IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

Numerical Study of a RC Slab Subjected to Blast: A Coupled Eulerian-Lagrangian Approach

To cite this article: Mircea D. Botez and Lucian A. Bredean 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **471** 052036

IOP Conf. Series: Materials Science and Engineering 471 (2019) 052036 doi:10.1088/1757-899X/471/5/052036

Numerical Study of a RC Slab Subjected to Blast: A Coupled Eulerian-Lagrangian Approach

Mircea D. Botez [1], **Lucian A. Bredean** [1]

[1] Faculty of Civil Engineering, Technical University Cluj-Napoca, 28 Memorandumului Str., 400114, Cluj-Napoca, Romania

mircea.botez@mecon.utcluj.ro

Abstract. The behaviour assessment of structures affected by extreme loads, such as explosions, has recently become an interesting topic for the research community. The response of structures (or sub-assemblages) subjected to explosions can be assessed through experimental and/or numerical approaches. Due to increased costs and constraining infrastructure requirements, experimental studies related to this topic are available in a limited number in the technical literature. The increased computational power and the advanced FEM software available nowadays, facilitate the efficient use of numerical approaches in the study of blast effects on structures. The goal of the current study is to numerically investigate the structural response of a reinforced concrete slab, subjected to close-in explosion by using the Coupled Eulerian-Lagrangian (CEL) approach in combination with an erosion algorithm. Four nonlinear dynamic analyses are performed on a numerical model assembled in Abaqus/Explicit software package. The numerical results reveal a good agreement with experimental data available in technical literature, the differences varying between 1.2% and 11.4%.

1. Introduction

Extreme events, such as explosions or impacts, have a significant effect on the structural integrity and could trigger a total or a disproportionate collapse of buildings. Characterised by the application of a force in a very short time, such events have recently generated important human casualties and have had a significant economic impact on society. Due to such threats it is important to understand and if possible to mitigate the effects of extreme loads on structures.

Explosion and their impact on structural components have recently become an important topic among the civil engineers' community. Two main approach categories can be distinguished when it comes to investigate such phenomenon: experimental methods, respectively numerical methods. Due to increased costs and constraining infrastructure requirements, experimental studies related to this topic are available in a limited number in the technical literature. The increased computational power and the advanced FEM software available nowadays, facilitate the efficient use numerical approaches in the study of blast effects on structures.

Reviewing the methods that can be used for predicting bomb blast effects on buildings, Remennikov [1] emphasized that while the "simplified analytical techniques can be used for obtaining conservative estimates of the blast effects on buildings, the numerical techniques (including Lagrangian, Eulerian, Euler-FCT, ALE) and finite element modelling should be used for accurate prediction of blast loads". Several simulation methods for modelling the air blast waves and their ability to be used for complex geometries are described by Larcher and Casade [2]. A numerical investigation of RC plates subjected to explosion is made by Xu and Lu [3]. Their study reveals that a good agreement between the numerical and the experimental results can be obtained by considering concrete spallation. A similar conclusion is obtained by Wang et al. [4]; they numerically and experimentally investigate the damage mode of a square reinforced concrete slab subjected to close-in detonation. Although the technical literature mentions several methods for predicting the air blast loads effects on structures, two numerical approaches are reported as being the most widely used [1, 2, 5, 6]: a pure Lagrangian approach (ConWEP) where the loads are applied to the affected surfaces without the computation of the propagation [5], respectively a Coupled Eulerian-Lagrangian (CEL) approach where the blast waves propagation through air, from the deflagration point to the adjacent surfaces, is computed and accounted for.

Using the second approach (CEL), the current study intends to numerically investigate the structural response of a reinforced concrete slab subjected to close-in blast loads. To achieve this goal a series of four nonlinear dynamic analyses is performed on numerical models assembled in Abaqus/Explicit software package [7]. The obtained results, expressed in terms of vertical displacements and degradation patterns are compared with the results revealed by the experimental study conducted by Wang et al. [4].

2. Experimental test

The structural response of a one-way reinforced concrete slab subjected to close-in blast is investigated by Wang et al. [4] through a series of experimental tests. A steel frame (Figure 1), composed by 8mm steel angles placed on the ground was built for preventing the slab uplifting on both right and left edges during the explosion. Four loading scenarios are studied by using different TNT charges of 0.2kg, 0.31kg, 0.46kg and 0.55kg. A 0.40m distance (with respect to the slab centre point) between the slab and the explosive is considered in all situations.

