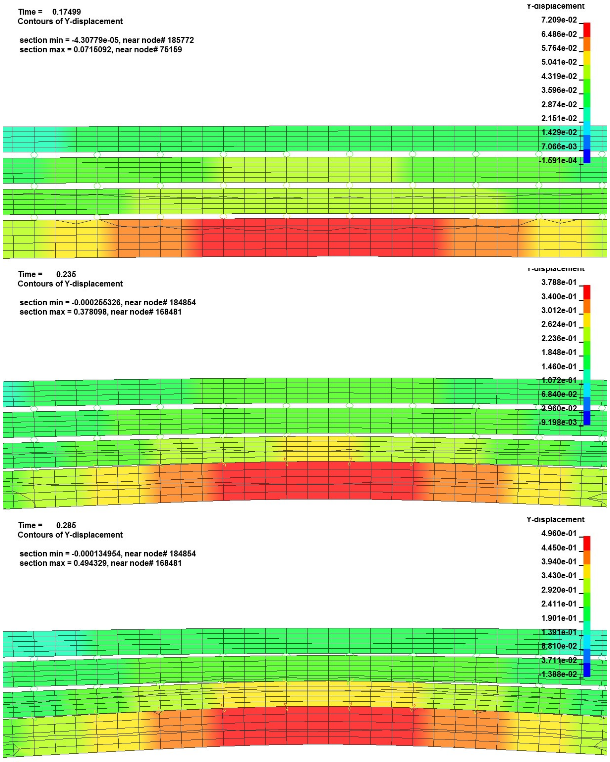


Fig. 8. Deformation states of the Multilayer Wall System due to APC A320

2.3 Comparison of the Dynamic Response of MW and MLWS due to the Load Case APC of an A320

The maximum tension and compression strains of the massive wall (MW) and the multilayer wall system (MLWS) developing over time of impact are presented in Fig. 9.

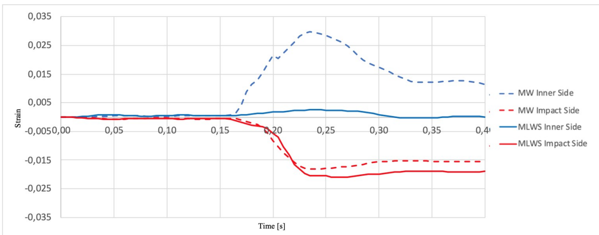


Fig. 9. Maximum tension and compression strain of MW and MLWS

The compression strain of the concrete at the impacted side does exceed the limits of -0,5 % prescribed by RCC-CW [2] both for MW and MLWS.

The tension strain at the inner side of the MLWS are just 0,25% and by a magnitude lower compared to the tension strain at the inner side of MW 2,99 %.

Out of the performed analyses it can be summarized:

The compression strains at the impacted side are both for MW and MLWS higher than the limit of -0,5% according to RCC-CW [2]. 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 varied 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

3. Multilayer Wall System for Protection of Critical Infrastructure Against Close-In Explosions

The favourable dynamic response of the MLWS to APC is the basis for development of a scaled MLWS system for protection of critical infrastructure like dry storage nuclear waste buildings, military, ambassies and other significant buildings against terrorist attack of close-in explosions.

Additional encouragement for usage of MLWS for protection of building structures against explosions were experiments performed by the german University of the Army [13], where it was demonstrated that green hedges, as shown in Fig. 10 do reduce the pressure wave by up to 60% and a curtain of chains and water, depicted in Fig. 11, by up to 50%

Fig. 10. Green Hedge - Reduction of Pressure Wave up to 60%

Fig. 11. Chain & Water Curtain: Reduction of Pressure Wave up to 50%

Numerical and experimental studies [14], [15] 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 of 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.

The numerical calculations are performed with the explicit computer code LS-DYNA [10]. 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 [10] 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 [16].

The material model for the concrete, used in the current study, has been calibrated on the basis of experimental results by Fang et al. [14] of close-in explosion tests of 2 kg TNT applied on a reinforced concrete plate with 30 cm thickness and damage pattern, shown in Fig. 12.

Fig. 12. Damage Pattern of a 30 cm Massive Wall Exposed to 2 kg TNT [14]

3.1 Reference Massive Wall (MW)

The massive wall, shown in Fig. 13, 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.

