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FINITE ELEMENT SIMULATION OF A METALLIC FOAM MULTILAYER PROTECTIVE SYSTEM FOR REINFORCED CONCRETE WALLS SUBJECT TO BLAST LOADS

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Abstract. In the last decades blast loads caused by intentional explosions had acquired great importance. The analysis of structures subjected to this type of loads and its design to mitigate their effects have been and still is the subject of numerous investigations, especially in the United States and Europe. This paper investigates the feasibility of applying a method to reduce the response of reinforced concrete (RC) walls exposed to dynamic loads generated by explosives. For its validation, a numerical model was created with the program Abaqus. The idea is to adhere several layers of metallic foam to the exposed side of the RC Wall. The system, which consists of metallic foams made of aluminum in a sandwich configuration with metal plates, is referred to as Metallic Foam Multilayer Protection System (MFMPS). Keeping a constant thickness and varying its density and yield properties to determine the most effective type. First a linear dynamic analysis was carried out for a preliminary design. Next a full nonlinear dynamic analysis is performed to evaluate its efficiency under realistic conditions. The dynamic pressures due to explosions with several intensities and standoff distances were computed with a subroutine inside Abaqus called CONWEP (Conventional Weapons Effects) developed by the US Army Corp of Engineers. Due to computational time involved, only the case of a rectangular wall fixed in all borders was considered for the analyses. The results showed that the MFMPS is able to reduce the displacements and stresses on the wall.

1 INTRODUCTION

The last decade has seen a notorious increased in terrorist activities in the form of bombing of train stations, embassies and military complexes. This led to the need for more accurate prediction of explosive effects on civil structures and better and novel blast mitigation technology. The explosives discharge generates a high-pressure wave that impacts a structure in fractions of seconds and then dissipates in a similar length of time. This poses a problem because the current design standards do not take into account this kind of extremely impulsive and high-intensity load. The dynamic loads that are considered in the codes, for example, those arising from strong earthquakes are cyclic, have a much longer duration, and are not localized as those from an explosive event. The passive protective systems used to mitigate earthquake effects such as fluid viscous or viscoelastic dampers are not useful to reduce the response of blast loads because these devices simply do not have enough time to dissipate energy.

There has been numerous research works involving a large variety of methods and materials to mitigate the effect of the loads caused by explosions. Among them, there a few methods that stand out and look promising for further studies. For example, the use of composite laminates such as fiber-reinforced polymers (FRP) which focus on strengthening of the structure (Orton, et al., 2014). Another method involves the use of spray-on elastomeric polymers such as polyurea and polyurethane which have strengthening attributes as well as additional debris protection (Raman, et al., 2012).

Recent research at the University of Adelaide in Australia examined the application of mobile and lightweight materials like metallic foams (e.g. aluminum foams). Metallic foams consist of a matrix of metal (i.e. aluminum) that is impregnated with air pockets (Wu, et al., 2011). These materials have shown promising to results mitigate and redistribute the pressure wave generated by explosives events (Wu, et al., 2011). An extension of this idea forms the basis of the investigation reported in this paper. The goal is to assess whether a multilayered system consisting of metallic foams with different properties restrained by rigid metal plates attached to a reinforced concrete (RC) wall can be used to reduce the response to blast loading. As explained by Wu et al. (2011), the effect of the metallic foam cladding is to modify the time variation of the original dynamic pressure acting on the protected surface, as shown in Figure 1.

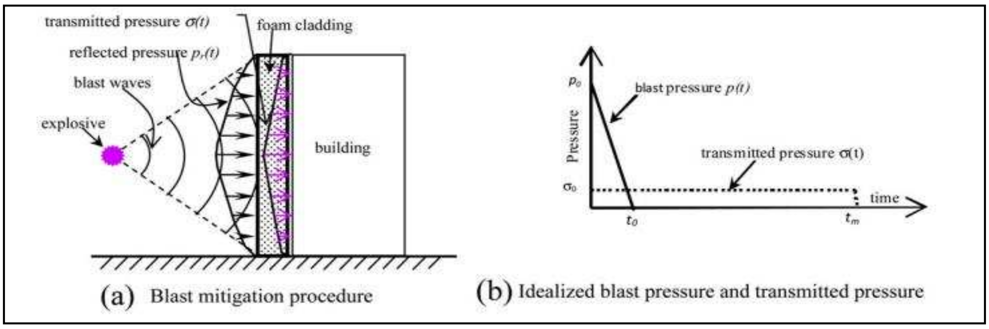

Figure 1: Mitigation of explosive effects with metal foam cladding (from Wu et al., 2011).

A finite element numerical model of the protective system and the RC wall was created with the program Abaqus. First the response of the system is computed assuming that the assembly has a linear behavior. Later the system is allowed to enter into the nonlinear range for a more realistic simulation. Two types of loads are used to investigate the dynamic response of the proposed protective system and the structure: one is a short-duration high-intensity dynamic pressure with a triangular time variation. The other is a procedure (a series of algorithms and equations) known as CONWEP, which was specifically developed to simulate the pressures caused by explosions.

1.1 CONWEP

Weapons that include land mines, homemade explosives, bombs, missiles and other non-nuclear weapons have been denominated as Conventional Weapons (CONWEP) as opposed to nuclear weapons (Kumar et al, 20110). An explosive detonation involves a chemical reaction that results in an accelerated heating and expansion of the components of the detonated product, creating a strong shock wave known as blast wave that propagates at high speed from the point of origin (Kumar et al, 20110).

Blast waves generate changes in the atmospheric pressure around an object. These changes in pressure can be divided in two phases: the positive phase which after an initial jump has an exponential decay and a negative phase just right after that works as a suction force (see Figure 2). Several researchers working directly or indirectly with defense organizations have developed a qualitative model that takes into consideration these phases. This model has been adapted and implemented in software such as LS-DYNA and Abaqus as well as a software developed by the Protective Design Center of the U. S. Army Corps of Engineers (USACE).

