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Hardened Aircraft Shelters with Concrete Outer Shell and Steel Inner Shell Behaviour from Severe Blasts and Ballistic Threats

Mageirou G[1,*], Pantazopoulos D[2]

[1]Hellenic Air Force Academy, Dekeleia Air Base, 13671 (1010), Dekeleia, Athens, Greece.
[2]Hellenic Air Force, Dekeleia Air Base, 13671 (1010), Dekeleia, Athens, Greece.

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[*]**Corresponding author:** Mageirou G, Hellenic Air Force Academy, Dekeleia Air Base, 13671 (1010), Dekeleia, Athens, Greece.

Abstract

Dynamic impacts caused by explosions from weapon systems are crucial in the design of Air Force structures such as Hardened Aircraft Shelters or steel aircraft maintenance hangars. The influence of such loads on the response of structures depends on the distance of the explosion from the structure as well as on the weapon. This research investigates the influence of the distance of the explosion on a dynamic impact due to a GP750 (M117) bomb explosion on the response behavior of a 3rd generation Hardened Aircraft Shelter (H.A.S). Parametric finite element analysis is conducted to demonstrate the effects of a GP750 -M117 bomb on a NATO 3rd generation Hardened Aircraft Shelter (H.A.S). The parameter which varies is the distance of the structure from the blast point.

Keywords

Hardened aircraft shelters; concrete shell; steel shell; blast load; explosive load; ballistic threats; structural failures; dynamic behaviour; explosion distance

1. Introduction

Hardened Aircraft Shelters (HAS) are crucial military shelters that keep planes, personnel, and operations safe from enemy attacks. High-explosive bombs, artillery shells, missiles, and mortar rounds are all modern dangers that work together to cause explosions, break things, and get through protective buildings. In contrast to traditional civil explosive scenarios, HAS design must consider significant overpressures, brief impulsive loads, and high-velocity fragmentation that frequently occur simultaneously. As a result, a lot of experimental, analytical, and computational research has been done to test the blast and ballistic resistance of airplane shelters and other comparable protective buildings.

When explosives impact aircraft shelters, they make the air blast overpressure, reflected pressure, impulse, and ground shock. Sometimes, the ammo casings break apart after this. Elshenawy et al. [4] stressed that mortar and artillery rounds are a double threat: the main blast wave causes a global structural response, and the high-velocity fragmentation causes localized damage and penetration. The cumulative impacts make structural failure much more likely than loads that just generate blasts. Qi et al. [10] found that blast load parameters can change a lot depending on the charge weight, standoff distance, and structural geometry. This shows how important it is to use reliability-based blast load factors when designing protective structures like domed or arched aircraft shelters.

Numerous investigations have concentrated on the nonlinear dynamic response of HAS subjected to extreme explosive stress. Zaghw et al. [15] conducted a finite element analysis of a protected aircraft shelter exposed to a general-purpose bomb detonation, utilizing nonlinear material models and explicit dynamic solvers. Their research indicated that reinforced concrete shelters endure significant stress at the roof-wall junctions, potentially resulting in cracks, spalling, and the risk of progressive collapse if energy is not adequately absorbed.

Anas et al. [1] also studied the RC on-the-ground blast-resistant shelter of a novel interior cylindrical configuration consisting of vertical and inclined walls with a flat roof in M40 concrete and Fe500 steel is proposed and its investigation is carried out under two different blast scenarios namely; spherical air detonation (SAD) and hemispherical surface detonation (HSD) using ABAQUS/Explicit code. Their research showed that typical static design methods greatly underestimate how strong structures need to be when they are hit by really strong blasts.

Airplane shelters must not only be able to survive worldwide blasts, but they must also be able to keep pieces from going through. Elshenawy et al. [4] presented multi-layer protective systems that integrate reinforced concrete, steel plates, and energy-absorbing layers to reduce blast pressure and fragment impact. Their experimental and numerical findings exhibited significant decreases in penetration depth and internal damage. The development and underlying approaches used in UFC 4–023-03 [13], [14] and furthermore, the field tests and numerical simulations are presented by Stevens et al. [11].

Recent studies have looked into how new materials might make shelters work better. Gu et al. [6] performed experimental and numerical investigations on polyurea-coated shelters, demonstrating that elastomeric coatings markedly decrease spalling, prolong fracture propagation, and enhance energy dissipation during intense blast loading. These findings are especially pertinent for the improvement of existing airplane shelters, especially where augmenting wall thickness is not feasible. Modern trends in protective design favor materials that absorb energy and prevent harm over those that merely focus on strength.

Using LS-DYNA, AUTODYN, and ABAQUS/ for numerical simulations Explicit are frequently employed to bolster design concepts for hardened aircraft shelters, as evidenced in the literature. These techniques give a good picture of how blast waves flow, how contact detonation occurs, how materials operate in nonlinear ways, and how damage spreads.

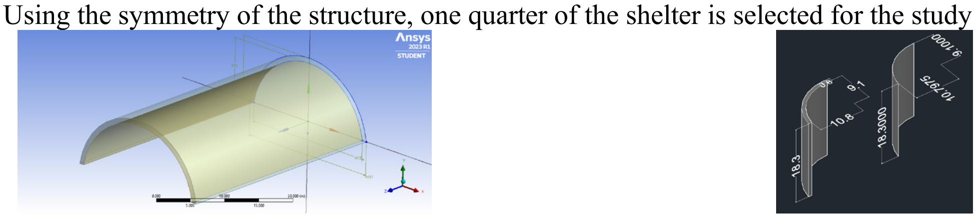
A lot of the time, blast-resistant design is based on military design standards like UFC 3-340-02 [13]. Peer-reviewed research, on the other hand, checks, improves, and adds to these requirements. For safe shelter design against big explosive threats, it is important to combine finite element analysis with material models that have been tested in real life.

Notwithstanding significant advancements, various shortcomings remain in the literature, including inadequate thorough experimental assessments of reinforced aircraft shelters exposed to concurrent explosive and ballistic impacts, the quantification of uncertainty (through probabilistic analysis) in threat parameters such as charge mass, impact angle, and fragment dispersion, the evaluation of structural behavior following partial destruction (progressive collapse), and retrofit technologies in the aftermath of repeated blasts. Addressing these difficulties is crucial for the future of aircraft shelter architecture, particularly in light of evolving military threats.

2. Aircraft Shelter

A parametric investigation of the behavior of the shell of a NATO 3rd generation Hardened Aircraft Shelter (H.A.S) and a metal panel covering a typical metal aircraft canopy in a dynamic impact caused by the explosion of a general-purpose bomb, the GP 750 or otherwise M117, with the distance of the explosion from the structure as a parameter is carried out. The parameter which varies is the distance of the structure from the blast point (20m, 10m and 5m).

The geometry of the aircraft shelter and aircraft hangar was selected based on standard designs for aviation and military facilities [2], [13]. The NATO 3rd generation Hardened Aircraft Shelter consists of an 80 cm thick concrete outer shell with a 5 mm thick steel inner sheet. The dimensions of the Aircraft Shelter under study are 36.6 m x 21.6 m x 9.1 m. Using the symmetry of the structure, one quarter of the shelter is selected for the study (Figure 1).