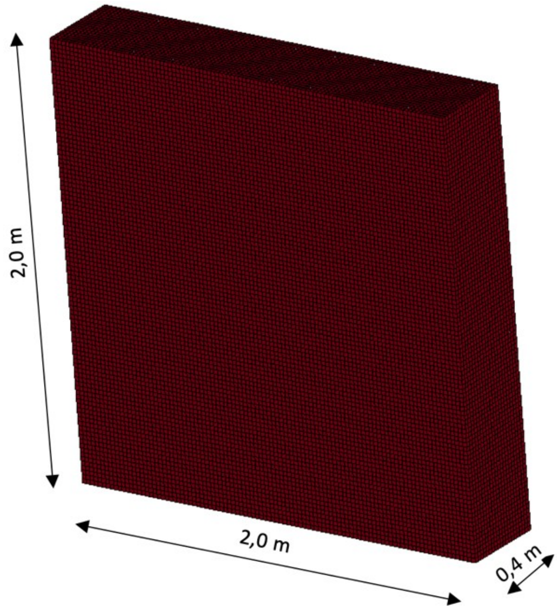


Fig. 13. Finite Element Model of MW

3.2 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 Fig. 14. 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 concrete elements at selected locations in case of increased requirements.

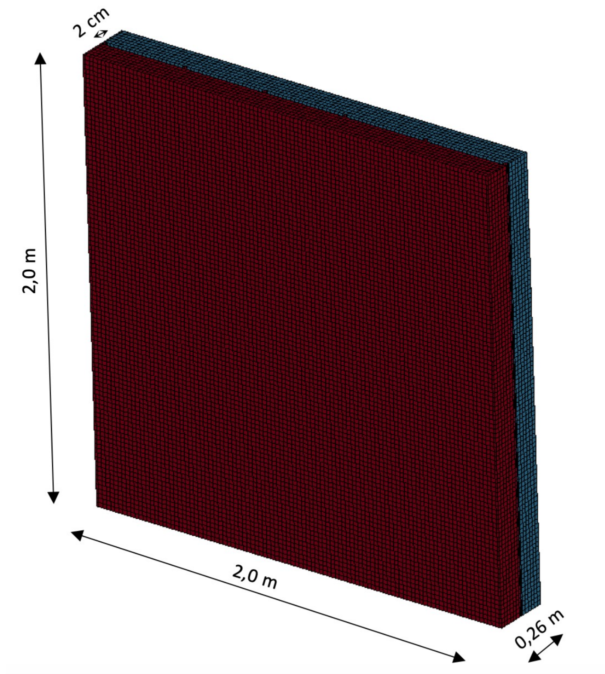


Fig. 14. Finite Element Model of MLWS

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 Fig. 15., 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.

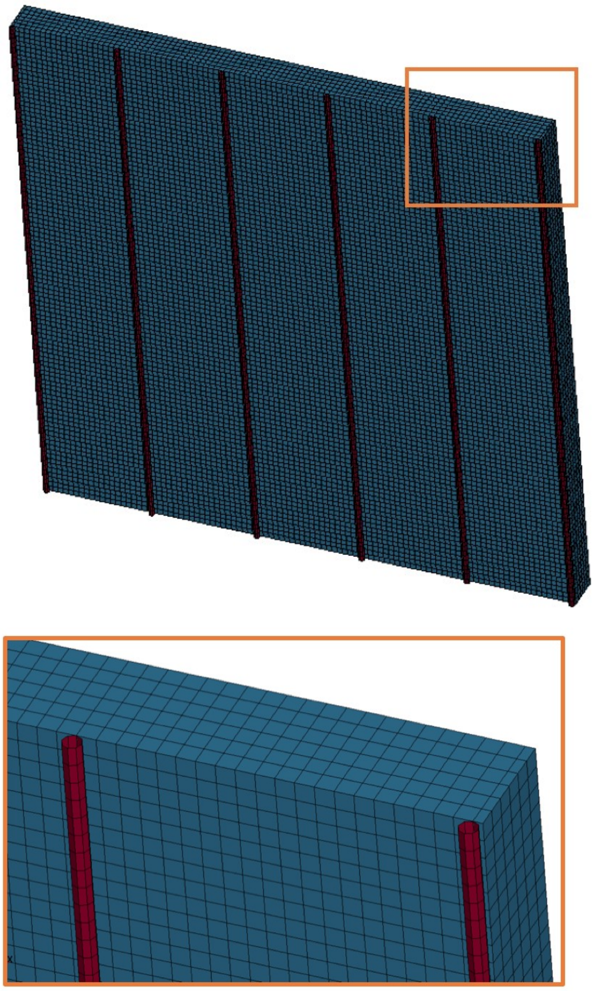


Fig. 15. Inner Plate and Pipes of MLWS

3.3 Dynamic Response of MW 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 Fig. 16 and for the inner side in Fig. 17.

The displacement time histories, depicted in Fig. 16 and Fig. 17 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.