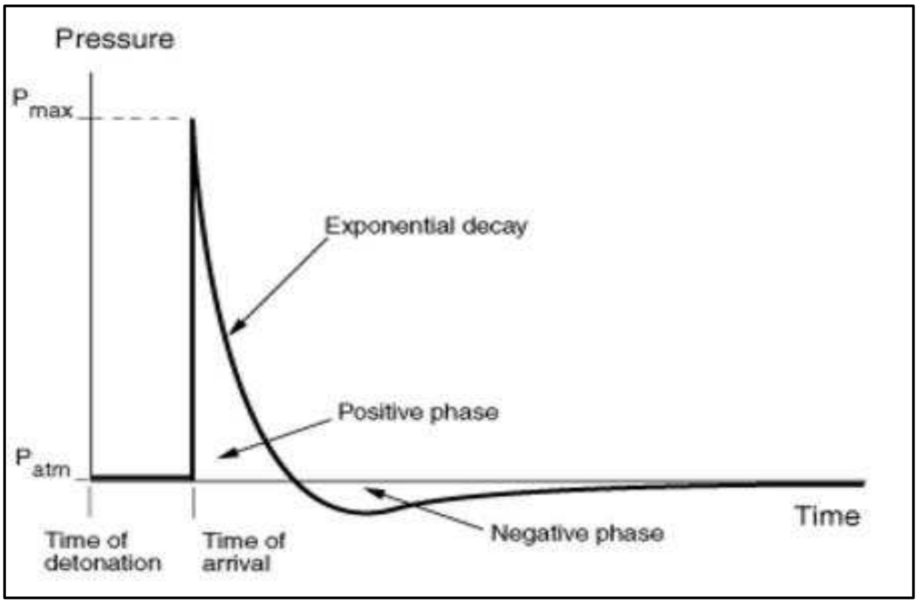

Figure 2: Idealize explosive pressure behavior. Source: Abaqus 6.13 Analysis User’s Guide.

The time history of the pressure induced by the blast wave and shown in Figure 2 can be described by expressing a free-field pressure time response using the modified Friedlander equation (Abaqus/User'sGuide, 2013):

$$p(t) = (p_{max} - p_{atm})\left[1 - \frac{t-t_a}{t_d}\right] e^{-\frac{a(t-t_a)}{t_d}} \tag{1}$$

where p_{atm} is the atmospheric pressure, t_{a} is the time of arrival, t_{d} represents the duration of the positive phase, a is a decaying constant and (p_{max} - p_{atm}) is the overpressure. An important factor to take into consideration which also affects the time of arrival and the duration of the positive phase of the curve is the standoff distance of the explosive. This numerical model implemented in CONWEP is the result of a wide collection of real test data gathered by several researchers. The program Abaqus has a subroutine that uses equation (1) but this finite element software is unitless. However, to use the CONWEP approach it is necessary to consider an explosive standoff distance given by a reference point in the model, a TNT mass equivalent and four conversion factors: mass to kilograms, length to meters, time to seconds and pressure to Pascals. All these factors must be input into Abaqus. Because CONWEP simulates the real propagation of a spherical wavefront, the dynamic pressure due to the explosion needs to be defined as an “incident wave interaction” instead of as a typical distributed load.

2 NUMERICAL MODEL

The analysis, design, assessment and mitigation of the effects of conventional explosions on civil engineering constructions are complicated tasks. Ideally the best way to approach the problem is via experimental testing. However, this method has associated critical safety issues, in addition to high costs and the need of very specialized expertise to deal with explosives, availability of isolated facilities, etc. A more rational approach is first to simulate numerically the problem, in this case the protective system, and once it is validated, to perform the experimental work. Powerful finite element software tools such as Abaqus are very helpful to carry out the preliminary numerical simulations. This is precisely the main object of the investigation reported in this paper.

2.1 Model specification and properties

To assess the capability of the Metallic Foam Multilayer Protection System (MFMPS) to mitigate the effects of explosive loads, four numerical models were developed in Abaqus. First a model of a reinforced concrete wall was used as a control prototype. The other three models consisted of the same concrete wall with three variants of alternating layers of aluminum foam and thin constraining aluminum alloy plates, as shown in Figure 3. Three metallic foams with different stiffness and slightly dissimilar densities were considered in order to compare their effect on the protection action. The material properties and the geometry of the components of the MFMPS are displayed in Table 1. The properties of the aluminum foams were obtained from a report by a German research institute (IFAM) that developed a manufacturing process called FOAMINAL for foamed metal materials (IFAM, 2010). The values for the aluminum metallic sheet and the concrete presented in Table 1 are typical for these materials.

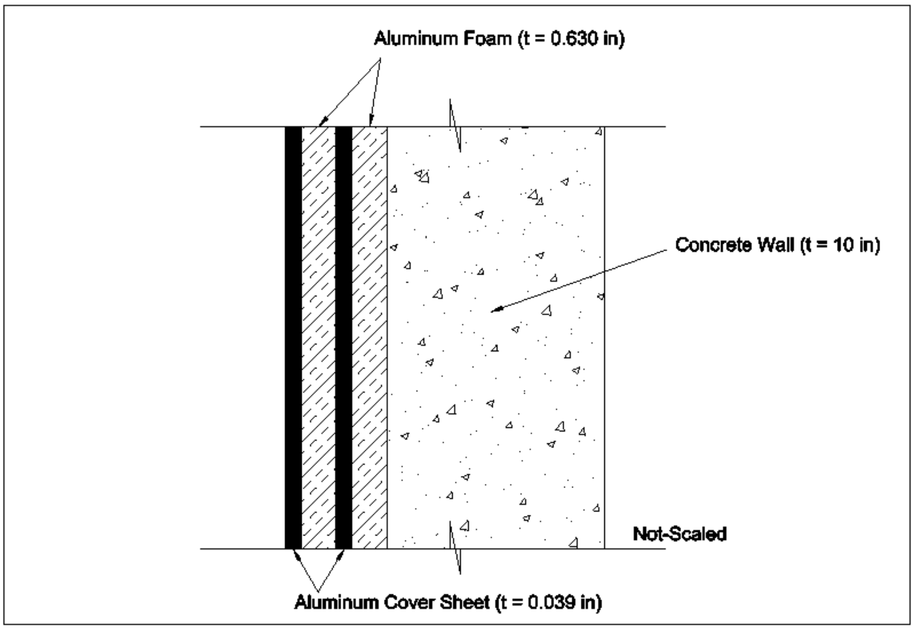

Figure 3: Metallic Foam Multilayer Protective System (MFMPS) configuration

Material	Width (in)	Height (in)	Thickness (in)	Unit weight (lb/in^3)	Modulus E (ksi)	Poisson ratio	Compressive yield strength (psi)
Concrete	180.0	120.0	10.00	0.083	3604.99	0.180	4000.00
Aluminum Foam (FoamA)	180.0	120.0	0.630	0.018	507.63	0.334	2016.02
Aluminum Foam (FoamB)	180.0	120.0	0.630	0.022	710.68	0.334	2726.709
Aluminum Foam (FoamC)	180.0	120.0	0.630	0.025	957.249.07	0.334	3524.42
Metallic Sheet (Al)	180.0	120.0	0.039	0.097	10200.00	0.334	40000.00

Table 1: Dimensions and properties for the numerical model components.

