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3D NUMERICAL SIMULATIONS OF SHOCK WAVE PROPAGATION DUE TO BLAST LOAD AND COMPARING THE RESULTS BETWEEN EMPERICAL AND FINITE ELEMENT METHODS

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ABSTRACT

Explosions near buildings can cause catastrophic damages on the building external and internal frames, and most important can cause injuries and loss of life to the occupants of these buildings. Due to these extreme conditions, efforts have been made in the last few decades to develop methods to evaluate the pressure loads generated from explosions and the structural response to these loads and to enhance the design of the structures to withstand it. Experiments on explosions can be very expensive, dangerous and time consuming compared to simulation using finite element analysis software. UFC 3-340-02, 2008 , is limited and not applicable for complicated buildings. Due to this lack of these experimental methods and their inability to deal with complex buildings and their surrounding conditions, many studies were conducted to represent explosions using the finite element method to obtain the design pressure values for each building in any location that we need to study. The empirical analyses based on UFC 3-340-02, 2008 is performed to get the peak overpressure of the building sides for comparison between UFC method and the 3D numerical simulation by ABAQUS software. The 3D numerical simulations of shock wave propagation using ABAQUS software is used to study the effect of various mesh size on the peak overpressure of the building sides to get results similar to the results obtained by UFC method. The difference between peak positive overpressures of UFC and Abaqus methods were 10% , -10% , -11% , 7% and -15% for front face , left side , right side , back side and the roof respectively . Since UFC results base on empirical experiments, their quality should not be questioned. Thus, some defects of the numerical approach, especially for the tensile elements, can explain these differences. The Abaqus the negative phase merely does not exist, and the positive phase is extended. This can lead to the statement, that Abaqus solution is valid only for the positive phase of pressure-time relation. Based on the performed analyses, the general convergence of results has been proven for all faces, and further investigations should be carried out to find the source of the absence of the negative phase, although the peak positive overpressure values were considered in the design. The study confirms the results' dependence on the mesh density.

KEYWORDS: Numerical Simulation of Blast Action; Blast wave propagation; Peak Positive Pressure.

تمثيل ثلاثي الابعاد لانتشار الموجات نتيجة احمال الانفجارات ومقارنة النتائج بين الطرق التجريبية وطريقة العناصر المحددة

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الملخص

الانفجارات القريبة من المباني تسبب اضرارا كبيرة على الهياكل الخارجية والداخلية للمبنى والأهم من ذلك أنها يمكن أن تسبب إصابات وخسائر في الارواح لشاغلي هذه المباني. وبسبب خطورة ذلك قد بذل الباحثون جهودا كبيرة في السنوات الماضية لتطوير طرق حساب أحمال الضغط الناتجة عن الانفجارات وتصميم الهياكل لتحملها وتتم بطريقتين: تجارب حقيقية أو باستخدام برامج العناصر المحددة. وحيث إن التجارب على الانفجارات مكلفة للغاية وخطيرة وتحتاج لموافقات من الجهات الحكومية وتستغرق وقتا طويلا إذا تم المقارنة بينها وبين استخدام برامج تحليل العناصر المحددة لهذه الأسباب اتجه الباحثون لاستخدام برامج تحليل العناصر المحددة بدلا من إجراء تجارب حقيقية. هناك مواصفات UFC 3-340-02, 2008 صادرة من وزارة الدفاع الامريكية وهي طرق تجريبية مبنية على أساس إجراء انفجارات حقيقية. وهذه المواصفات تعتبر محدودة وغير قابلة للتطبيق على المباني المعقدة وعدم أخذ الظروف المحيطة بها في الاعتبار لذا اتجه الباحثون لتمثيل الانفجارات باستخدام طريقة العناصر المحددة للحصول على قيم الضغط التصميمي لكل مبنى في أي موقع نحتاج دراسته داخليا أو خارجيا. في الدراسة الحالية سوف يتم حساب قيم الضغط التصميمي على جوانب المبنى باستخدام طريقة العناصر المحددة ببرنامج ABAQUS بتمثيل المبنى 3D ولمعايرة والتأكد من دقة النتائج سيتم حساب الضغط التصميمي باستخدام طريقة UFC ، خطوات الدراسة: الحصول على قيم الضغط التصميمي ورسم المنحنيات الخاصة بها على الاوجه المختلفة للمبنى باستخدام طريقة UFC كما في مثال 2A-10 page 482. ثم تمثيل المبنى 3D على برنامج ABAQUS وحيث إن حجم العنصر المحدود finite element mesh size يؤثر على نتائج التحليل لذا تم دراسة أحجام مختلفة للعناصر للوصول إلى الحجم المناسب والحصول على نتائج قريبة من التحليل باستخدام طريقة UFC قبل مقارنة النتائج بين طريقتي UFC and ABAQUS. وكانت النسبة المئوية للاختلاف بين طريقة UFC وطريقة ABAQUS كما يلي: 10 % للواجهة الامامية، 10- % للواجهة اليسرى، 11- % للواجهة اليمنى، 7 % للواجهة الخلفية، 15- % للسقف. وحيث إن نتائج طريقة UFC مبنية على تجارب عملية فلا ينبغي التشكيك فيها وبالتالي هناك عيوب في طريقة ABAQUS تفسر هذه الاختلافات فالطور السالب غير موجود بينما الطور الموجب ممتد وهذا يؤدي إلى القول بأن الحل بطريقة ABAQUS صالح فقط للطور الموجب ، وبناء على التحليلات التي أجريت تم إثبات التقارب العام للنتائج بالنسبة لجميع الواجهات وينبغي إجراء مزيد من الدراسات لمعرفة مصدر غياب الطور السالب، بالرغم من أن التصميم يعتمد فقط على قيم ضغط الانفجار الموجبة القصوى. وتؤكد الدراسة اعتماد النتائج على كثافة الشبكة.