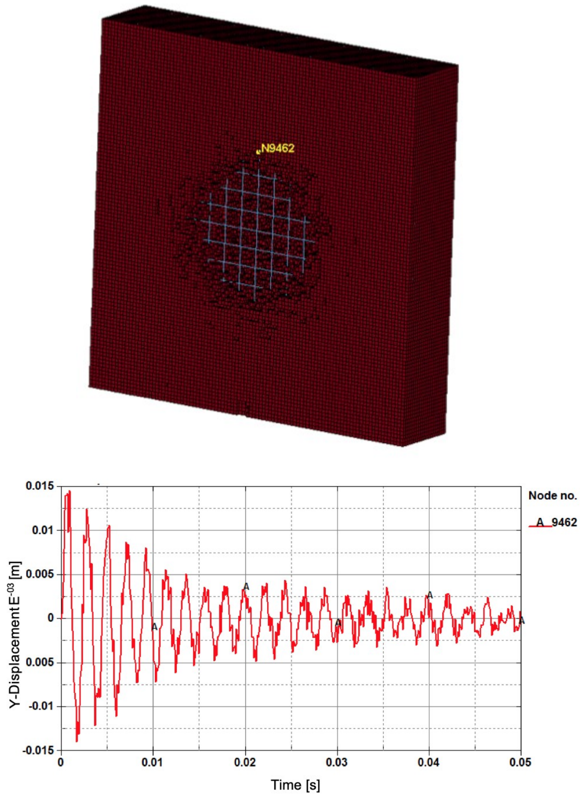


Fig. 16. Dynamic Response of the MW at the Impacted Side

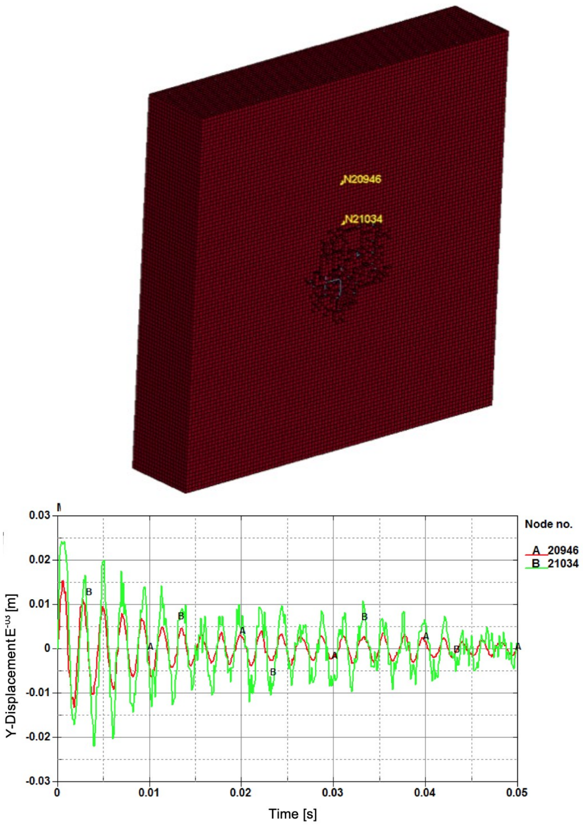


Fig. 17. Dynamic Response of the MW at the Inner Side

It is evident out of Fig. 18 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 Fig. 18 that the MW is not suitable to provide full protection against close-in explosions.

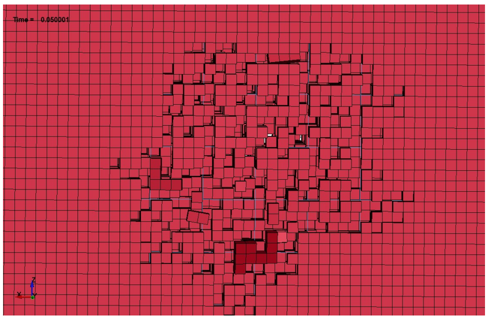


Fig. 18. Area of MW Failure at Inner Side

3.4 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 Fig. 19 and for the inner plate in Fig. 20.