Abaqus is a finite element analysis program that works without any particular system of units. Therefore it is important to keep a consistent set of units throughout all modeling and analysis to avoid any discrepancy and errors. The four models created follow the same configuration in every aspect. The concrete wall was modeled with C3D8R elements whereas for the MFMPS the elements selected are S4R (these are four nodes doubly curved shell elements) which help to avoid shear and membrane locking.

2.2 Modeling the damping properties

For dynamic analysis with Abaqus the damping characteristics of the material and structure are introduced by means of the Rayleigh damping model, also known as proportional damping. In this model a damping matrix [C] is defined as a linear combination of the mass and stiffness matrices through two coefficients α and β

$$[C] = \alpha\,[M] + \beta\,[K] \tag{2}$$

To determine the constants α and β the values of the damping ratios ξ_m and ξ_p for two specific modes with natural frequencies ω_m and ω_p are chosen. It is straightforward to show that the two coefficients can be determined with the following expressions:

$$\alpha = \frac{2\omega_m\omega_p}{\omega_p^2-\omega_m^2}\left(\omega_p\xi_m-\omega_m\xi_p\right) \tag{3.a}$$

$$\beta = \frac{2\omega_m\omega_p}{\omega_p^2-\omega_m^2}\left(\frac{\xi_p}{\omega_m}-\frac{\xi_m}{\omega_p}\right) \tag{3.b}$$

In this work ω_m and ω_p are selected as the first and second natural frequencies of the concrete wall. Their values are 563.94 rad/s (89.75 Hz) and 853.51 rad/s (135.840 Hz).

Metallic foams, in particular, have a damping capacity typically between 5 and 10 times that of the metal they are made from (Ashby et al., 2000). For the present analysis, an average factor of 7.5 times the damping capacity of aluminum was assumed. Table 2 displays the parameters used to define the damping matrix.

Material	ξ	α	β
Concrete	0.020	15.723	0.00002
Aluminum Foam (FoamA)	0.300	203.743	0.00042
Aluminum Foam (FoamB)	0.300	203.743	0.00042
Aluminum Foam (FoamC)	0.300	203.743	0.00042
Metallic Sheet (Al)	0.040	27.1657	0.00006

Table 2: Material damping parameters for the Abaqus models.

3 ANALYSIS AND RESULTS

The model of the RC wall is assumed to be fully restrained at its four edges. This constraint is used to simulate the actual boundary conditions of a wall in a building, i.e. the upper and lower floor slabs as well as the left and right columns.

3.1 Impulsive load

Two impulsive loads that simulate those due an explosion are considered. The first of them is the triangular pressure load with a peak value of 140 pounds per square inch (psi) and a total duration of 0.005 seconds shown in Figure 4. This pressure load was uniformly applied to one of the faces of the RC-wall of the control model and in the free face of the aluminum cover sheet when the MFMPS was included in the model.

This triangular load is an approximation of the positive phase in the idealized pressure used in the Conventional Weapon Effect (CONWEP) shown in Figure 4. The triangular shape pressure is used because it allows us to have full control of its parameters. On the other hand, the pressure generated by CONWEP is more realistic and complex but the user dos not have direct control of the shape and the parameters (duration, peak pressure) of the load imposed on the structure.

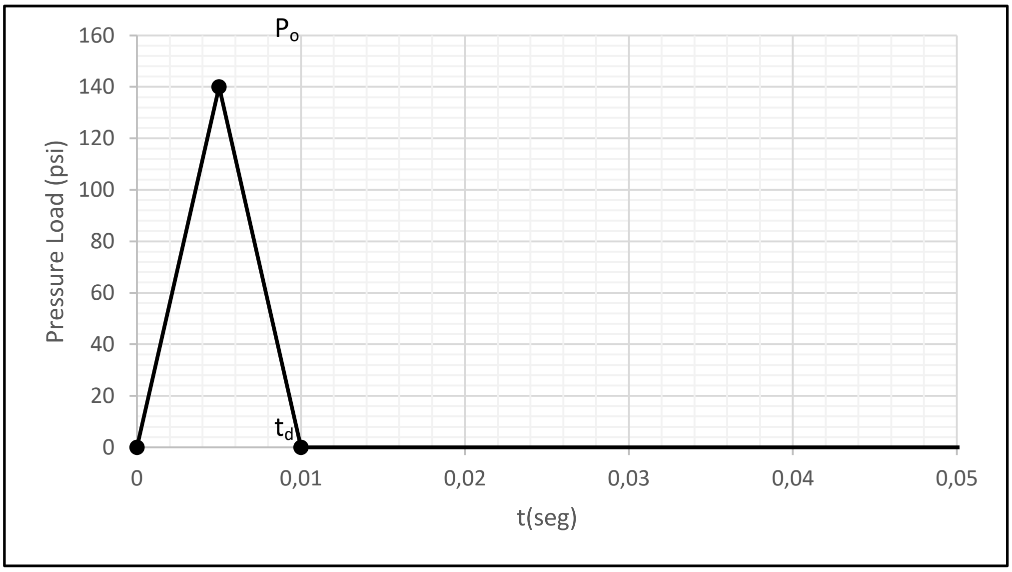

Figure 4: Time variation of the idealized dynamic pressure.