الكلمات المفتاحية : تمثيل انتشارموجة الانفجارات بطريقة العناصر المحددة ، انتشار موجات الانفجارات ، اقصي قيم للضغوط نتيجة الانفجارات.

1. INTRODUCTION

The increase in terrorist attacks has made public facilities, like military sites and skyscrapers, more vulnerable to explosions. While nuclear plants and dams can endure such impacts, analyzing destructive loads and non-destructive testing can be expensive and lengthy, often needing government approval. Specialized numerical programs can simulate these phenomena. This paper focuses on modeling explosions and shock waves propagation with the finite element analysis by Abaqus program, using an explicit dynamic solver and Coupled Eulerian-Lagrangian elements, where air is modeled with Eulerian elements and buildings with Lagrangian elements. It also provides an analytical solution for building based on UFC [1] standards. The study aims to optimize the finite element mesh size for efficiency and reliability, validated against the UFC [1] analytical solution.

1.1. Objectives

The objective is to run a list of analyses related to the explosion caused blast wave. This means that certain important points in the pressure-time curve should be returned. That can later be used to define the structure loading or to evaluate the degree of the structure destruction. Generated models will depend on the following parameters: For the discretization of the model, we have examined mesh sizes of finite elements equal to 0.2, 0.25, 0.3, 0.4, 0.5, and 1.0 meters.

1.2. Explosions and The Blast Phenomenon

An explosion is a rapid release of energy that creates a shock wave, typically resulting from Chemical Reactions (TNT and dynamite) produce Rapid reactions that produce gas and heat, Nuclear Reactions (Atomic and hydrogen bombs) that Release immense energy, resulting in widespread destruction and Physical Changes (Boiler explosions or gas line ruptures) produce Rapid gas expansion or pressure buildup.

The Blast wave characterized by three phases. Firstly, Initiation which is the moment the explosive detonates, forming a shock front. Next, Propagation which is the shock wave travels through the air, compressing and heating it. After that, The Reflected Wave which is the shock wave interacts with surfaces, creating additional destructive effects.

Explosions cause various effects, including, Blast Pressure which causes damage to structures, strong Wind Effects that can move debris, Thermal Radiation that ignites fires and Fragmentation as Flying debris that can result in injuries.

1.3. Design considerations of effect of blast load on buildings

The main objective of designing explosion-resistant buildings was to reduce the likelihood of structural failure and to protect occupants from the effects of explosions. In the event of an explosion, the aim was to safeguard the entire structure from operational collapse while minimizing blast waves that could harm occupants. It was also necessary to consider design priorities in cases where achieving both aesthetic appeal and blast resistance was challenging.

One study introduced a novel approach to modeling fluid-structure interaction (FSI) in blast environments using advanced numerical techniques. It highlighted the role of air as a fluid medium in distributing loads generated by explosions and examined how structures responded to these loads [2].

Another study focused on the latest developments in simulating blast loads using coupled fluid-structure interaction models. It explained methods to improve the prediction accuracy of structural behavior under dynamic loads caused by explosions [3].

A further study discussed recent advancements in numerical modeling of fluid-structure interaction under blast loads. It emphasized improving simulation accuracy to provide more realistic predictions of structural response [4].

Another review covered the latest advancements in blast-resistant structural design. It focused on techniques that enhanced a structure’s resistance to blast loads and discussed experimental and numerical data supporting these design improvements [5].

One study integrated experimental and numerical analyses to investigate the response of reinforced concrete buildings subjected to high-intensity blast loads. It provided valuable experimental data showing how concrete structures reacted to these explosive forces [6].

A comprehensive review presented the latest developments in finite element modeling for analyzing structures exposed to blast loads. It discussed recent challenges and proposed solutions for accurately simulating dynamic load scenarios [7].

2. EMPIRICAL ANALYSES

2.1. Verification study

To ensure the accuracy of the modelling and compare the results between the two methods UFC and Abaqus, the next model shows the empirical analysis by UFC method. This study aims to obtain pressure-time loading curves (both positive and negative phases) on the interfaces of a cubic structure due to an unconfined surface explosion. Pressure measurements are taken from the front wall, roof, rear wall, and side walls following the detonation of a 2000 kg (4409.24 pounds) hemispherical TNT charge at 40 meters (131.23 feet) from the front wall. The structure measures 6 × 6 × 6 m (19.69 × 19.69 × 19.69 feet), as illustrated in **Fig. 1**, with all calculations based on UFC [1].