The dimensions of the tested specimens were 1000 mm x 1000 mm x 40 mm. The steel bars used for reinforcement had a 6 mm diameter and were disposed at 75 mm one from another on both directions. Hence, a 1.43% reinforcement ratio was obtained for both bending planes. A 20 mm concrete cover thickness was considered.

The compressive strength, tensile strength, respectively Young's modulus value of 39.5 MPa, 4.2 MPa and 28.3 GPa was obtained for cylindrical concrete samples. The steel used for rebars had a yield strength of 600 MPa, respectively a Young's modulus value of 200 MPa.

Figure 1. Wang et al. [4] experimental test setup

3. Numerical analysis procedure

The dynamic response of structures or structural elements subjected to extreme loads such as explosions can be numerically investigated by using different methods. There are two well-known numerical approaches that are widely used in assessing the blast effect on structures: ConWEP procedure, respectively CEL procedure, each one offering advantages depending on the context.

First option, the ConWEP (Conventional Weapon Effects Program) approach represents a pure Lagrangian technique. This method allows the user to impose pressure loadings caused by an air blast by defining the location of the explosion, the time of detonation and the directly affected surfaces [7]. The loads are applied without the necessity of a fluid domain (air) for propagation. The main drawback in this case is represented by the fact that ConWEP doesn't have the capacity to represent the second order interactions, between the reflected pressure waves that may occur and the adjacent elements. A load propagation example generated by an explosion produced in air, obtained using the ConWEP model, is illustrated in Figure 2.

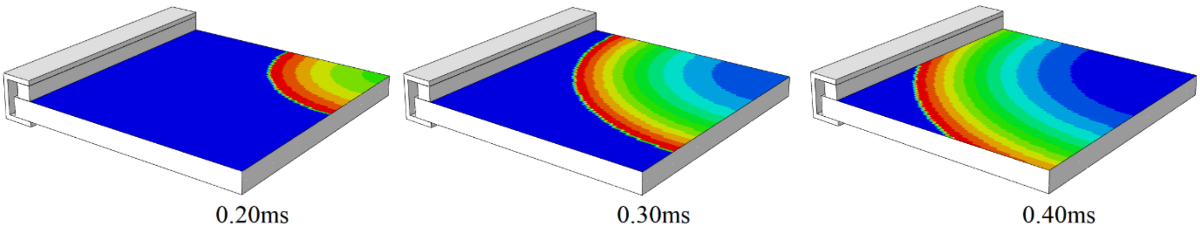


Figure 2. Loads propagation due to an air blast at 0.2ms, 0.3ms and 0.4ms (ConWEP model)

The second option is based on a Coupled Eulerian-Lagrangian (CEL) approach and involves the definition of a fluid domain (Eulerian part) in which the blast waves propagation can occur, as illustrated in Figure 3. In contrast to a pure Lagrangian analysis where the nodes are fixed within the material and elements deform as the material deforms, in a Eulerian analysis the mesh is represented by a grid of elements in which the material can move and deform [7]. The Coupled Eulerian-Lagrangian method is more suitable for cases where large deformations like those caused by explosions may appear. The main benefit of this method, compared to the previous one, is represented by the fact that the interactions between the reflected pressure waves and the structural elements (Lagrangian parts) can be successfully represented. The main downside of this approach consists in the significant impact of the numerical simulation of the pressure waves propagation through the fluid domain on the computational capacities demanded [8, 9].

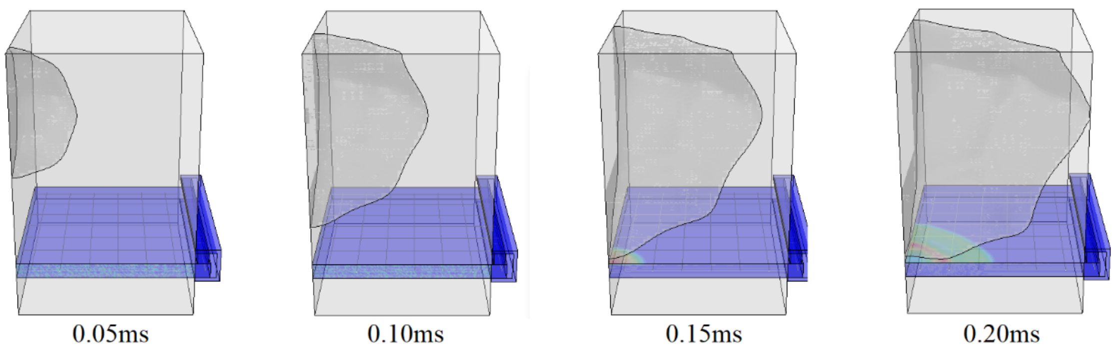


Figure 3. CEL blast wave propagation

In the current paper the Coupled Eulerian-Lagrangian (CEL) approach is used to numerically investigate the structural response of a RC slab subjected to close-in blast. Four nonlinear dynamic