3.2 CONWEP Analysis Considerations

The CONWEP approach permits to define more realistic loads generated by an explosion. For the CONWEP analysis three standoff distances, 10 ft, 20 ft and 30 ft, were selected. Taking into account the data from the UFC-4-010-1 standard, the first distance can be considered as a critical case, the second corresponds to a typical case and the third one is a conservative case for typical explosive events. The amount of explosives was also varied in a hundred increments (100 lb, 200 lb, and 300 lb) for each distance. To establish a comparison between the wall and each protective system the maximum value for both the stresses and displacement were taken.

For both the triangular load and the CONWEP-defined pressure as well as for the linear and nonlinear analysis, the response will be examined at a point in the middle of the wall surface. Because of the geometry of the system this is the point where the normal stress and the displacements will be maximum.

3.3 Results of the linear dynamic analysis

Figure 5 illustrates the normal stresses at the middle of the RC-Wall caused by the pressure with triangular variation. The three metallic foam configuration are shown in different graphs. Figure 6 shows the displacement in the direction normal to the wall at the same point. In both cases the solid line is the response for the control model (wall alone) and the dashed line corresponds to the case with the protective system. It can be seen that due to the high damping capacity provided by the MFMPS, the wall comes quickly to rest.

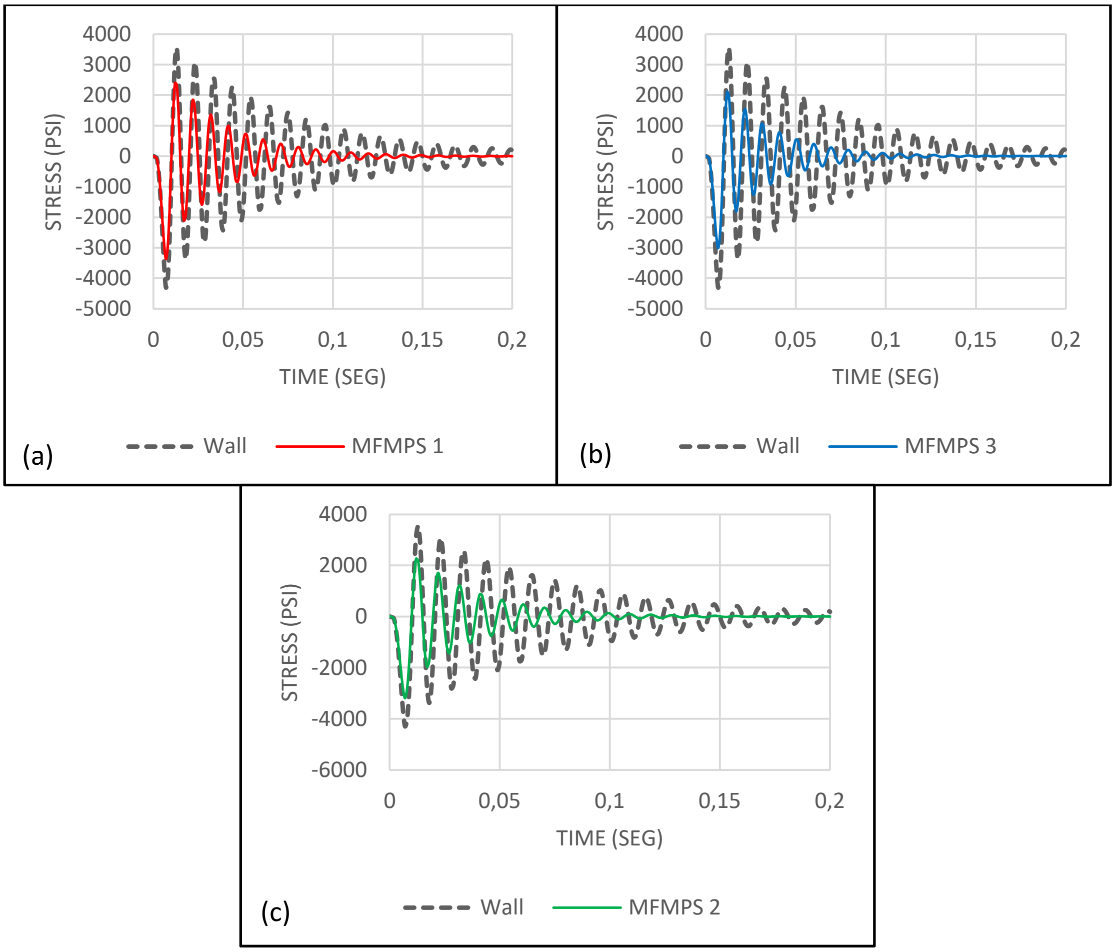

Figure 5: Linear stress time histories in the RC-Wall with and without MFMPS.