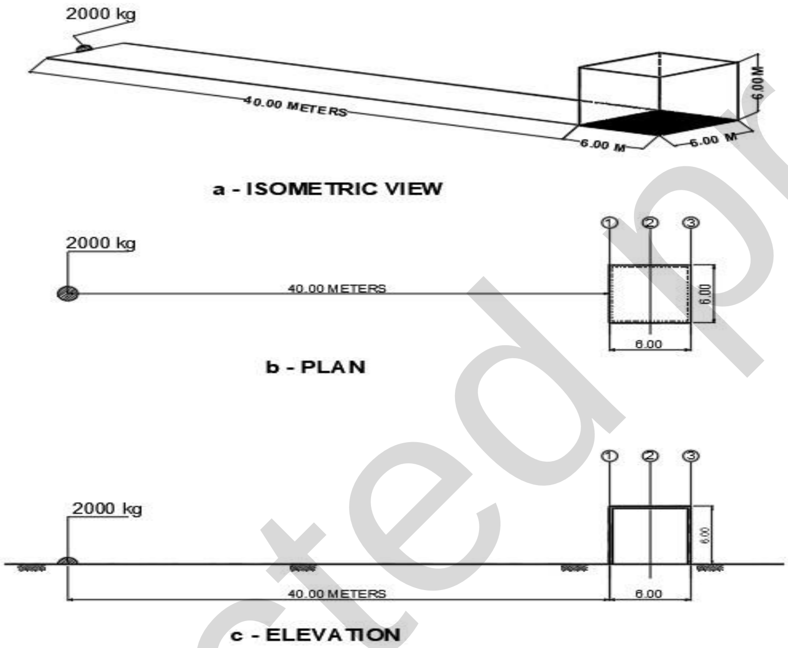

Fig. 1: Simulation model: a) Isometric View, b) Plan View and c) Elevation View

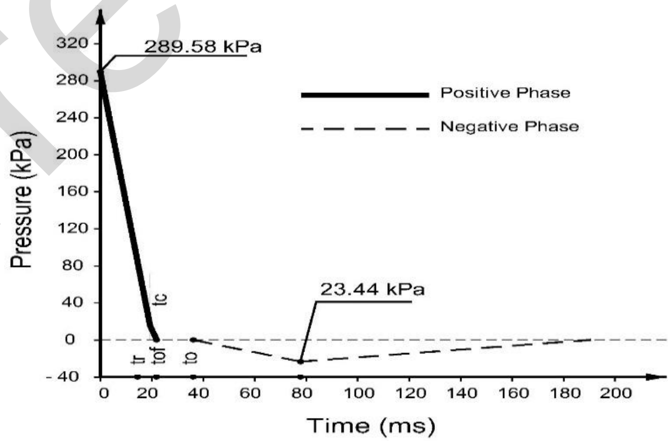

Fig. 2: Pressure-time curve for the front wall

Where (t_r) time of fictitious duration of the reflected pressure, (t_c) clearing time, (t_{of}) time of fictitious positive phase duration and (t_o) duration of positive phase of blast pressure