IOP Conf. Series: Materials Science and Engineering 471 (2019) 052036 doi:10.1088/1757-899X/471/5/052036

analyses which determine the behaviour of the analysed element for a time interval of 0.015sec, following the blast initiation, are performed. The capabilities of the ConWep technique with respect to the same experimental study are also emphasized in a previous paper [10].

4. Proposed numerical model

Starting from the details provided by the experimental setup [4], a 3D numerical model is developed to investigate the dynamic response of a reinforced concrete slab subjected to different close-in blast loads. With this purpose, Abaqus/Explicit [7] software package, a numerical tool developed based on the Finite Element Method, is used. Since the investigation of a dynamic response involves an increased computational power, considering the slab symmetry by both transversal and longitudinal directions, the numerical model can be reduced at 1/4 of the original size (Figure 4).

For concrete and steel reinforcement bars, solid C3D8, respectively truss T3D2 finite elements with a dimension of 3mm (on each direction for the solid elements) are considered. A Eulerian domain is used to numerically represent the air component. To obtain accurate results, an increased mesh density would be suitable; however, such an approach could lead to unfeasible requirements from the computational power perspective. Thus, a parametrical investigation with respect to the mesh density was conducted to obtain a balance between the results accuracy and the used computational resources. A variable mesh size from 7mm to 10mm was considered appropriate for the Eulerian domain modelled using EC3D8R elements. The finer mesh is set around the detonation point while coarser elements are used towards the domain limits.

Since by default the analysis software is not able to represent the concrete spallation phenomenon, an erosion algorithm is used. Therefore, finite elements for which the tension strain exceeds 10% are definitively deleted from the numerical model.

The authors of the experimental study used as a reference in the current numerical study aimed to obtain fixed boundary conditions for the tested slab element. According to their own statement the boundary conditions obtained based on their experimental setup were "somewhere between fixed and pinned" [4]. Thus, for an accurate numerical representation, both the wood bar and the steel angle are modelled, as illustrated in Figure 4. The interaction between the support elements (steel angle and wood bar) and the slab is considered through the normal and tangential contact options.

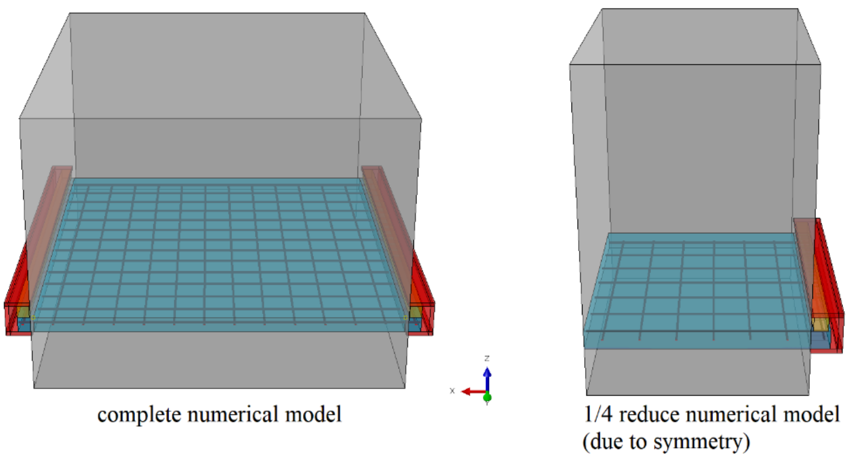


Figure 4. Proposed numerical model

The stress-strain curves for both materials (illustrated in Figure 5) are obtained starting from the concrete and steel characteristics specified by Wang et al. [4] and are developed in accordance with the Eurocode [11] provisions. The Concrete Damage Plasticity option (for concrete), respectively the Plastic option (for steel) are used to represent the nonlinear material behaviour.