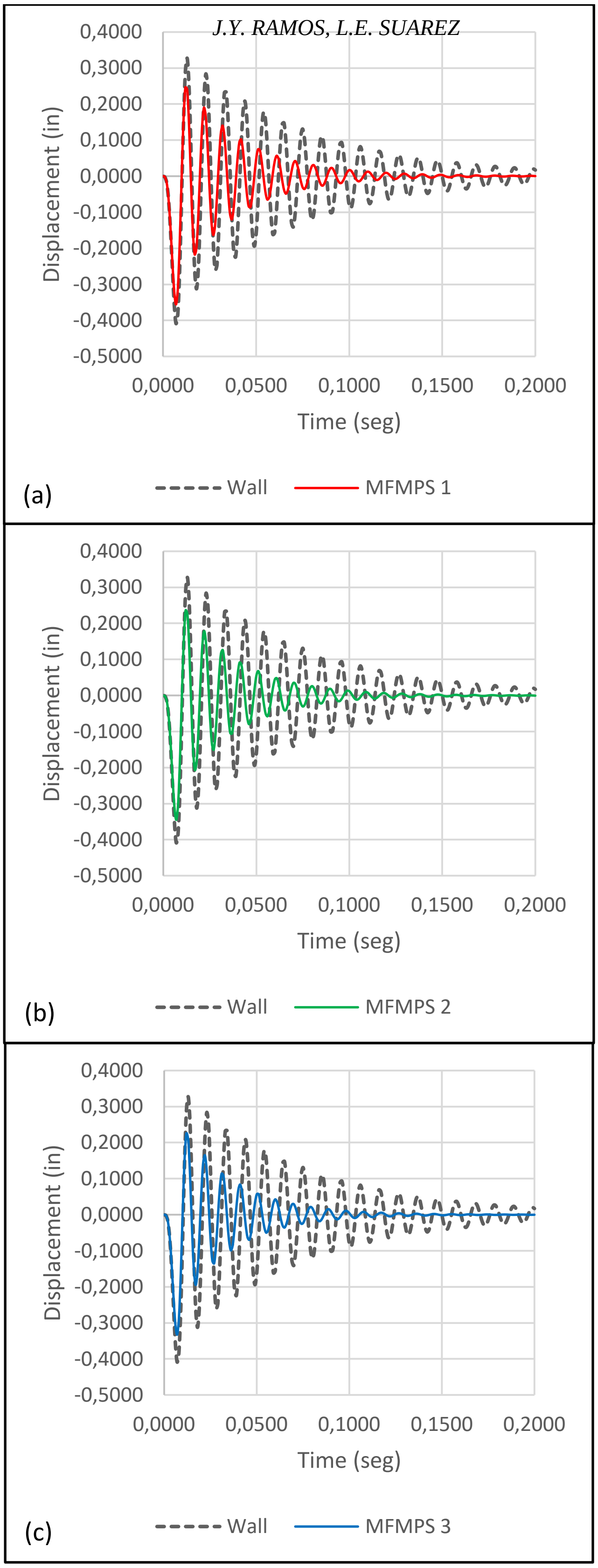

Figure 6: Linear displacement time histories in the RC-Wall with and without MFMPS.

The maximum value for the normal stresses and displacements are presented in Table 3, along with the reduction achieved by the three MFMPS. It can be seen that the third metallic foam configuration is the one that produces the highest response reduction, although the differences with the other two systems are not substantial.

Model	Max. displ (in)	Max. stress (psi)	U % reduction	σ % reduction
MFMPS 1 + Wall	0.3554	6036.580	13.861	16.719
MFMPS 2 + Wall	0.3445	5826.500	16.957	20.231
MFMPS3 + Wall	0.3324	5594.990	20.490	24.235
Wall	0.4083	7137.880	-	-

Table 3: Peak displacements and stresses for the triangular load case and linear analysis.

3.4 Results of the nonlinear dynamic analysis

In order to consider the nonlinear capabilities of the system, the plastic properties of the aluminum foam must be added to the material properties. For the RC-Wall, Abaqus have two methods to add the plasticity effect on concrete. The first one is the *Smear Cracking* and the second is *Concrete Damage Plasticity* for this research the later ones used due to a more complete input of properties for the concrete. The presence of a grid of steel reinforcement adds an additional complication to the nonlinear analysis. Abaqus has the option of embedding a steel reinforcement grid into the concrete wall. We tried this approach but it led to a substantial increase in computational time and there were some convergence problems in some situations. Therefore, it was decided to make an important assumption for the nonlinear analysis: the material of the wall was considered to have the same resistant in tension than in compression. This conjecture will be inappropriate if the material were only concrete; however, since the main purpose of adding steel reinforcement to the concrete is to increase its capacity in tension, the assumption is acceptable. Nevertheless, the accuracy of the assumption needed validation. In order to do this, a pushover analysis was carried out to obtain the stress versus strain curve. In one case the full concrete plus embedded steel grid was used and in the other the equivalent material assumption was applied. Figure 7 displays the two curves: it is evident that the results obtained with one or the other approach are practically the same. Therefore, the material with the same capacity in tension and compression will be used for the upcoming nonlinear analyses.

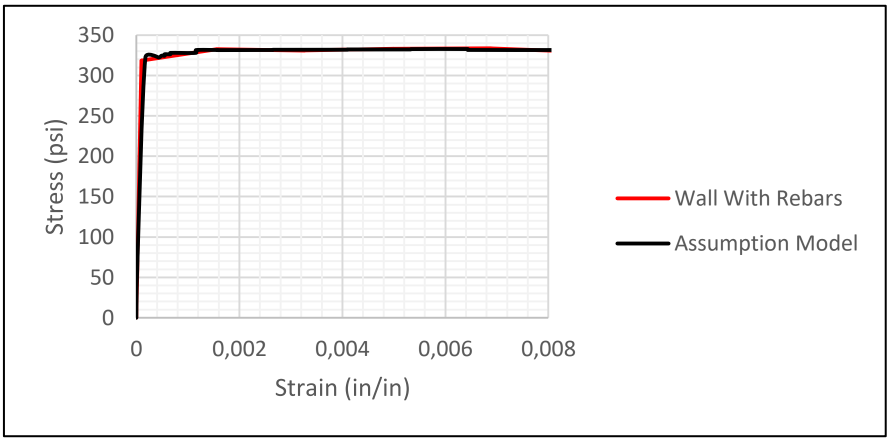

Figure 7: Results of pushover analysis with the model with steel rebar and the equivalent model.

Figure 8 shows the time variation of the normal stresses at the midpoint of the RC wall when the system is subjected to the dynamic pressure with triangular shape and the nonlinear behavior is accounted for. Figure 9 displays similar results but for the displacement at the same point. The results for the bare wall (continuous line) are compared with those for the wall protected by each of the three metal foam configurations (dashed line).