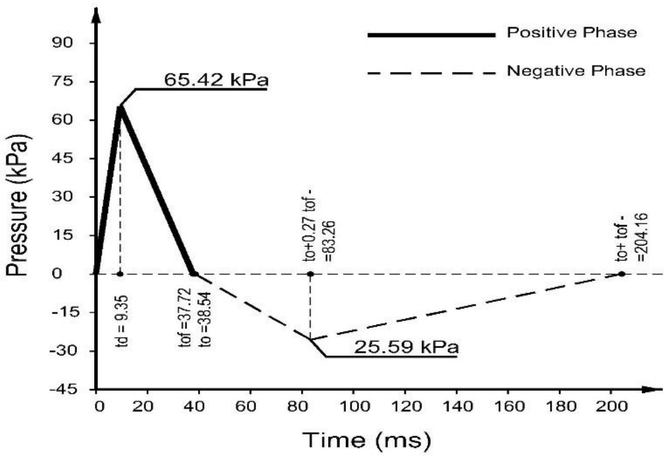

Fig. 3. Pressure-time curve for the side wall

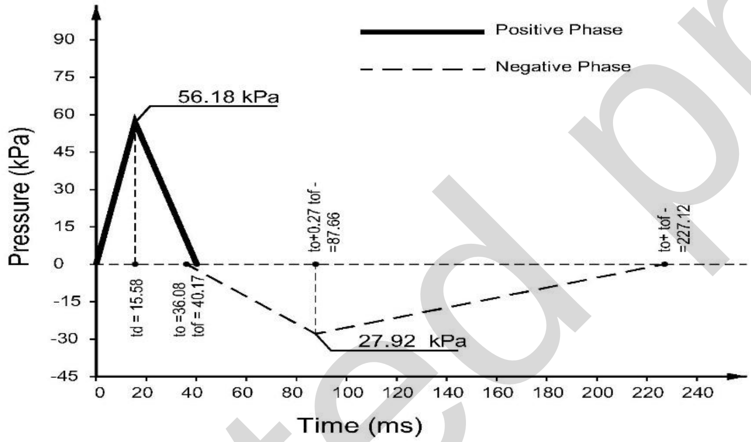

Fig. 4. Pressure-time curve for the roof

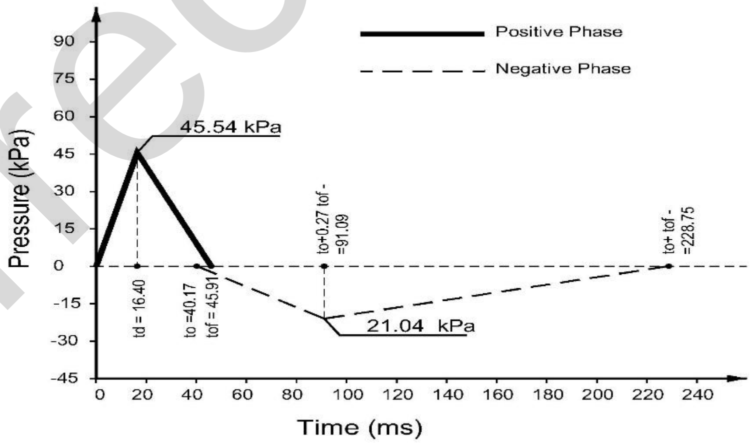

Fig. 5: Pressure-time curve for the rear wall

Where (t_d) time of fictitious reflected pressure duration, (t_{of}) time of fictitious positive phase pressure duration and (t_o) time of duration of positive phase of blast pressure.

2.2. Results and Conclusions

In **Table 1** peak over positive negative pressure values for all faces with and without ambient pressure (101.325 kPa) are presented. In **Fig. 2, 3, 4 and 5** show the pressure-time curve (straight line) for all faces. The front wall's peak reflected overpressure is 4.42, 5.15, and 6.35 times that of the side wall, roof, and back wall, respectively. The peak reflected overpressure on the side wall greater than the roof and rear wall by 16.44% and 43.6% respectively. Negative peak pressure doesn't vary considerably across the walls, the difference between the front and rear wall is 2.40 kPa.

Table 1. Positive and negative pressures for various faces

Face	Peak over/under-pressure without ambient pressure		Peak over/under-pressure with ambient pressure	
	Positive	Negative	Positive	Negative
	kPa	kPa	kPa	kPa
Front wall	289.58	-23.44	390.91	77.89
Side wall	65.42	-25.59	166.75	75.74
Roof	56.18	-27.92	157.51	73.41
Rear wall	45.54	-21.04	146.87	80.29

2.3. Comparison of Peak Overpressure (UFC vs. SPEC)

In **Table 2** The results show a strong consistency between UFC 3-340-02 [1] and SPEC 905 [12], with differences not exceeding ±1.5%. The largest variation appears at the side wall (1.45%), while the roof shows a slight negative deviation (-0.43%). Overall, the discrepancies are minor and within acceptable engineering margins, indicating that both codes provide nearly identical predictions for peak overpressure.

Table 2. Comparison of Peak Overpressure Values: UFC 3-340-02 vs. SPEC 905

Face	Peak overpressure		Difference	Percentage
	UFC 3-340-02	SPEC 905		
	kPa	kPa	kPa	
Front wall	289.58	285.60	3.98	1.374%
Side wall	65.42	64.47	0.95	1.452%
Roof	56.18	56.42	-0.24	-0.427%
Rear wall	45.54	45.52	0.02	0.044%

3. NUMERICAL ANALYSIS

Due to the high expense of conducting experiments, researchers have been using computers for this analysis in recent decades. To expand the scope of this investigation to 3D numerical simulations of shock wave propagation due to Blast load, three-dimensional finite element models were simulated using the Abaqus V 2017 program [8],[9]. The empirical analyses experimental data discussed was used to cross-check and validate the finite element models' results. Performing a series of analysis on the blast wave propagation resulting from the explosion is the main goal. As a result, the pressure-time curve at certain significant points at the centre of each face as shown in **Fig. 6** should be returned. The pressure, that can be later used to specify the loading of the structure or to estimate the level of its destruction. The mesh size study, which aims in finding the proper size of the finite element, yet computationally efficient and producing reliable results. Obtained results are verified for correctness based on empirical analyses from the UFC [1].

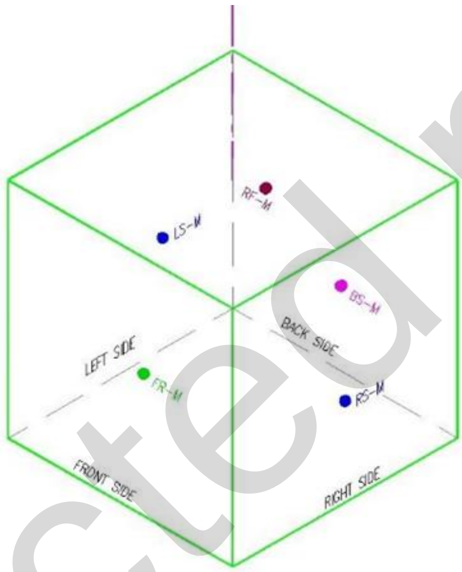

Fig. 6: Schematic Diagram for the Pressure Measurement Points

3.1. General assumptions

The air medium dimensions (width= 14m, length=54m and height =10m) modelled as Eulerian elements. The building dimensions (width= 6m, length=6m and height =6m) modelled as Lagrangian elements .A hemisphere TNT charge (radius=0.838 m) has been used, weight 2000 kg. Building and ground have been assumed as rigid, non-deformable bodies. The values of the pressure have been measured at each face in its middlecentre.TNT and air parameters that have been used in corresponding equations of state [10].