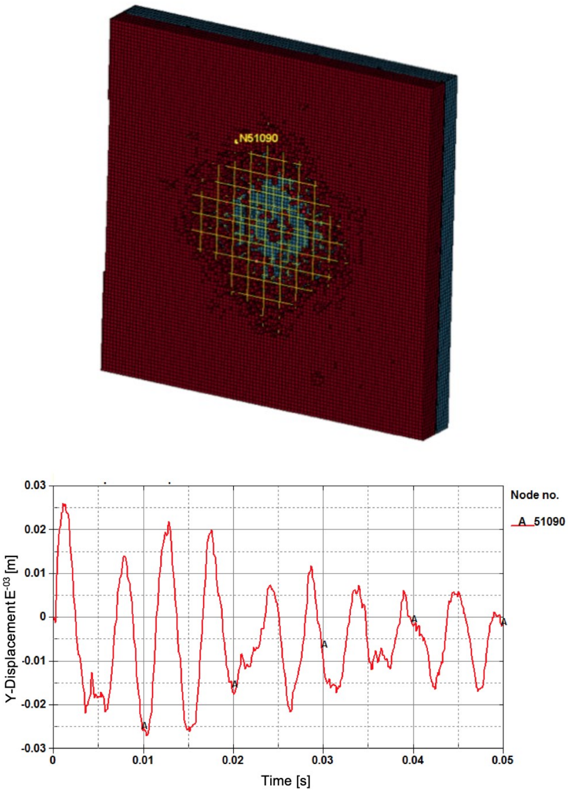


Fig. 19. Dynamic Response of the MLWS at the Impacted Side

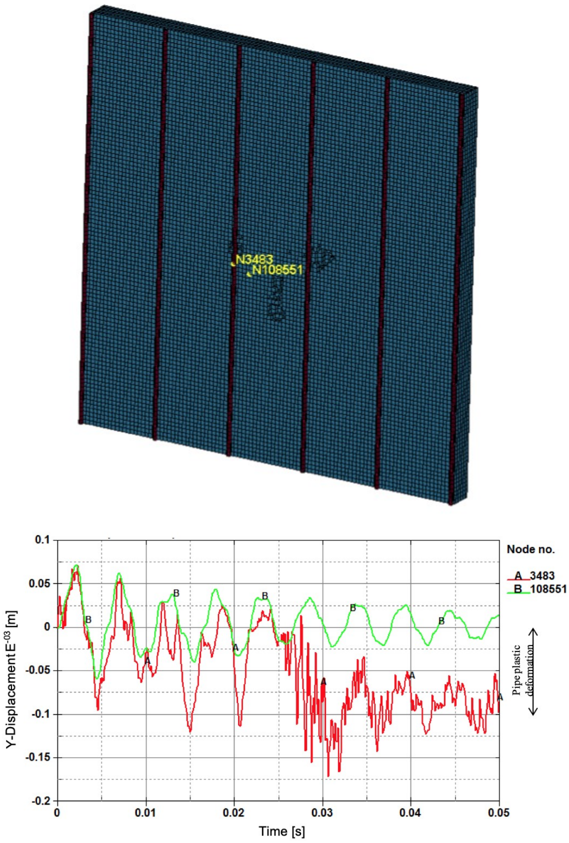
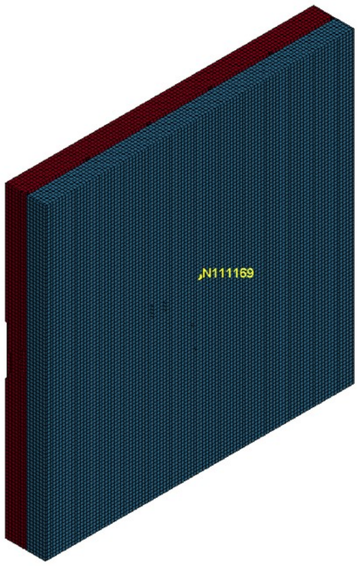


Fig. 20. Dynamic Response of the MLWS at the Inner Side

Due to the low thickness of 12 cm, the impacted plate of the MLWS suffers increased damage, as shown in Fig. 19, in comparison to the MW, with a thickness of 40 cm with damage pattern, presented in Figure 16. 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 Fig. 20 (MLWS) and Fig. 17 (MW).

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 Fig. 20, but the inner plate is not perforated.

The pipes (Node 3483 on Fig. 20) 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 reinforced concrete plate. The concrete on the outer side of the inner MLWS, shown in Fig. 21, vibrates in the linear range without high frequency content.



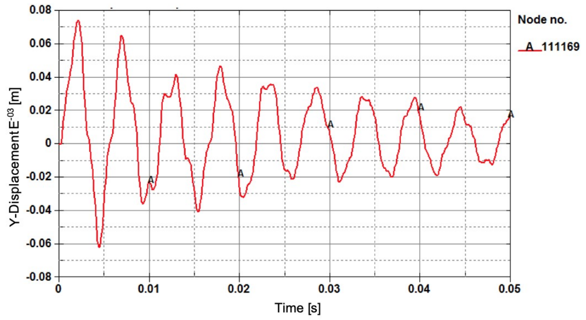


Fig. 21. Dynamic Response of the MLWS at the Inner Side

3.3 Comparison of the Dynamic Response of MW and MLWS due to the Load 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.

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.

4. Conclusions

A new Multi-Layer-Wall-System (MLWS) for protection of nuclear facilities against the load case airplane crash and of critical infrastructure against close-in-explostions has been introduced.

Due to nonlinear deformation of the MLWS steel pipes, energy absorbtion takes places, which results in significant reduction of the required concrete thickness in comparison to a massive wall (MW) and filtration of high frequency content induced inside the building structure.

MLWS is modular and therefore suitable for new build and upgrade of existing structures.

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