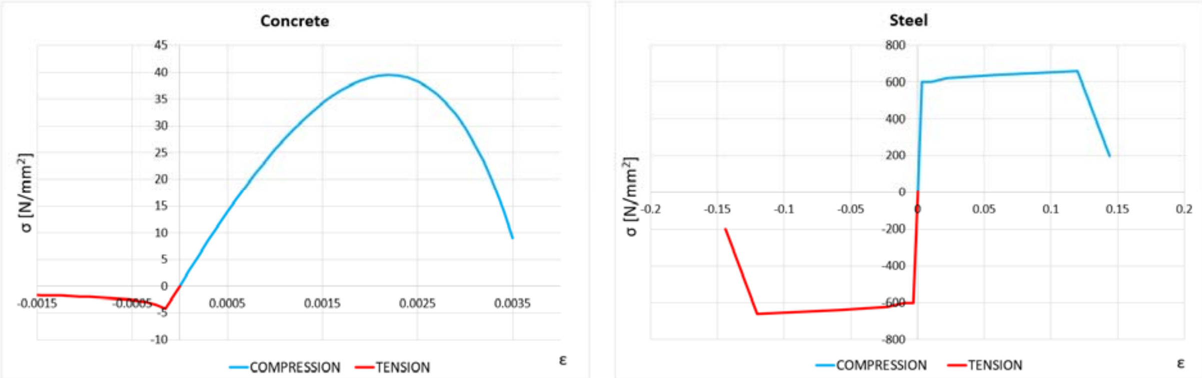


Figure 5. Stress-strain curves for concrete and steel

For the blast simulation, two materials are used. The ideal-gas equation is considered to account the behaviour of the air domain, respectively the Jones-Wilkins-Lee (JWL) equation is used to describe the blast phenomenon including the wave propagations. The JWL parameters values [2, 12, 13, 14, 15] used for the TNT explosive, respectively the ideal-gas characteristics used for air [14, 15] are summarized in Table 1.

Table 1. Parameters for TNT (JWL model) and for air (ideal-gas model)

	TNT (JWL model)	**AIR (Ideal-gas model)**	**Units**
Mass density	1630	1.293	[kg/m^3]
Detonation wave speed	6930	-	[m/s]
A	3.738×10^{11}	-	[Pa]
B	3.747×10^{9}	-	[Pa]
R_1	4.15	-	[-]
R_2	0.90	-	[-]
ω	0.35	-	[-]
Specific Energy	3.68×10^{6}	-	[J/kg]
Ambient pressure	101325	101325	[N/m^2]
Specific gas constant	-	286.9	[J/kg·K]
Specific heat	-	717	[J/kg·K]
Viscosity	-	1.82×10^{-5}	[kg/m·s]

5. Results

In the current paper, the response of a reinforced concrete slab subjected to close-in detonation is numerically investigated. Four nonlinear dynamic analyses are conducted to assess the damage level of the RC slab when subjected to different TNT charges: 0.20kg, 0.31kg, 0.46kg and 0.55kg. The numerical results, obtained by using the Coupled Eulerian-Lagrangian (CEL) approach, are expressed in terms of vertical displacements and degradation patterns.

The maximum vertical displacement values obtained numerically and experimentally, for each of the four analysed scenarios are summarized in Table 2 and graphically illustrated in Figure 6. The differences between the two sets of results, measured in percentage, are also computed with respect to the experimental values obtained by Wang et al. [4].

Table 2. Maximum displacement values: numerical vs. experimental [4] results

Tested slabs	TNT charge [kg]	Experimental test	Numerical model	Error [%]
A	0.20	10	9.74	2.60
B	0.31	15	14.82	1.20
C	0.46	35	31.01	11.40
D	0.55	-	43.82	-