Table 3. Definition of materials [11]

Material	Kind	Property	Value	Unit
TNT	Density	Mass density	1,630	kg/m^3
	JWL Eos	Detonation wave speed	6,930	m/s
		A	3.7377E+11	N/m^2
		B	3.75E+09	N/m^2
		ξ	0.35	-
		$R1$	4.15	-
		$R2$	0.9	-
		Detonation energy density	0	J/kg
		Pre-detonation bulk modulus	0	N/m^2
	Initial state	Specific energy	3.68E+06	J/kg
		Ambient pressure	101,325	N/m^2
Air	Density	Mass density	1.293	kg/m^3
	Eos	Specific gas constant	287	J/kgK
		Ambient pressure	101,325	N/m^2
	Specific heat	Specific heat	717.6	J/kgK
	Viscosity	Viscosity	6.924e-06 at 100.0K	kg/s*m
	Initial state	Specific energy	193,300	J/kg
		Ambient pressure	101,325	N/m^2
Cube (Steel)	Density	Mass density	7,850	kg/m^3
	Elastic	Young's modulus	2E+11	N/m^2
		Poisson's ratio	0.3	-

3.2. Boundary Conditions :

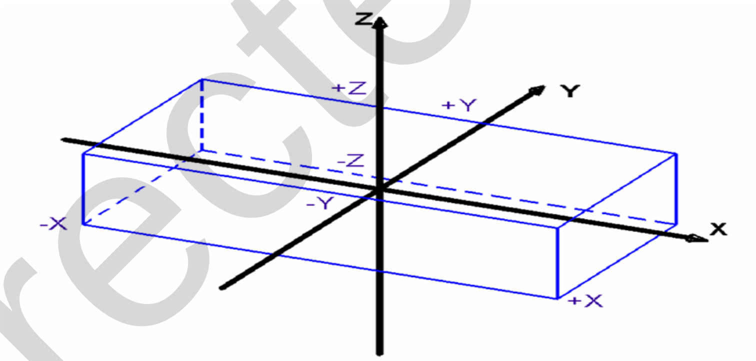

Fig. 7: 3D View of Eleurian elements

Table 4. Definition of Boundary Condition

Restrain Faces	Supporting Condition
Faces Perpendicular to X-Axis	B.C., (Category: Others) , Type: Eulerian Boundary , Flow Type: Outflow and non reflected
Faces Perpendicular to Y-Axis	B.C., (Category: Others) , Type: Eulerian Boundary , Flow Type: Outflow and non reflected
Faces Perpendicular to Z-Axis (Bottom)	B.C., (Category: Mechanical) , Type: Velocity/ Angular Velocity and prevents translation in X, Y and Z-direction
Faces Perpendicular to Z-Axis (Top)	B.C., (Category: Others) , Type: Eulerian Boundary , Flow Type: Outflow and non reflected

3.3. Mesh size study

This study aims to obtain the values of the pressure curves on the faces of the building and compare these results with the values resulting from the empirical methods as shown in Section 2 in this paper. Finding the finite element size at which the findings may be regarded as comparable involves comparing the UFC and Abaqus results to a different mesh size. Finite elements with mesh sizes of 1.0, 0.5, 0.4, 0.3, 0.25, and 0.2 have been studied. As the wave propagates and recedes from its origin, it decays in strength, lengthens in duration, decreases in velocity, and the hemispherical front becomes flatter. Hence, in the case of large stand-off distance, the assumption taken by UFC about the plane wave front is acceptable. Analysis of results starts with verification and comparison of peak positive overpressures, which are the most significant parameter describing the blast wave, and later proceeds to the analysis of pressure-time curves.

3.4. Results and Discussion

As can be seen in **Fig. 8, 9, 10, 11 and 12** (relation between the peak positive pressure and the mesh size of FEM), the peak positive pressure increases while the mesh size decreases. This is valid for any face. The gradient of pressure growth decays and stabilizes for finite element size of 0.25m - 0.20m. From this it can be assumed that further mesh refinement won't have an important effect on obtained results. Meshes finer than 0.25 m showed only minor differences (less than 3%) compared to the 0.25 m mesh, while requiring significantly higher computational time and cost. Therefore, the following curves for all faces are based on the 0.25 m mesh size.