(a) (b)

Figure 1. (a) Aircraft shelter, (b) Geometry of the concrete shell (left) and steel shell (right) of the Shelter model (dimensions in m).

Concrete quality C35 is selected for the aircraft shelter, using the RHT concrete model [3], [12]. The model uses a variety of parameters in combination with a polynomial equation of state and a pressure - porosity equation (P-alpha EOS) to describe confinement and residual strength after failure. The parameters used are derived experimentally [7]. The metal components, including the inside coating of the aircraft shelter's metal sheet, are constructed from S355 steel in accordance with the stipulations of Eurocode 3 [5]. The simulation of the influence of dynamic loading on material behavior – Cowper Symonds modelling [8] is presented by equation (1.1).

$$\sigma_d = (A + n\frac{B \cdot E}{E-B} \cdot \varepsilon_{eff}^{p})\left[1 + (\frac{\dot{\varepsilon}}{D})^{1/q}\right] \quad (1.1)$$

where:

σd: dynamic yield stress

E: Elastic modulus or Modulus of Elasticity

εeffp; plastic strain

n: hardening coefficient

$\dot{\varepsilon}$: strain rate

A, B, D, q: experimentally determined coefficients

The aforementioned methodology is based on experimental measurements. In this study, the parameters presented in Table 1 were selected [9]. The stress – strain graph is presented at Figure 2.

Table 1. Cowper-Symonds method parameters [9]

A	B	n	D	q
440MPa	865MPa	0.37	38370	2.395

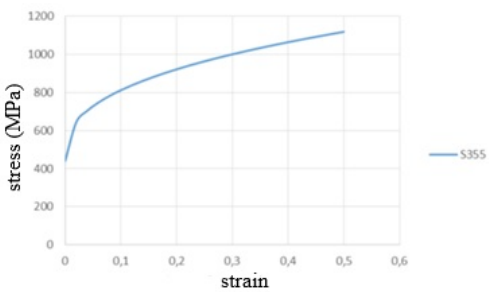
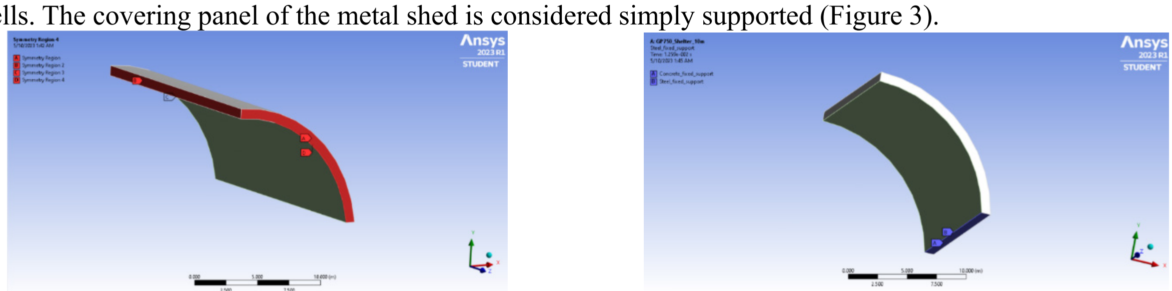


Figure 2. Stress-strain diagram for S355 steel (Cowper-Symonds model).

The simulation of the aircraft shelter is performed using a) finite solid elements (brick elements) to discretize the outer concrete shell and b) surface finite elements (shell elements) to discretize the internal steel shell. The dimensions of the solid elements (brick elements) and the shell elements are 450mm x 450mm x 400mm as well as 15mm x 15mm x 5mm respectively. The cohesion between the finite elements of the outer concrete shell and the corresponding elements of the inner steel shell, and thus the transfer of stresses and deformations, is achieved using "Bonded Interaction". The discretization of the metal roof covering panel is performed using surface finite elements. The surface that simulates the shell of the aircraft shelter is supported by fixed supports at both the base of the outer and inner shells. The covering panel of the metal shed is considered simply supported (Figure 3).



(a) (b)

Figure 3. Supports at both the base of the a) outer and b) inner shell of the aircraft shelter.

3. Threat details

The dynamic impact is caused by an explosion from a general-purpose bomb, the GP 750 (M117). This weapon is a particularly realistic choice as it can be mounted on a variety of aircraft and is designed to strike targets such as shelters and aircraft hangars. It has an explosive charge of 175 kg of Tritonal, equivalent to 221 kg of TNT, while the design fragment weighs 38.6 g. Its total weight is 332 kg. The explosion is considered to occur at ground level (reflective surface of the blast wave) and is followed by a hemispherical wave. The pressure-time diagrams for a dynamic impact from a GP 750 (M117) bomb, at distances of 20 m, 10 m, and 5 m from the structure, are shown in the figures below (Figure 4, 5, 6, 7 and 8).

Table 2. Characteristics of the impact of a GP 750 (M117) bomb at various distances from the structure

	Explosion distance - Range (m)		
	20	10	5
Charge Weight (kg)	175.10	175.10	175.10
Equivalent Weight of TNT (kg)	221.50	221.50	221.50
Peak Pressure (kPa)	94.58	440.40	2004
Impulse (kPa msec)	514.20	968.10	1251
Time of arrival (msec)	18.460	7.182	2.013
Duration (msec)	25.390	12.600	5.475
Decay coefficient	9.994	2.824	0.7187