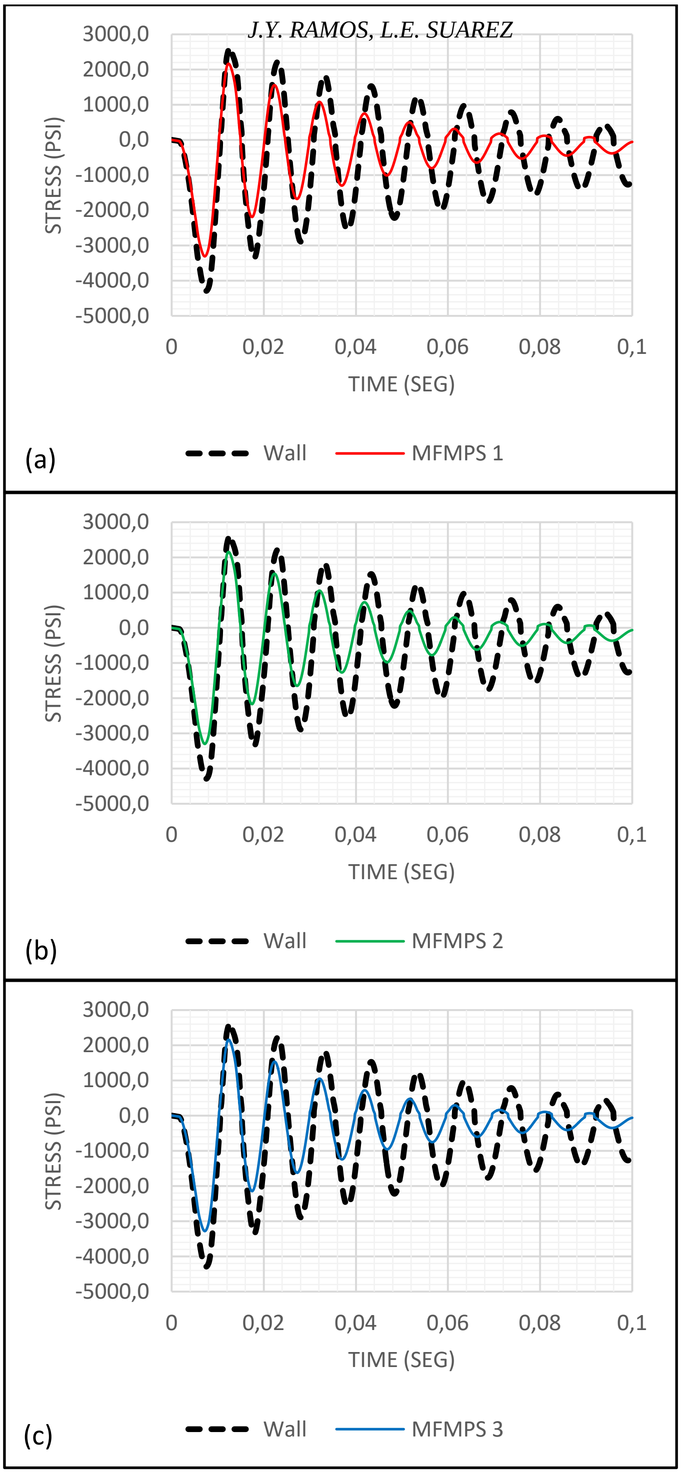

Figure 8: Nonlinear stress time histories in the RC-Wall with and without MFMPS.

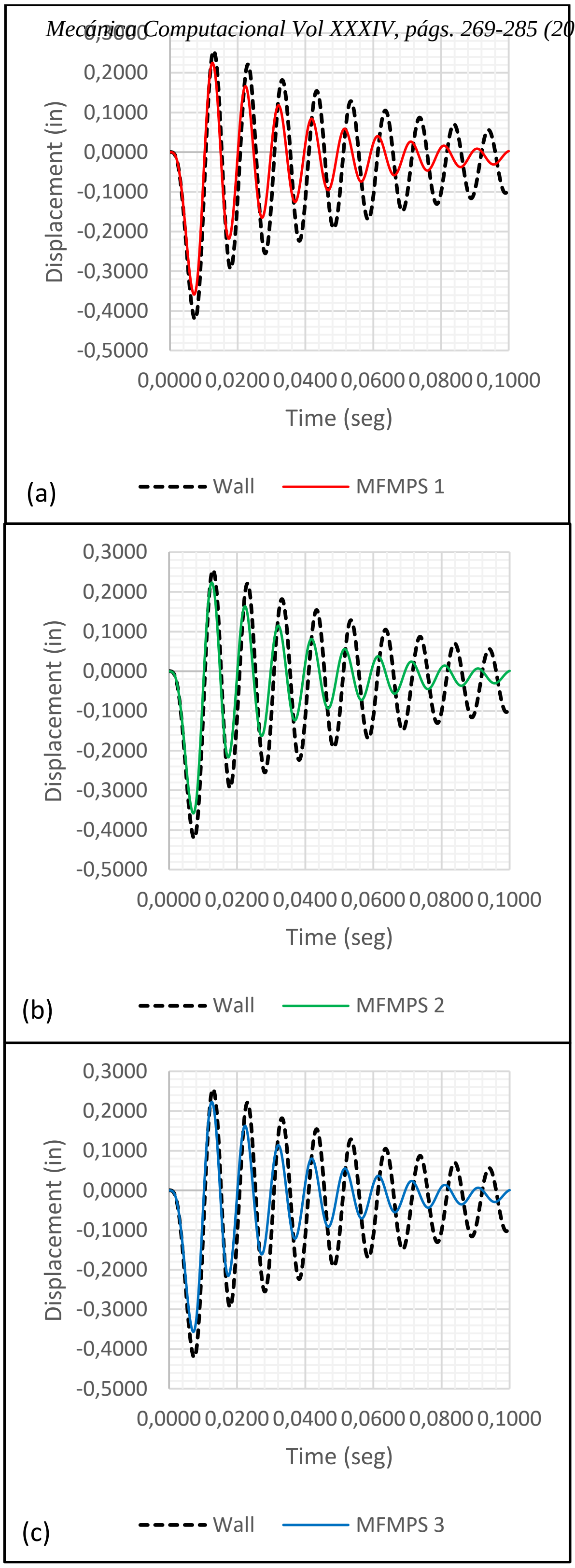

Figure 9: Nonlinear displacement time histories in the RC-Wall with and without MFMPS.

The peak stresses and displacement in absolute values were retrieved from the time series and are displayed in Table 4. Here again the MFMPS3 configuration is the most favorable but the differences among the three variants are very small.

Model	Max. displ. (in)	Max. stress (psi)	U % reduction	σ % reduction
MFMPS 1 + Wall	0.359	3306.40	15.898	25.916
MFMPS 2 + Wall	0.358	3294.79	16.280	26.262
MFMPS3 + Wall	0.356	3284.24	16.623	26.577
Wall	0.421	4290.85	-	-

Table 4: Peak displacements and stresses for the triangular load case and nonlinear analysis.