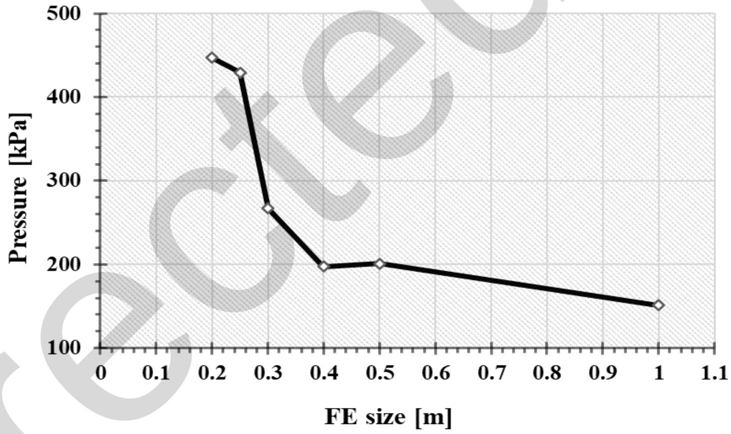

Fig. 8: Peak positive overpressures at front face for various finite element size

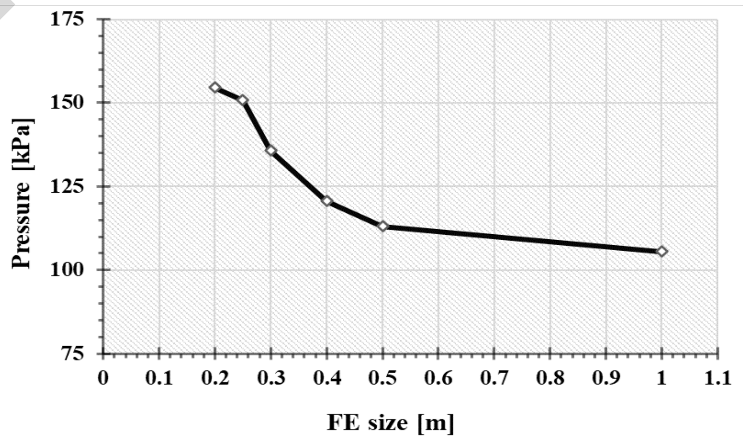

Fig. 9: Peak positive overpressures at left side face for various finite element size

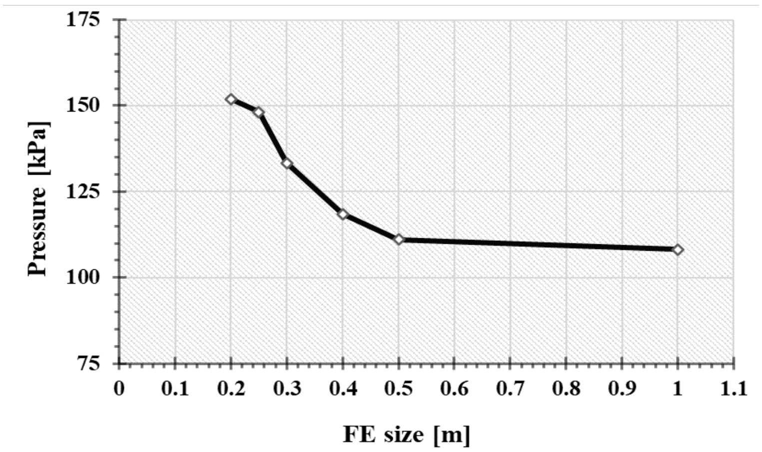

Fig. 10: Peak positive overpressures at right side face for various finite element size

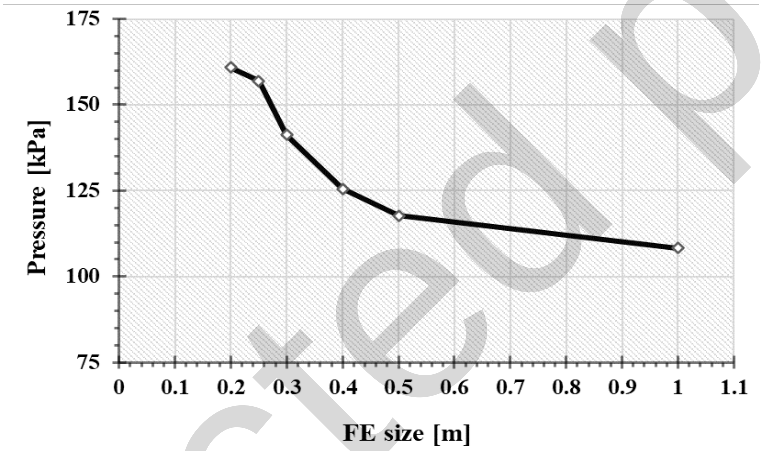

Fig. 11: Peak positive overpressures at back side face for various finite element size

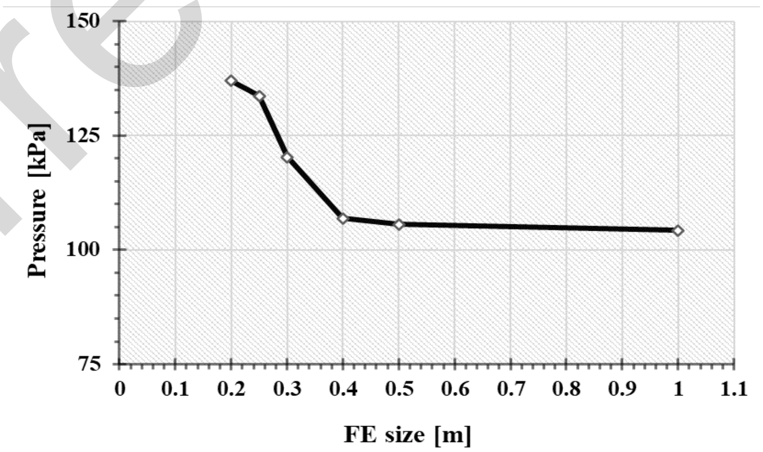

Fig. 12: Peak positive overpressures at roof face for various finite element size

As can be seen in **Fig. 13** (relation between the Spatial Dispalcement U and the mesh size of FEM), the Spatial Dispalcement U inceases while the mesh size decreases for front face (Center Point).