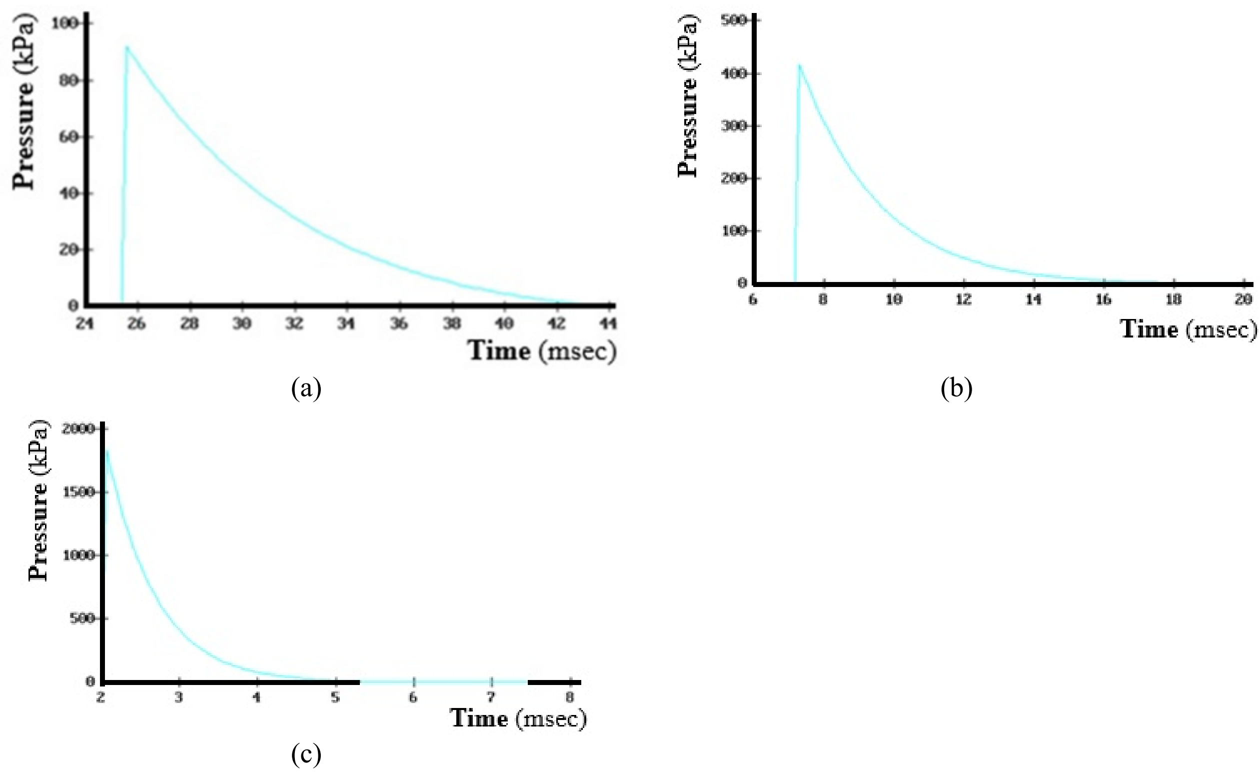


Figure 4. Time pressure diagram for dynamic impact from an M117 bomb explosion at a distance of a) 20m, b) 10m and c) 5m from the structure.

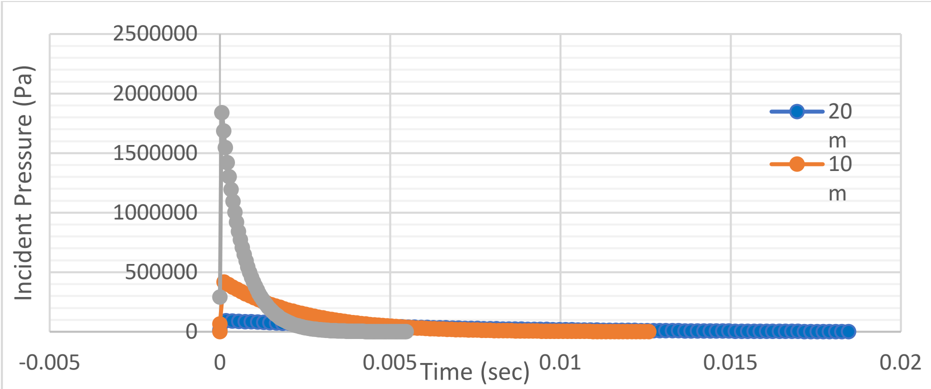


Figure 5. Time pressure diagrams for dynamic impact from an M117 bomb explosion at distances of 20m, 10m and 5m from the structure.

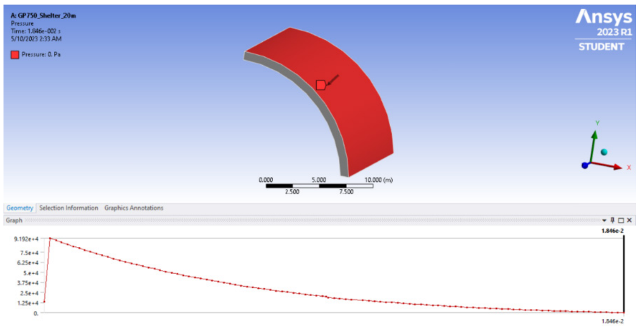


Figure 6. Dynamic impact load on the surface of the aircraft shelter for an explosion at a distance of 20m.

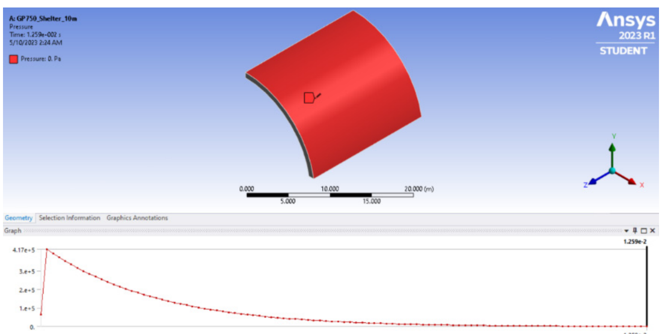


Figure 7. Dynamic impact load on the surface of the aircraft shelter for an explosion at a distance of 10m.

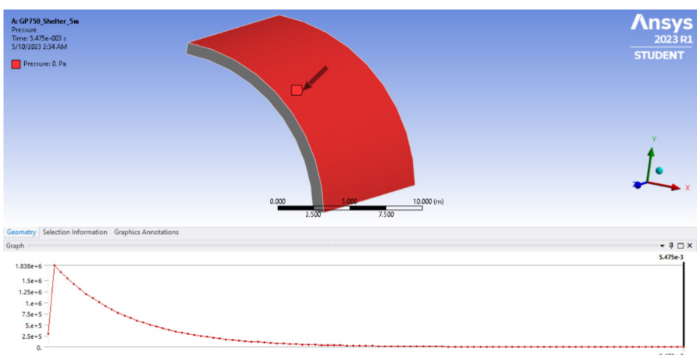


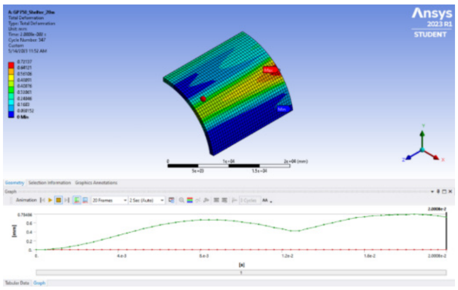
Figure 8. Dynamic impact - load on the surface of the aircraft shelter for an explosion at a distance of 5m.

4. Results of nonlinear dynamic parametric analysis

A nonlinear dynamic analysis of the above models was performed using Ansys finite element software.

4.1 Explosion distance 20m from the structure

The behaviour of the shelter for explosion distance 5m from the structure is presented at Figures 9, 10, 11, 12, 13, 14 and 15.



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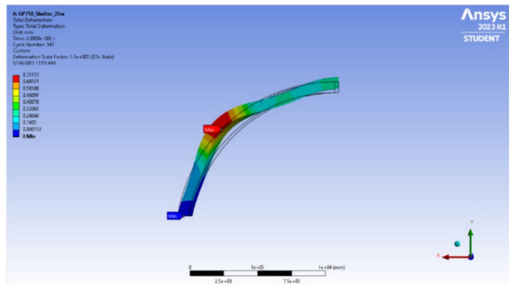
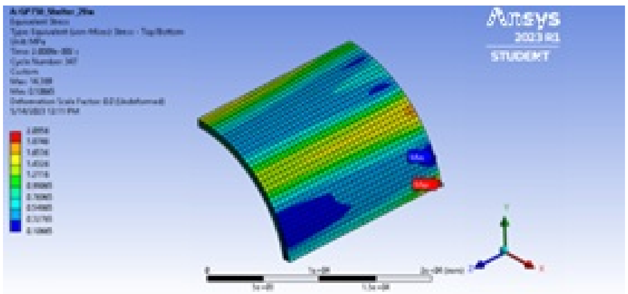


(b)

Figure 9. a) Total deformation of the outer concrete shell of the aircraft shelter, b) Total deformation of the concrete outer shell of the aircraft shelter, explosion distance (range) 20m from the structure.