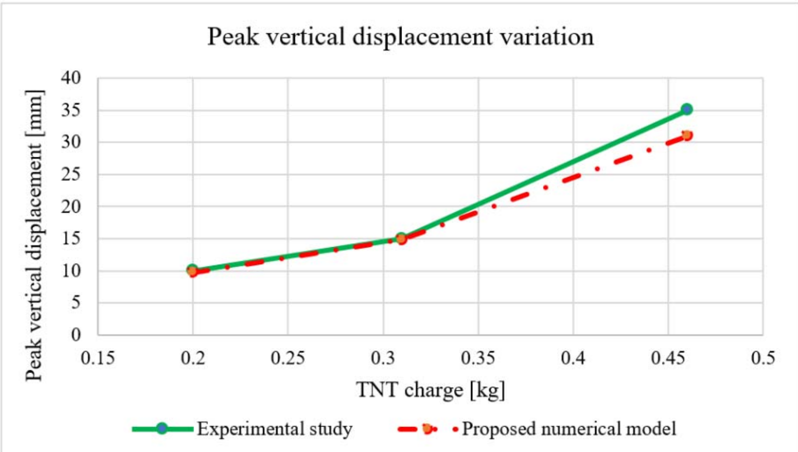


Figure 6. Peak vertical displacement variation with respect to the TNT charge

The damage modes of the tested slab specimens can be illustrated numerically by extracting the degradation patterns which measure (in percentage) the concrete material stiffness deterioration in tension and compression. Illustrated in the following figures (Figure 7-12) are the damage modes for the 0.31kg, 0.46kg and 0.55kg TNT charges scenarios, obtained through both experimental and numerical approaches.

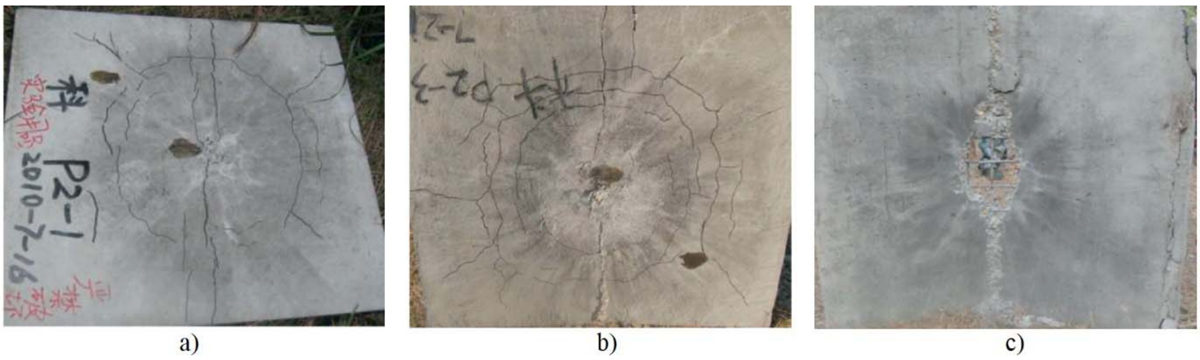
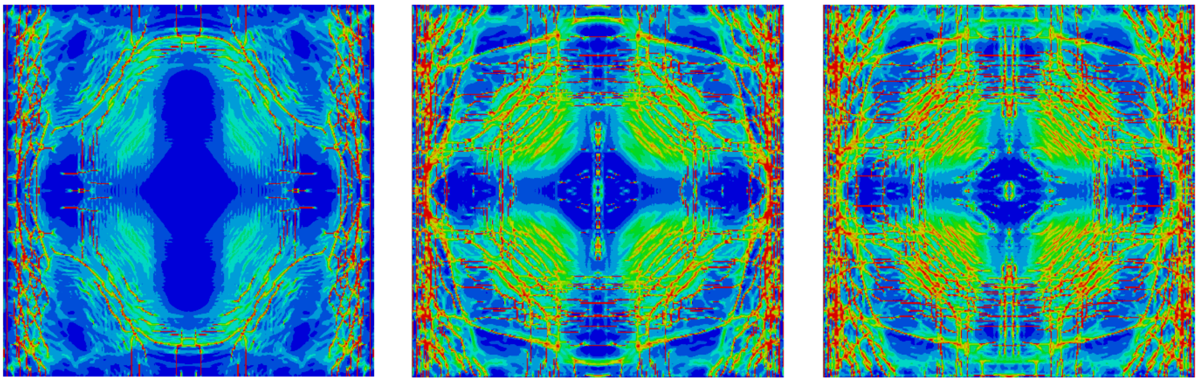
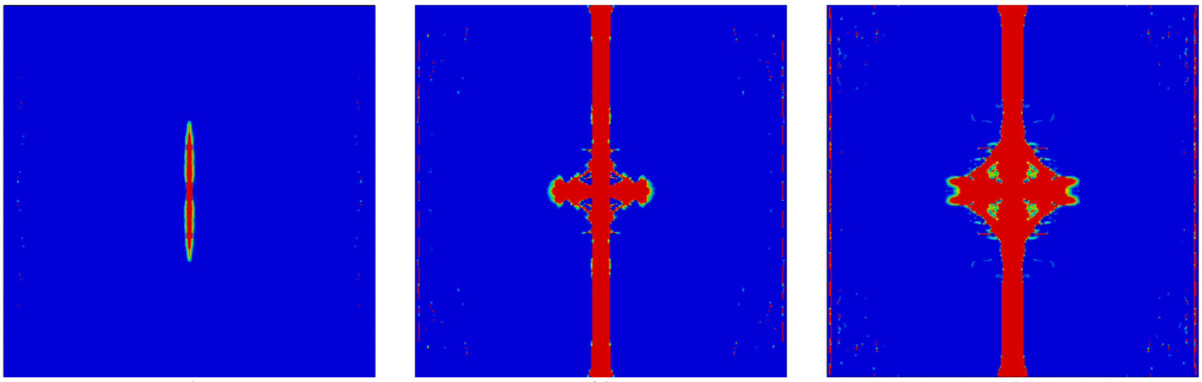