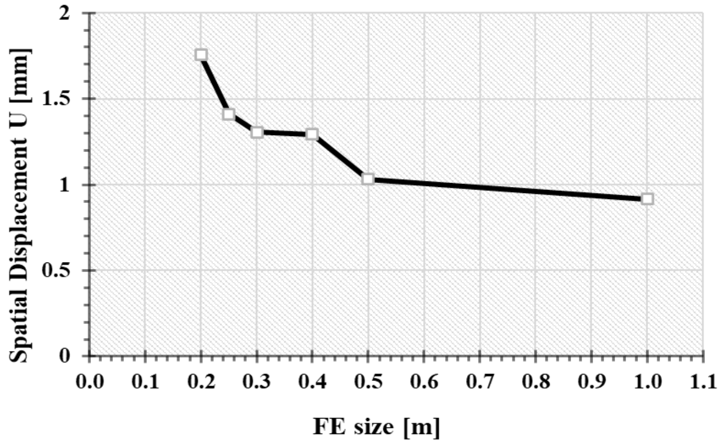

Fig. 13: Spatial Dispalcement U for front face for various finite element size

Fig. 14 - 18 represents the Pressure-time blast loading curves for each face. The maximum pressure values include ambient pressure (101.325 kPa) are 429.603, 150.823 ,148.186, 156.922 and 133.673 kPa for front face, left side, right side, back side and roof face respectively. For comparison these values with UFC empirical analyses we must detect the value of ambient pressure where the pressure values got from the empirical analyses are without this value.