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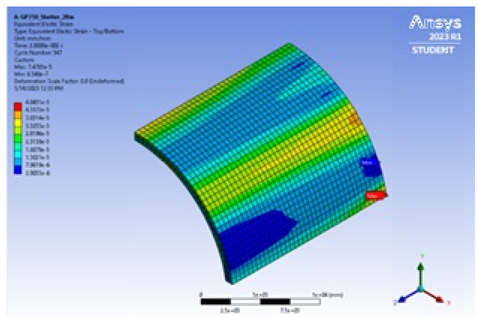
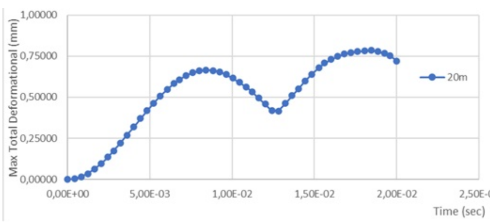


(b)

Figure 10. a) Von Mises Stress distribution for the concrete outer shell of the aircraft shelter, b) Equivalent elastic strain distribution for the concrete outer shell of the aircraft shelter, explosion distance (range) 20m from the structure.



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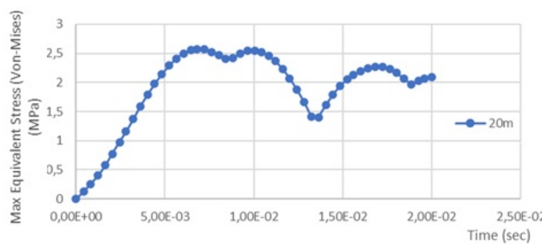

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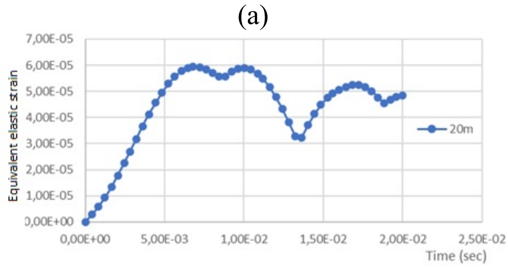
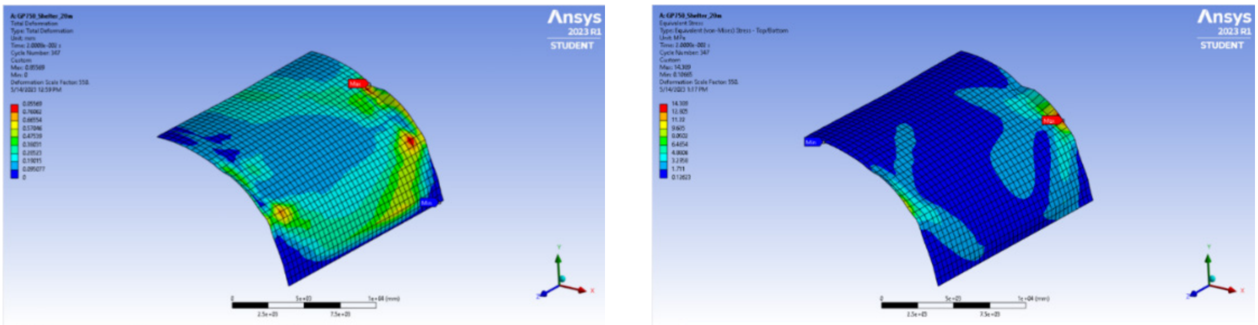


(c)

Figure 11. a) Total deformation vs time diagram of the concrete outer shell of the aircraft shelter, b) Von Mises Stress vs time diagram for the concrete outer shell of the aircraft shelter, c) Equivalent elastic strain vs time diagram for the concrete outer shell of the aircraft shelter, explosion distance (range) 20m from the structure.



(a) (b)

Figure 12. a) Total deformation of the inner steel shell of the aircraft shelter, b) Von Mises Stress distribution for the inner steel shell of the aircraft shelter, c) Equivalent elastic strain distribution for the inner steel shell of the aircraft shelter, explosion distance (range) 20m from the structure.

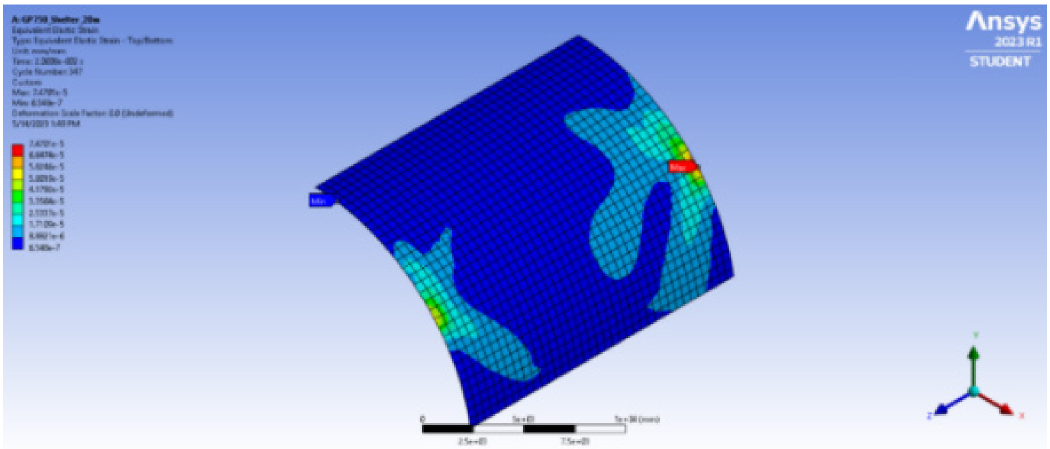
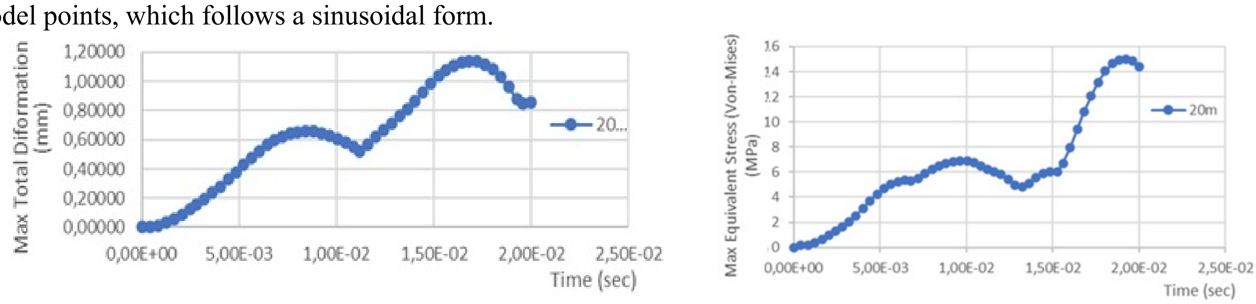


Figure 13. Equivalent elastic strain distribution for the inner steel shell of the aircraft shelter, explosion distance (range) 20m from the structure.