Figure 7. RC slab - top face - experimental test results [4] for TNT charges of:
a) 0.31kg, b) 0.46kg, c) 0.55kg



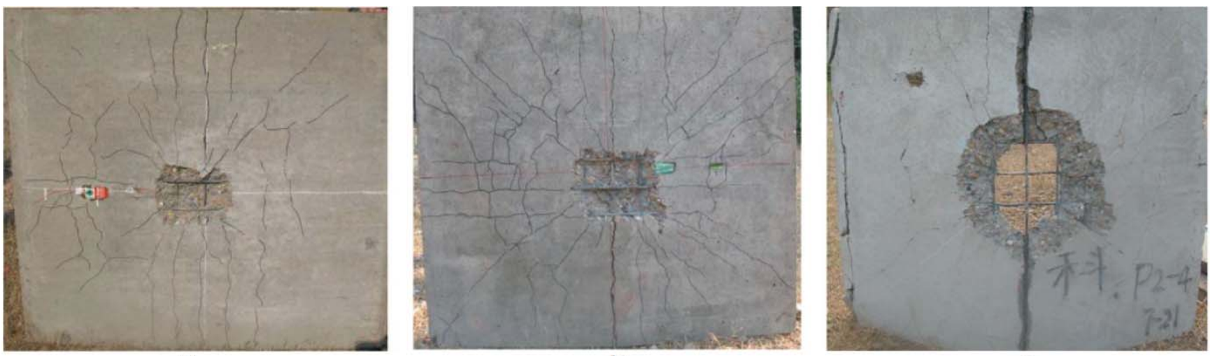
a) b) c)

Figure 8. RC slab - top face - tension stiffness degradation patterns for TNT charges of:
a) 0.31kg, b) 0.46kg, c) 0.55kg



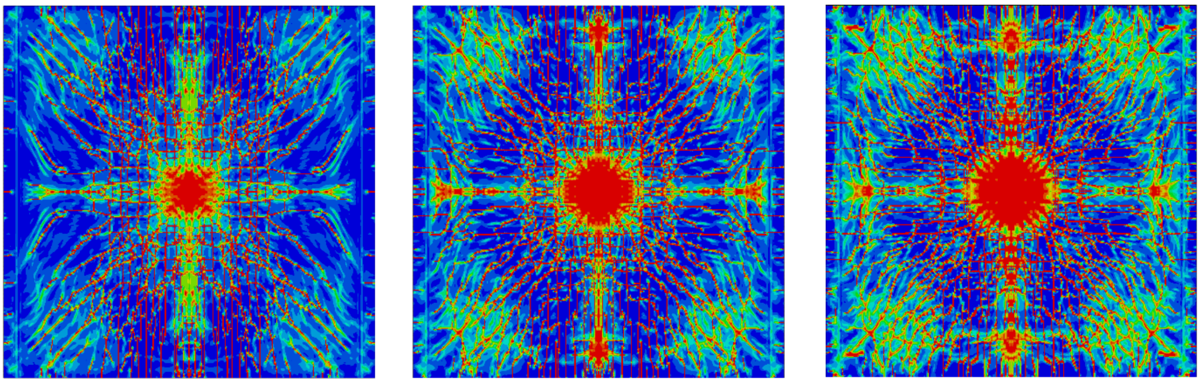
a) b) c)

Figure 9. RC slab - top face - compression stiffness degradation patterns for TNT charges of:
a) 0.31kg, b) 0.46kg, c) 0.55kg