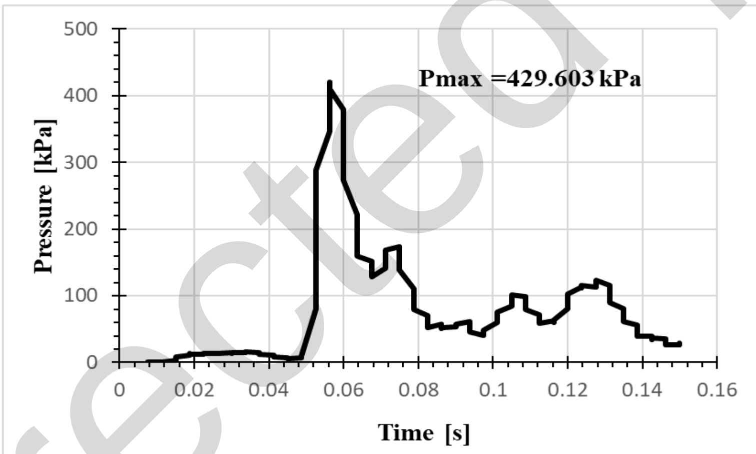

Fig. 14: Pressure-time blast loading curves for the front face

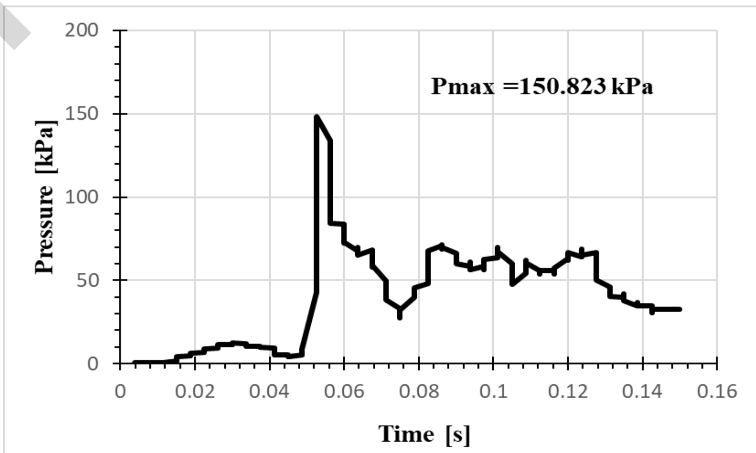

Fig. 15: Pressure-time blast loading curves for the left side face

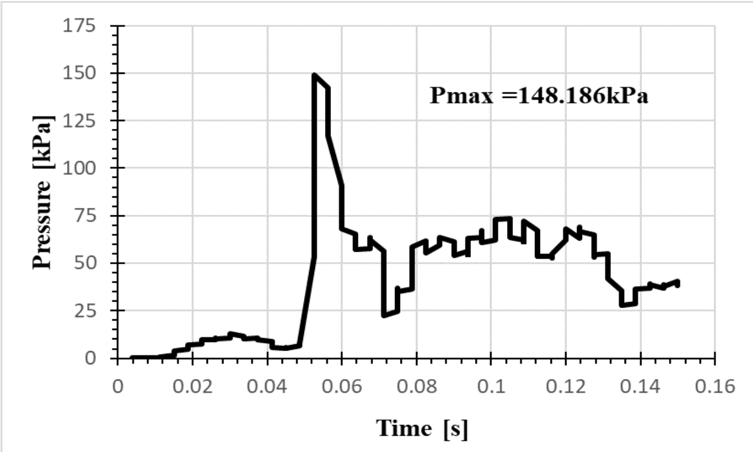

Fig. 16: Pressure-time blast loading curves for the right-side face

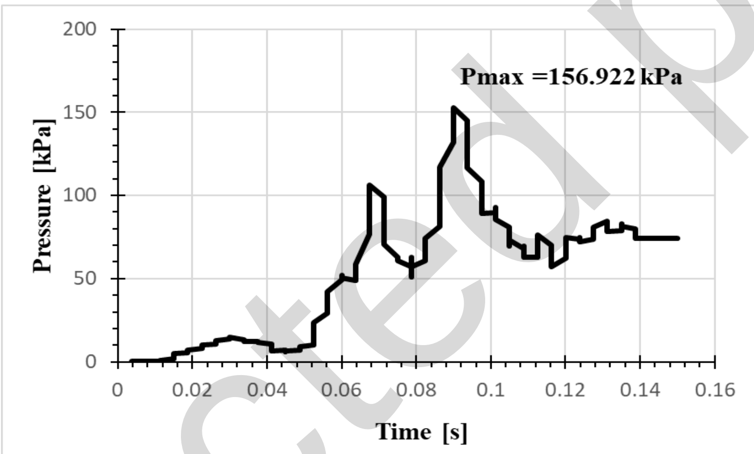

Fig. 17: Pressure-time blast loading curves for the back side face

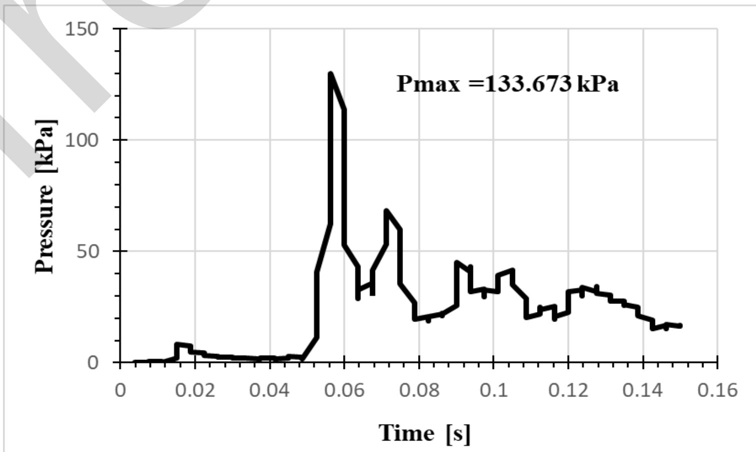

Fig. 18: Pressure-time blast loading curves for the roof face

Table 5 contains the comparison of peak overpressures from UFC and from Abaqus FEA. In the case of Abaqus FEA solution, results for 0.25m mesh element size has been taken into account as the most accurate. The difference in the peak positive overpressure for front face, left, right, backside and the roof are 10%, -10%, -11%, 7% and -15% respectively. Since UFC results base on empirical experiments, their quality should not be questioned. Thus, some defects of the numerical approach, especially for the tensile elements, can explain these differences. The differences in both positive and negative phase durations are meaningful, since in Abaqus FEA the negative phase merely does not exist, and the positive phase is extended. This can lead to the statement, that Abaqus FEA solution is valid only for the positive phase of pressure-time relation.

Table 5. Comparison of Peak positive overpressure for all faces FE size 0.25m

Face	UFC solution [kPa]	Abaqus solution [kPa]	Difference [kPa]	Difference [%]
Front	390.905	429.603	38.698	10%
Left side	166.745	150.823	-15.922	-10%
Right side	166.745	148.186	22.856	-11%
Back side	146.865	156.922	10.057	7%
Roof side	157.505	133.673	-23.832	-15%

CONCLUSION

In this study, a comparison was made between the empirical UFC 3-340-02 method and numerical simulation using Abaqus FEA for a 2000 kg TNT hemispherical surface explosion. The peak positive overpressures obtained from Abaqus simulations with a 0.25 m mesh size were:

- Front face: 429.603 kPa (UFC: 390.905 kPa → +10%)
- Left side: 150.823 kPa (UFC: 166.745 kPa → −10%)
- Right side: 148.186 kPa (UFC: 166.745 kPa → -11%)
- Back side: 156.922 kPa (UFC: 146.865 kPa → +7%)
- Roof: 133.673 kPa (UFC: 157.505 kPa → −15%)

These results indicate that the numerical simulation is generally consistent with empirical data, with deviations ranging between −15% to +10%. The optimal finite element mesh size was determined to be 0.25 m, as finer mesh sizes yielded no significant differcnec gain but increased computational cost. Additionally, the absence of a negative pressure phase in Abaqus and the extension of the positive phase suggest that the numerical approach is only reliable for positive phase analysis.

FUTURE TASKS

There are many important topics that can be extended to this thesis:

- Actual representation of the soil and not consider it as a solid or non-deformable body, and study the effect of its various properties on absorbing the energy generated by the explosions.
- Increasing the volume of air around the building.

- Investigate the influence of different geometries and structural configurations on blast pressure distribution.

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