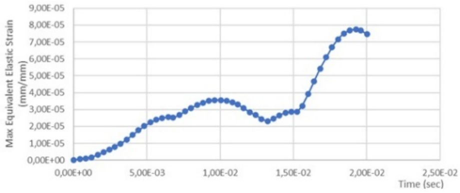
The structure is not subject to failure, since the maximum equivalent stresses are lower than the strength limits of the materials and the corresponding deformations are particularly small, on the order of thousands of a millimetre (Figure 14). The structure exhibits characteristics of decreasing oscillation, with the maximum oscillation amplitude varying over time, as shown above. This is also confirmed by the extraction of the total average displacement of the model points, which follows a sinusoidal form.



(a) (b)

Figure 14. a) Total deformation vs time diagram of the inner steel shell of the aircraft shelter, b) Von Mises Stress vs time diagram for the inner steel shell of the aircraft shelter, explosion distance (range) 20m from the structure.

The study of the model's average accelerations provides critical information about the behavior of the structure (Figure 15c). The measurements of the magnitude of the average accelerations can be used to verify the corresponding values obtained from empirical methods that give the influence of various reinforcement systems on structures. The resulting acceleration of 4g is expected for this particular weapon design and for the given distance of the explosion.



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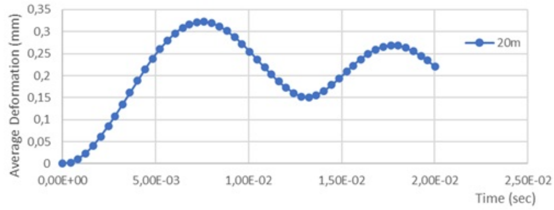

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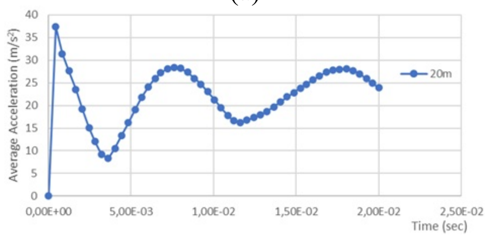


(c)

Figure 15. a) Equivalent elastic strain vs time diagram for the inner steel shell of the aircraft shelter, b) Average deformation vs time diagram of the aircraft shelter shell, explosion distance (range) 20m from the structure, c) Average acceleration vs time diagram of the aircraft shelter shell, explosion distance (range) 20m from the structure.

4.2 Explosion distance 10m from the structure

The behaviour of the shelter for explosion distance 10m from the structure is presented at Figures 16, 17, 18, 19, 20 and 21.

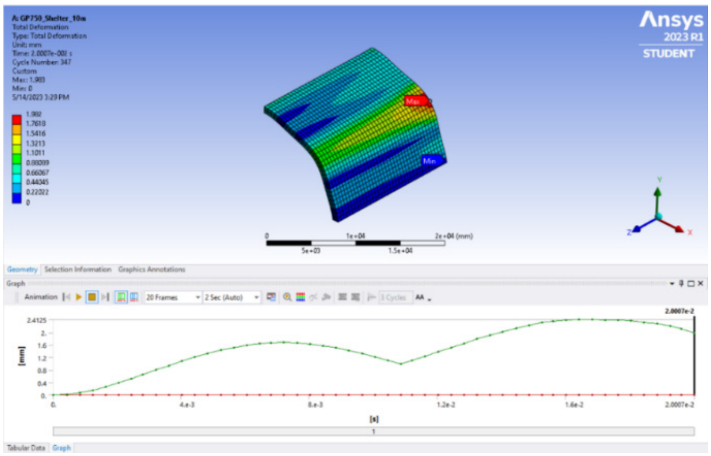
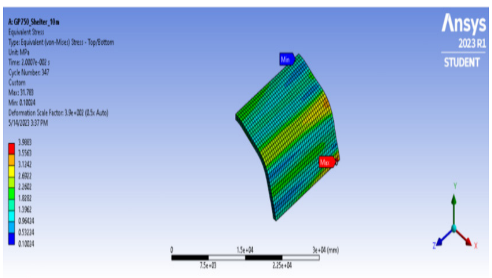


Figure 16. Total deformation of the outer concrete shell of the aircraft shelter, explosion distance (range) 10m from the structure.



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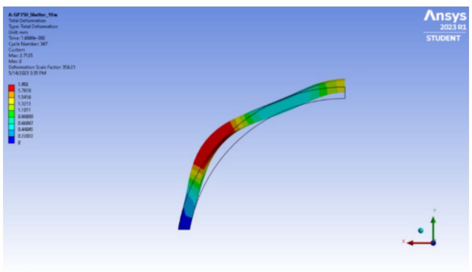
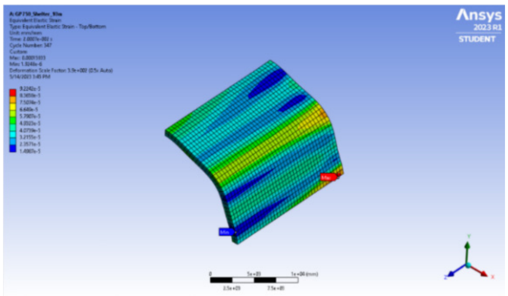


(b)

Figure 17. a) Von Mises Stress distribution for the concrete outer shell of the aircraft shelter, explosion distance (range) 10m from the structure, b) Total deformation of the concrete outer shell of the aircraft shelter, explosion distance (range) 10m from the structure.



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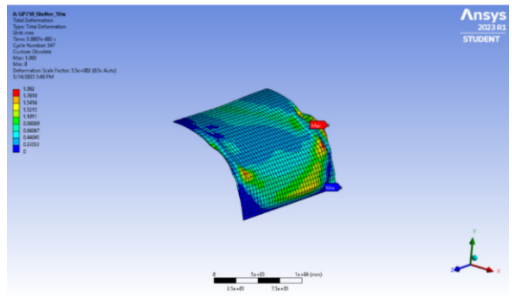

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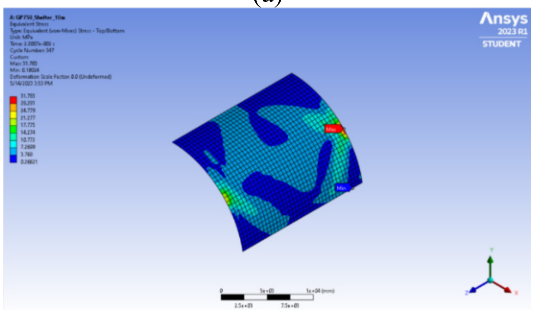

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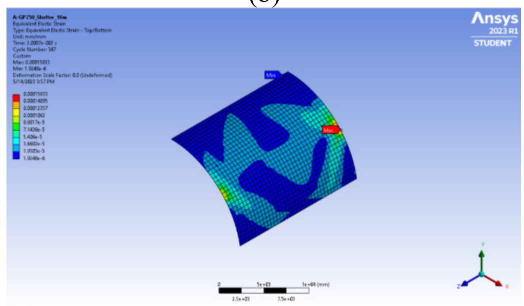
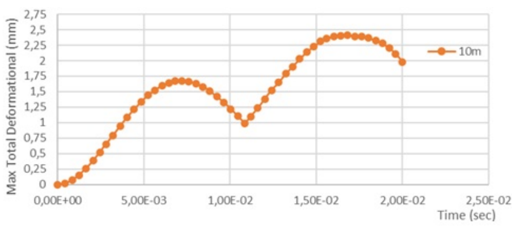


(d)

Figure 18. a) Equivalent elastic strain distribution for the concrete outer shell of the aircraft shelter, explosion distance (range) 10m from the structure, b) Total deformation of the inner steel shell of the aircraft shelter, explosion distance (range) 10m from the structure, c) Von Mises Stress distribution for the inner steel shell of the aircraft shelter, explosion distance (range) 10m from the structure, d) Equivalent elastic strain distribution for the inner steel shell of the aircraft shelter, explosion distance (range) 10m from the structure.