3.4 Linear and nonlinear analysis with CONWEP.

It was mentioned that the dynamic pressure generated by the CONWEP method is more accurate than the triangular pulse pressure considered in the previous sections. In addition to representing more faithfully the real time variation of the pressure caused by an explosion, it has another advantage. The blast pressure generated by the CONWEP subroutine is not applied uniformly throughout the front surface of the wall. The subroutine simulates a spherical wave impacting the surface and thus the pressure does not reach all the points on the plane surface simultaneously. However, if the point being monitored is still at the center of the front face of the wall, this will have much influence much the results. The stress time histories for the three standoff distances and for each model (RC-Wall, MFMPS 1, MFMPS 2 and MFMPS 3) are presented in Figure 10 for the linear case. Figure 11 shows parallel results but taking into account the nonlinear behavior. The different arrival time of the explosive wave pressure for the three standoff distances is clearly evidenced in the graphs.

The variation with time of the displacement at the midpoint of the RC wall were also obtained for the linear and nonlinear cases (they are not presented here). From these times series as well as from those shown in Figures 10 and 11, the peak values were retrieved. They are presented in Table 5 for the system with linear behavior and in Table 6 for the nonlinear case. Studying the results displayed in the tables, one concludes that the third MFMPS is the most effective in terms of blast mitigation: the stress reduction achieved is about 33%.

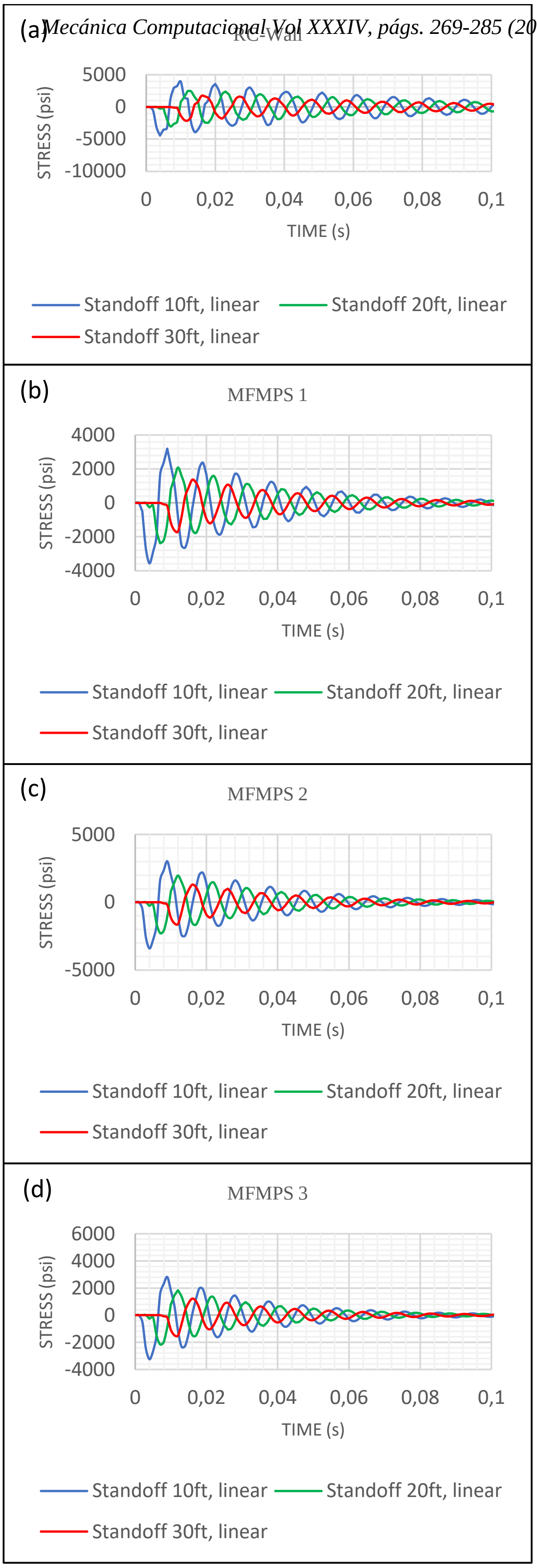

Figure 10: Linear stress time histories for each model and three standoff distances with CONWEP load.

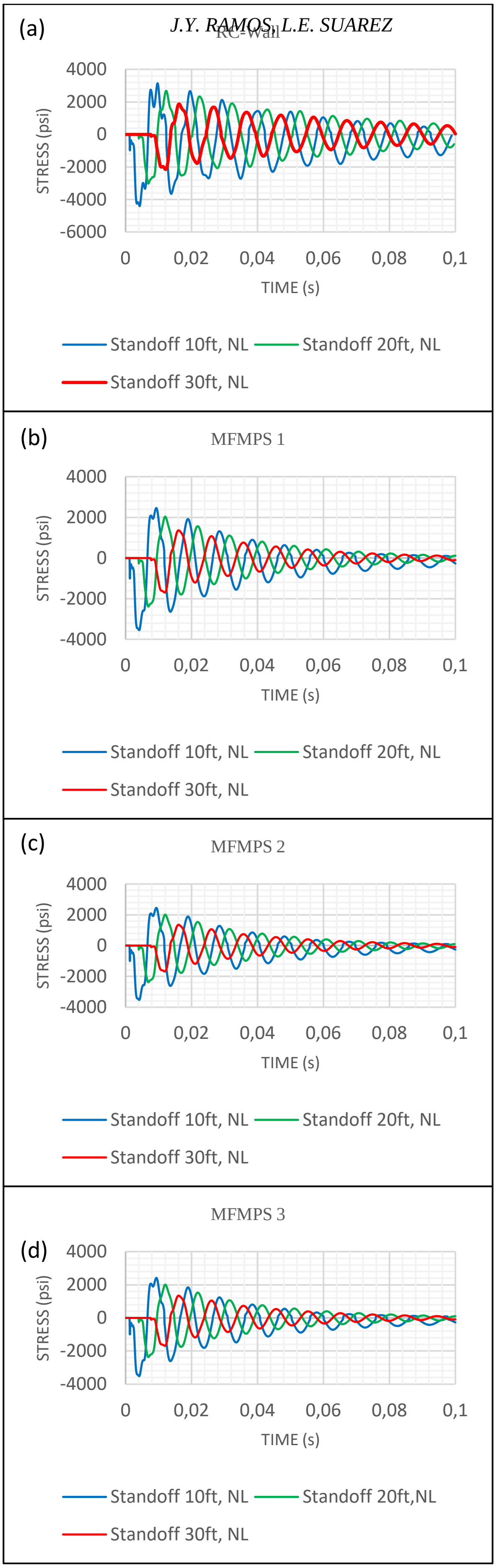

Figure 11: Nonlinear stress time histories for each model and three standoff distances with CONWEP load.