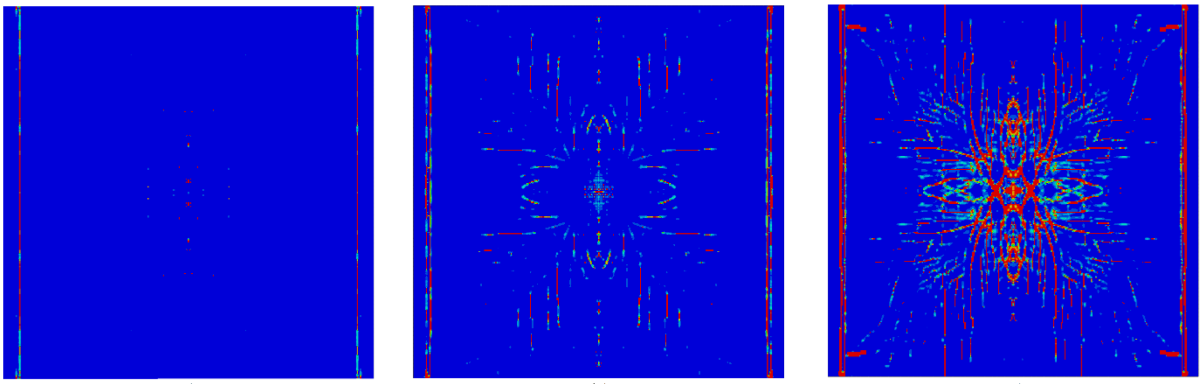
a) b) c)

Figure 10. RC slab - bottom face - experimental test results [4] for TNT charges of:
a) 0.31kg, b) 0.46kg, c) 0.55kg



a) b) c)

Figure 11. RC slab - bottom face - tension stiffness degradation patterns for TNT charges of: a) 0.31kg, b) 0.46kg, c) 0.55kg



a) b) c)

Figure 12. RC slab - bottom face - compression stiffness degradation patterns for TNT charges of: a) 0.31kg, b) 0.46kg, c) 0.55kg

The influence of the erosion algorithm on the slab structural response is the most pronounced for the analysis scenario involving the 0.55kg TNT charge. The algorithm performance in modelling the concrete spallation phenomenon can be assessed by analysing Figure 13. As illustrated, the concrete expulsion occurs in the central region of the slab and along the central line, parallel to the supports.

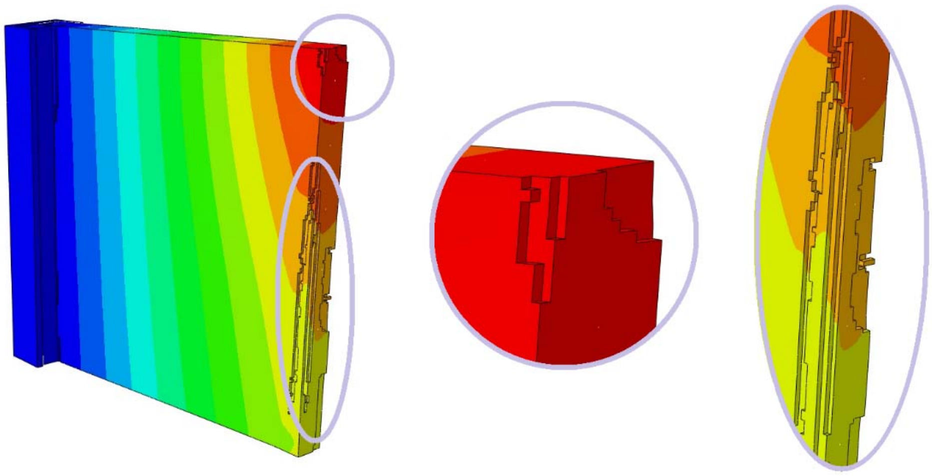


Figure 13. Proposed numerical model - concrete spallation: 0.55kg TNT scenario

6. Conclusions and discussions

Based on the Coupled Eulerian-Lagrangian (CEL) approach, the current study numerically investigates the structural response of a reinforced concrete slab subjected to close-in blast loads. The assumed objective is achieved by performing a series of nonlinear dynamic analyses on numerical models assembled in Abaqus/Explicit software package [7].

The maximum displacement results obtained numerically reveal a good agreement with the obtained during the experimental test, as Table 2 illustrates. The resulted differences vary between 1.2% and 11.4%. For the first two loading scenarios (0.2kg TNT and 0.31kg TNT) where the maximum difference is 2.6%, the erosion algorithm is not triggered since the erosion limit values is not reached. The maximum obtained difference of 11.4% associated to the loading scenario involving the 0.46kg of TNT could be explained by the fact that, although triggered, the erosion algorithm might need certain refinements to improve the accuracy in modelling the concrete spallation phenomenon.