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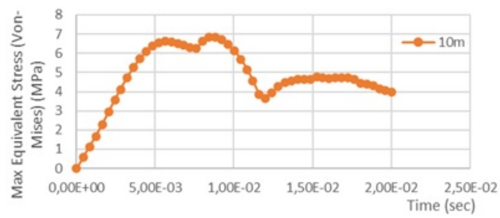
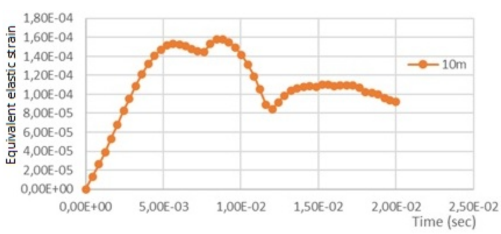


(b)

Figure 19. a) Total deformation vs time diagram of the concrete outer shell of the aircraft shelter, explosion distance (range) 10m from the structure, b) Von Mises Stress vs time diagram for the concrete outer shell of the aircraft shelter, explosion distance (range) 10m from the structure.



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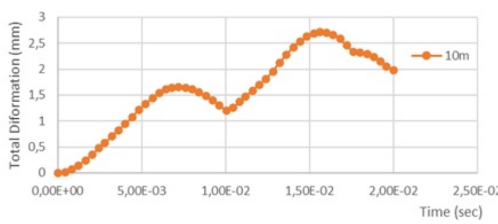
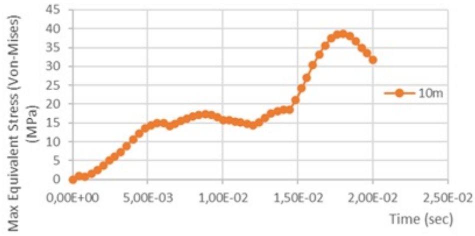


(b)

Figure 20. a) Equivalent elastic strain vs time diagram for the concrete outer shell of the aircraft shelter, explosion distance (range) 10m from the structure, b) Total deformation vs time diagram of the inner steel shell of the aircraft shelter, explosion distance (range) 10m from the structure.

Both stresses and deformations are well below the strength limits. Halving the distance leads to a doubling of stresses and deformations. Displacements are in the order of a few millimeters and therefore do not affect the functionality of the structure (Figure 21c).



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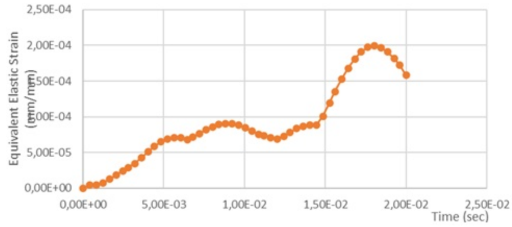

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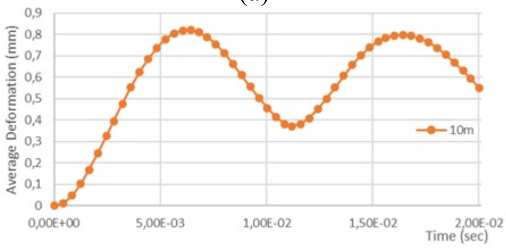

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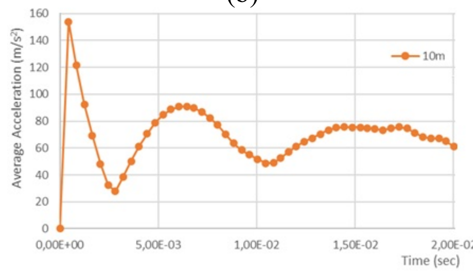
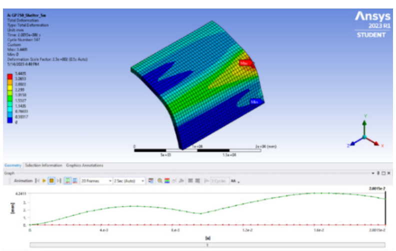


(d)

Figure 21. a) Von Mises Stress vs time diagram for the inner steel shell of the aircraft shelter, explosion distance (range) 10m from the structure, b) Equivalent elastic strain vs time diagram for the inner steel shell of the aircraft shelter, explosion distance (range) 10m from the structure, c) Average deformation vs time diagram of the aircraft shelter shell, explosion distance (range) 10m from the structure, d) Average acceleration vs time diagram of the aircraft shelter shell, explosion distance (range) 10m from the structure.

We expect a maximum acceleration of 15g for an explosion 10m from the structure, however the average acceleration value is 7g (Figure 21d). This acceleration value is related to a dynamic impact in the category of relatively strong explosions.

4.3 Explosion distance 5m from the structure



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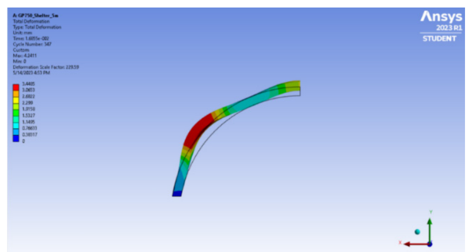
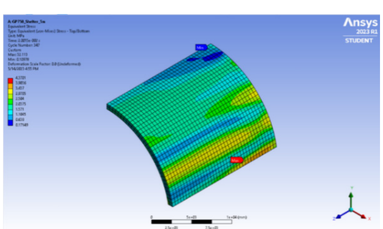
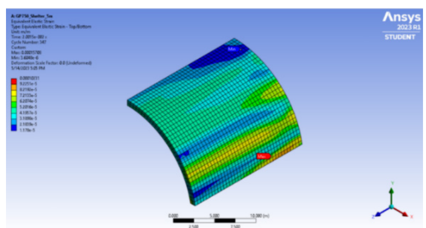


(b)

Figure 22. a) Total deformation of the outer concrete shell of the aircraft shelter, explosion distance (range) 5m from the structure, b) Total deformation of the concrete outer shell of the aircraft shelter, explosion distance (range) 5m from the structure.



(a)



(b)

Figure 23. a) Von Mises Stress distribution for the concrete outer shell of the aircraft shelter, explosion distance (range) 5m from the structure, b) Equivalent elastic strain distribution for the concrete outer shell of the aircraft shelter, explosion distance (range) 5m from the structure, explosion distance (range) 5m from the structure.