CONWEP (100 lb/TNT) - Standoff Distance 10 ft, Linear case

Model #	Umax (in)	σmax(psi)	U % reduction	σ % reduction
MFMPS 1 + Wall	0.361213	3565.42	6.145	22.087
MFMPS 2 + Wall	0.354859	3412.27	7.922	26.413
MFMPS3 + Wall	0.34812	3246.65	9.8356	31.284
Wall	0.384132	4450.68	-	-

CONWEP (200 lb/TNT) - Standoff Distance 20 ft, Linear case

Model #	Umax (in)	σmax(psi)	U % reduction	σ % reduction
MFMPS 1 + Wall	0.249462	2377.5	7.6122	24.125
MFMPS 2 + Wall	0.244765	2276.63	9.509	28.385
MFMPS3 + Wall	0.239587	2165.98	11.642	33.249
Wall	0.269203	3029.75	-	-

CONWEP (300 lb/TNT) - Standoff Distance 30 ft, Linear case

Model #	Umax (in)	σmax(psi)	U % reduction	σ % reduction
MFMPS 1 + Wall	0.177591	1690.87	10.782	22.129
MFMPS 2 + Wall	0.174129	1605.21	12.744	27.249
MFMPS3 + Wall	0.170263	1509.19	14.978	33.275
Wall	0.19783	2111.6	-	-

Table 5: Linear peak displacements and stresses in the MFMPS + Wall for the CONWEP load.

CONWEP (100 lb/TNT) -Standoff Distance 10 ft, Nonlinear Results

Model #	Umax (in)	σmax(psi)	U % reduction	σ % reduction
MFMPS 1 + Wall	0.371885	3545.86	11.652	21.515
MFMPS 2 + Wall	0.369608	3535.53	12.264	21.803
MFMPS3 + Wall	0.367653	3525.63	12.793	22.081
Wall	0.4179	4400.73	-	-

CONWEP (200 lb/TNT) -Standoff Distance 20 ft,, Nonlinear Results

Model #	Umax (in)	σmax(psi)	U % reduction	σ % reduction
MFMPS 1 + Wall	0.25591	2386.35	11.340	23.703
MFMPS 2 + Wall	0.254681	2377.24	11.820	24.080
MFMPS3 + Wall	0.253512	2369.2	12.278	24.414
Wall	0.286674	3028.04	-	-

CONWEP (300 lb/TNT) -Standoff Distance 30 ft, Nonlinear Results

Model #	Umax (in)	σmax(psi)	U % reduction	σ % reduction
MFMPS 1 + Wall	0.182855	1698.21	11.842	23.543
MFMPS 2 + Wall	0.182019	1688.98	12.299	24.080
MFMPS3 + Wall	0.181205	1680.06	12.745	24.602
Wall	0.205872	2151.36	-	-

Table 6: Nonlinear peak displacements and stresses in the MFMPS + Wall for the CONWEP load.

4 CONCLUSIONS AND RECOMMENDATIONS

The primary purpose of this research was a preliminary evaluation of the effectiveness of a protective system for blast loads consisting of layers of metal foams and constraining aluminum plates. As previous investigations has demonstrated (e.g., Wu et al., 2011; Wu and Sheikh, 2012b), due to its energy absorption capacity and tensile strength, the metallic foam can be a useful material for protective purposes. The fact that is a lightweight material avoids adding extra loads to the existing walls or other structural elements whose protection is required. These systems are intended as rehabilitation schemes for blast mitigation of pre-existing structures which were not designed to withstand this type of extreme loading.

A numerical model of a four layers protective system and a reinforced concrete wall with was implemented in the finite element program Abaqus (see Figure 2). The proposed arrangement is referred to as the Metallic Foam Multilayered Protective System (MFMPS). The response mitigation achieved with three configurations of MFMPS were studied (see Table 1) considering different material properties for the metallic foams obtained from commercial standards (IFAM, 2010). The combined systems were subjected to two dynamic pressures; one with a user-defined triangular shape and another defined by the CONWEP model implemented in the Abaqus program.

Dynamic linear and nonlinear analysis were performed with the program Abaqus. To model the RC wall for the nonlinear analyses, a smeared concrete model that takes into account the steel reinforcement grid was adopted to reduce the computation time and avoid convergence problem. The response quantities examined were the displacement and normal stress at the geometric center of the wall. The peak displacements and stresses were recovered from the time series and compared against the control model, i.e. the bare wall. In all the cases examined (two loading patterns and linear and nonlinear analyses) the MFMPS was able to reduce the response of the wall. Between the three metallic foam, the one with a higher density and elastic modules was the most promising of them in reducing the stresses and displacements generated by blast loads. Having a higher improvement percent’s from 6 to 16 percent of reduction for the displacement and 16 to 34 percent on stresses, either by linear analysis or nonlinear analysis. So it can be concluded that all of the MFMPS help in the reduction of displacements and stress. Being the MFMPS 3 with a higher density and elastic modules the best of the three.

For future work it is recommended to perform testing of the specific materials used in the MFMPS to obtain the properties required for the numerical simulations. The final goal should be a full scale experimental testing of the MFMPS and wall assembly subjected to real explosions or to the loads produced by a blast simulator. Also, creating a cracking limit to the RC wall as well as considering the crushing of the metal foam due to the blast load will also lead to more realistic results. Other issues worth of future studies are the bonding agent of the MFMPS with the RC wall, adding a protective layer at the back of the wall and using combinations of different protective systems available in the market such as polymers (Raman, et al., 2012) and high capacity concrete mixes (Wu, 2012).

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