The degradation patterns obtained numerically are a way to qualitatively assess the behaviour of the structural element subjected to extreme loads, as close-in blasts. The tension/compression stiffness degradation patterns of the concrete for both top and bottom slab faces, presented in Figures 7-12, reveal a good agreement with the experimental results, precisely describing the severely affected regions.

The numerical results reveal the capacity of the Coupled Eulerian-Lagrangian (CEL) procedure in accurately modelling the dynamic response of structural elements subjected to explosions. Thus, based on the obtained results and considering that the interactions between the reflected pressure waves and the structural elements can be modelled, the CEL approach can be further used to investigate entire structural systems (e.g. RC framed structures) subjected to blasts.

Acknowledgment

The results presented in this paper were obtained with the support of the Technical University of Cluj-Napoca through the research Contract no. 2007/2017, Internal Competition CICDI-2017.

References

[1] A. Remennikov, “A Review of Methods for Predicting Bomb Blast Effects on Buildings”, *Journal of Battlefield Technology*, vol. 6(3), pp. 5-10, 2003.
[2] M. Larcher and F. Casadei, “Explosions in complex geometries - a comparison of several approaches”, *JRC Scientific and Technical Report*, ISBN 978-92-79-15245-0, DOI 10.2788/73796, 2010.
[3] K. Xu, Y. Lu, “Numerical simulation study of spallation in reinforced concrete plates subjected to blast loading”, *Computers and Structures*, vol. 84, pp. 431–438, 2006, doi:10.1016/j.compstruc.2005.09.029.
[4] W. Wang, D. Zhang, F. Lu, S.Wang and F. Tang, “Experimental Study and numerical simulation of the damage mode of a square reinforced concrete slab under close-in explosion”, *Engineering Failure Analysis*, vol. 27, pp. 41-51, 2013, DOI: https://doi.org/10.1016/j.engfailanal.2012.07.010
[5] G. Le Blanc, M. Adoum, V. Lapoujade, “External blast load on structures – Empirical approach”, *5th European LS-Dyna Users Conference*, 2005.
[6] M. Shuaib, O. Daoud, “Numerical Modelling of Reinforced Concrete Slabs under Blast Loads of Close-in Detonations Using the Lagrangian Approach”, *Journal of Physics: Conference Series 628*, 2015, DOI:10.1088/1742-6596/628/1/012065.
[7] Abaqus, *Abaqus - User’s manual*, v. 6.13. Pawtucket, RI: Hibbit, Karlsson & Sorenson, 2013.
[8] D. Miller, H. Pan, R. Nance, A. Shirley and J. Cogar, ”A Coupled Eulerian/Lagrangian Simulation of Blast Dynamics”, *Proceedings of the IMPLAST 2010 Conference*, 2010.
[9] W. Mamrak, “Blast wave propagation in the air and action on rigid obstacles”, *Master Thesis*, Poznań University of Technology.
[10] M. D. Botez, L. A. Bredean and M. S. Buru, “Reinforced Concrete Slab Subjected to Blast.

IOP Conf. Series: Materials Science and Engineering 471 (2019) 052036 doi:10.1088/1757-899X/471/5/052036

Numerical Model Validation", *17th edition National Technical-Scientific Conference - Modern Technologies for the 3rd Millenium*, 2018.

[11] ASRO, "Eurocode 2: Design of Concrete Structures – Part 1-1: General Rules and Rules for Buildings", *SR EN 1992-1-1:2004,* Bucharest, 2004.

[12] B. Dobratz, P. Crawford, "LLNL Explosives Handbook: Properties of Chemical Explosives and Explosive Simulants", *Technical Report UCRL-5299-Rev.2*, University of California, Lawrence Livermore National Laboratory, 1985.

[13] R. Tiwari, T. Chakraborty and V. Matsagar, "Dynamic Analysis of Underground Tunnels Subjected to Internal Blast Loading", *11th World Congress on Computational Mechanics (WCCM XI), 5th European Conference on Computational Mechanics (ECCM V), 6th European Conference on Computational Fluid Dynamics (ECFD VI)*, 2014.

[14] W. Mamrak., "Blast wave propagation in the air and action on rigid obstacles", *Master Thesis*, Poznań University of Technology, Faculty of Civil and Environmental Engineering

[15] P. Mamrak, "Pressure evolution inside complex corridor system induced by blast action", *Master Thesis*, Poznań University of Technology, Faculty of Civil and Environmental Engineering.