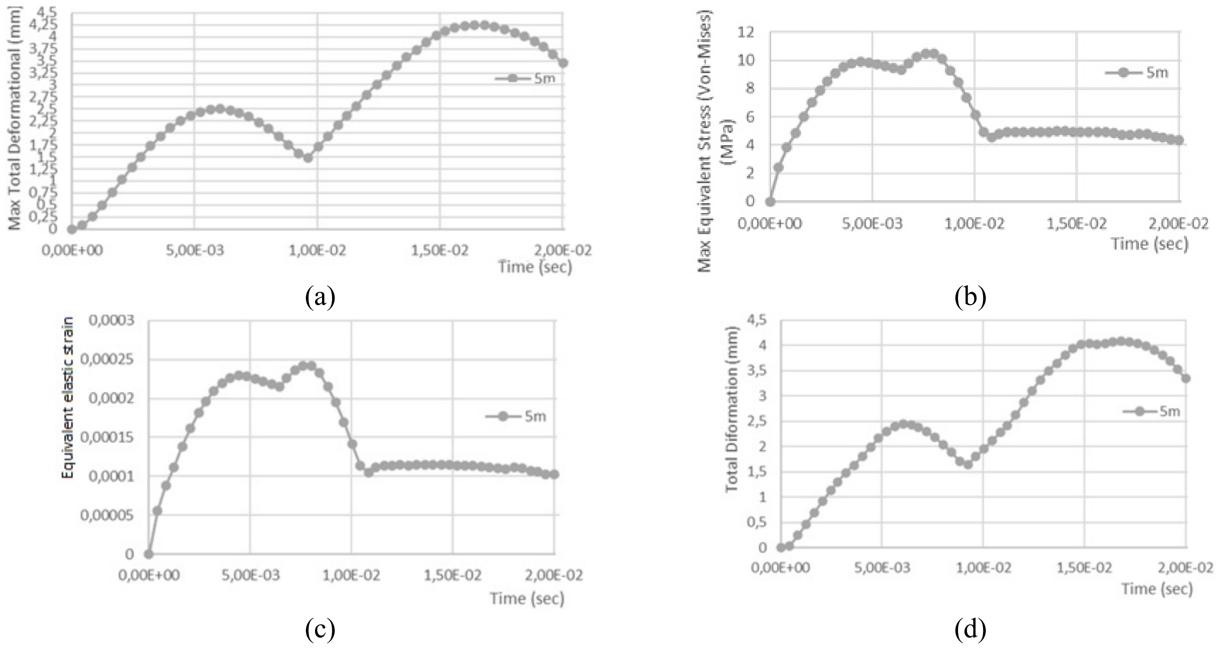


Figure 24. a) Total deformation vs time diagram of the concrete outer shell of the aircraft shelter, explosion distance (range) 5m from the structure, b) Von Mises Stress vs time diagram for the concrete outer shell of the aircraft shelter, explosion distance (range) 5m from the structure, c) Equivalent elastic strain vs time diagram for the concrete outer shell of the aircraft shelter, explosion distance (range) 10m from the structure, d) Total deformation vs time diagram of the inner steel shell of the aircraft shelter, explosion distance (range) 10m from the structure.

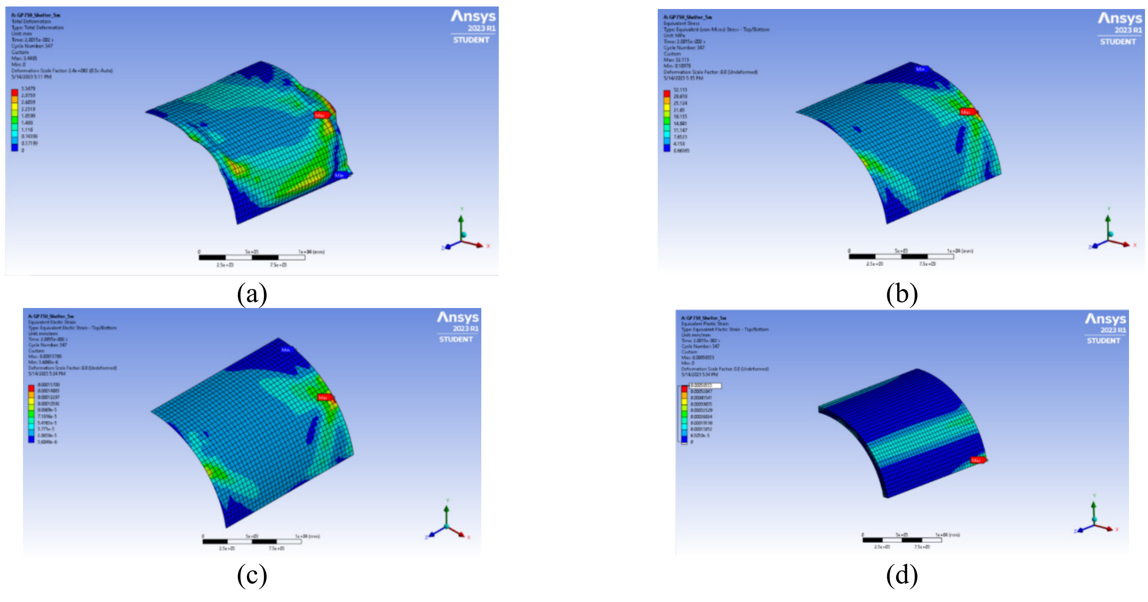


Figure 25. a) Total deformation of the inner steel shell of the aircraft shelter, b) Von Mises Stress distribution for the inner steel shell of the aircraft shelter, c) Equivalent elastic strain distribution for the inner steel shell of the aircraft shelter, d) Equivalent plastic strain distribution for the aircraft shelter, explosion distance (range) 5m from the structure.

The behaviour of the shelter for explosion distance 5m from the structure is presented at Figures 22, 23, 24, 25, 26 and 27. Plastic deformation of 0.5 ‰ is observed at the base of the aircraft shelter shell. Although minor, this deformation may indicate the onset of cracking and further potential failure in this specific area (Figure 26). The behaviour of the carrier in this case is satisfactory, and the consequences of the explosion are not considered catastrophic.

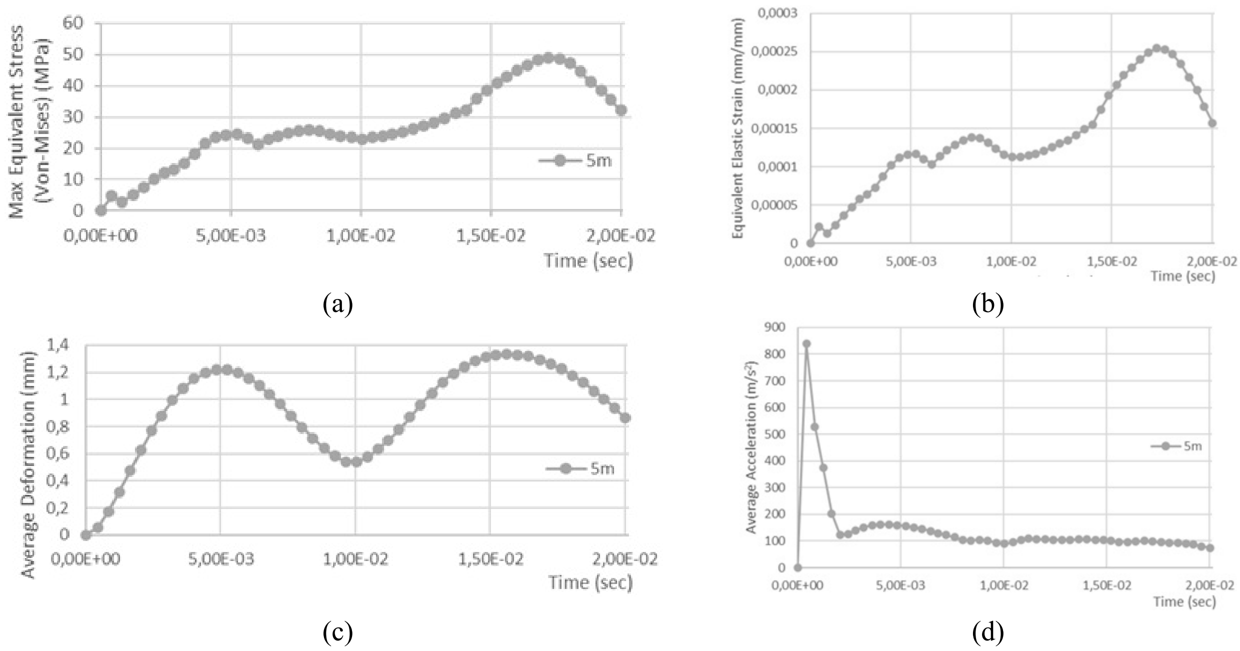


Figure 26. a) Von Mises Stress vs time diagram for the inner steel shell of the aircraft shelter, explosion distance (range) 5m from the structure, b) Equivalent elastic strain vs time diagram for the inner steel shell of the aircraft shelter, explosion distance (range) 5m from the structure, c) Average deformation vs time diagram of the aircraft shelter shell, explosion distance (range) 5m from the structure, d) Average acceleration vs time diagram of the aircraft shelter shell, explosion distance (range) 5m from the structure.

The maximum acceleration value momentarily reaches 84g (Figure 26d), which represents a particularly powerful explosion. However, this value lasts for less than a millisecond. The average acceleration value is 10g. The comparative diagrams from the aforementioned parametric analyses are presented, with the distance of the explosion from the structure as a parameter.

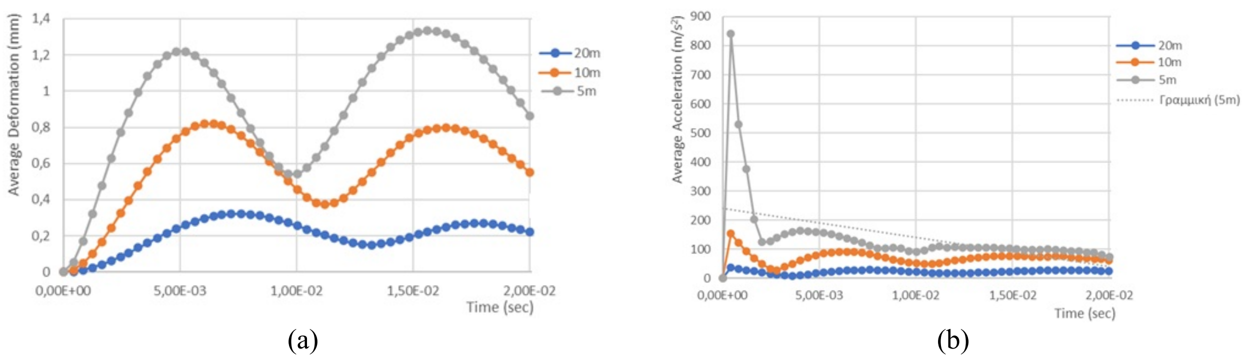


Figure 27. a) Average deformation vs time diagrams of the aircraft shelter, b) Average acceleration vs time diagrams of the aircraft shelter, for different explosion distances (range) 20m, 10m, 5m from the structure.

Table 3. Total Deformation, Von Mises Stress and Equivalent Elastic Strain for concrete outer shell of the aircraft shelter, for different explosion distances (range) 20m, 10m, 5m from the structure

Explosion distance (m)	Total Deformation (mm)	Von Mises Stress (MPa)	Equivalent Elastic Strain
20m	0.78486	2.5749	0.000059507
10m	2.4125	6.8278	0.00015779
5m	4.2411	10.483	0.00024225

Table 4. Total Deformation, Von Mises Stress and Equivalent Elastic Strain for the inner steel shell of the aircraft shelter, for different explosion distances (range) 20m, 10m, 5m from the structure

Explosion distance (m)	Total Deformation (mm)	Von Mises Stress (MPa)	Equivalent Elastic Strain
20m	1.1417	15.006	0.00007754
10m	2.7125	38.667	0.00019937
5m	4.0897	49.057	0.0002542

Table 5. Maximum acceleration of the aircraft shelter, for different explosion distances (range) 20m, 10m, 5m from the structure

Explosion distance (m)	Average acceleration (m/sec^2)
20m	37.368
10m	153.88
5m	840.79

Comparing the graphs, we can see the effect of distance on the results of the explosion on the structure (Figure 27). The closer the structure is to the epicentre of the explosion, the greater the stress it undergoes. In particular, with regard to accelerations, it can be seen that halving the distance causes multiple acceleration values. Furthermore, different explosion distances cause different oscillation periods. It is crucial to compare these periods with the natural period of the structure and determine whether we are in resonance conditions. Aircraft shelters are designed with technical specifications to withstand similar dynamic impacts and remain operational. The parametric study of this model confirmed the above.

Conclusion

The dynamic effects of explosions from armament systems are essential in the construction of Air Force structures, including Hardened Aircraft Shelters. The impact of such pressures on structural reaction is contingent upon the proximity of the explosion to the structure and the type of weapon employed. This study examines the effect of explosion distance on the dynamic response of a third-generation Hardened Aircraft Shelter (H.A.S) following a GP750 (M117) bomb detonation. Parametric finite element analysis is performed to illustrate the impact of a GP750-M117 bomb on a NATO 3rd generation Hardened Aircraft Shelter (H.A.S). The variable parameter is the distance of the structure from the detonation point.

The distance of the explosion site from the structure has a decisive effect on its response. It has been found that a structure affected by an explosion performs a periodic motion, a decreasing oscillation. Depending on the distance of the explosion (intensity of the explosion), accelerations ranging from 2-3g to over 50g are expected for the shelter.

It is useful to make certain recommendations for further reinforcement of existing structures and/or the possible design of future protected structures. Facilities can be protected from debris in many ways, one of which is to install protective walls around the structures we want to protect. These elements will not only absorb a large part of the energy of the blast wave but will also ensure that the structure is not damaged by the debris (primary or secondary) produced by the explosion. This safeguards not just the building and its equipment but, above all, the lives of the people who inhabit it. An additional solution would be to use backfill around a shelter. Backfill combined with a concrete slab would be a particularly effective method of protection. Comprehending the effects of different explosive charges and the structural weaknesses of these shelters is essential for devising efficient protection strategies. Utilizing sophisticated materials, blast-resistant designs, and proactive monitoring systems can effectively limit damage from explosive incidents. Ongoing investigation into novel materials and blast-absorbing technologies will be crucial for future advancements in shelter safety

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