10th INTERNATIONAL SCIENTIFIC CONFERENCE
ON DEFENSIVE TECHNOLOGIES
OTEH 2022
Belgrade, Serbia, 13 – 14 October 2022

HIGH PERFORMANCE MULTI-FUNCTION PANELS FOR EXTREME LOADING EVENTS

DAMJAN CEKEREVAC
ISISE, University of Coimbra, Coimbra, damjan.cekerevac@uc.pt

CONSTANÇA RIGUEIRO
ISISE, Institute Polytechnic of Castelo Branco, Castelo Branco, constanca@ipcb.pt

JOSÉ CAMPOS
LEDAP/ADAI, University of Coimbra, Coimbra, andrade.campos@dem.uc.pt

EDUARDO PEREIRA
ISISE, University of Minho, Guimarães, eduardo.pereira@civil.uminho.pt

ALDINA SANTIAGO
ISISE, University of Coimbra, Coimbra, aldina@dec.uc.pt

Abstract: *Global climate change has led to extreme events (high tides, storm surges and floods) resulting in severe consequences for coastal areas and communities. In addition, the increasing terrorist attacks on unprotected targets has resulted in efforts to develop infrastructure that acts as protective barriers. Resistant wall protection to blast requires a precise blast information. This paper aims to present the research already carried out by the authors related to metallic panels when subject to blast action.*

Keywords: *Blast, Impact, Sandwich pannels, Energy dissipation, Numerical modeling.*

1. INTRODUCTION

Sandwich panel solutions have been used for a wide range of applications, namely façade and roofing systems, temporary protection of public spaces or multi-purpose interior walls. These portable systems provide adaptability to the spaces; they are designed for safety and resistance to permanent, transient and accidental actions such as fire.

This article presents a framework of the research already done related to these metallic structural systems and their applicability. Since they have enormous potential to be multifunctional, able to protect critical infrastructures (as already been used by oil and gas sector) and mitigate the extreme climatic effects. The research under development pretends to propose a design of new kind of lightweight multi-layer sandwich structure with improved mechanical properties and high blast resistance.

2. LITERATURE REVIEW

Half of the world's population lives by the sea and three quarters of all large cities are located near large stretches of water. Coastal zones are a privileged place, where the population is concentrated and consequently activities such as commerce, industry and tourism are developed. Portugal is an example of this, with the intensive occupation of a large part of its coastal strip. According to the United Nations, between 1901 and 2010, the rise in the average sea level occurred at an accelerated rate, the fastest in the last 2,800 years. This rise, associated with global warming and greenhouse gas emissions, leads to various effects: coastal erosion, flooding, contamination of fresh-water reserves, among others [1]. These changes lead to the exceptional occurrence of extreme meteorological phenomena such as storms and waves and have serious consequences for coastal areas and communities. To face the challenges of climate change effects it is necessary to provide sustainable solutions to protect coastal communities and infrastructures.

Regarding the solutions developed for coastal protection (onshore and foreshore) there is a great diversity; however these solutions do not present a wide consensus among experts about their efficiency, long-term durability, costs and influence on Habitat [3]. The development and implementation of coastal protection solutions should not only meet safety and sustainability criteria (minimum environmental impacts) in the marine environment, but also maximize adaptability for other uses, such as supporting human activities and promoting biological colonization (Figure 1).

In the area of infrastructure protection, several types of structures and protection devices are presented in [5] (Figure 2). According to [4], collisions of vessels with bridges are a frequent type of accidental action that can result in severe damage to the structure and lead to loss of life, as well as environmental pollution due to induced leaks. Thus, accidental loads resulting from vessel collisions represent an important scenario to be considered when assessing the safety of these devices. The most common devices in protection systems are made of steel due to their behavior when subjected to impact forces. However, they are vulnerable to corrosion and fire [6]. Moreover, some of these protection systems can cause serious damage to vessels and can be expensive for bridges located in poor geological areas [5]. In addition, in order to avoid compromising the integrity of vessels, the design of these protection systems must have a compromise between strength and ductility, as required by the Norwegian standards in this field [7].

Figure 1. Protective systems in the marine environment

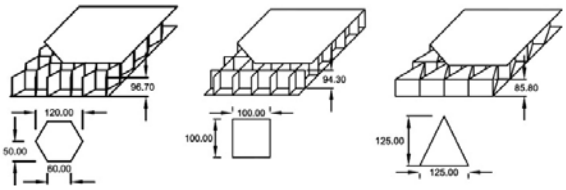
Figure 2. Examples of infrastructure protection systems in a maritime environment

Due to the possibility of terrorist attacks on civil structures, the consideration of blast from fuel explosions, sonic booms or shock waves [8] cannot be neglected in this analysis of extreme actions. The tendency is to reinforce and or protect structures that have not previously been conceived to deal with this type of threat. Blast mitigation strategies traditionally used in industrial plants can provide additional safety. One such solution is the blast wall, which can be used for façade systems or for the protection of assembly areas and evacuation routes of metro and train stations or airports, for example.

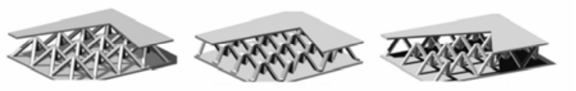
Possessing the favourable combination of strength and toughness, traditional solutions widely used by both the civilian and military sectors were typically monolithic and based on high-strength steel, aluminium [9,10] and ceramic materials [11,12]. These systems provide adequate protection for heavy armoured vehicles, aircraft and helicopters, but when low weight, mobility and adaptability are the key design parameters, their use becomes limited. In order to meet these requirements, lightweight and flexible solutions are important, with preference given to mixed steel solutions (considering composite materials).

The development of (lightweight) protection elements has been the subject of research in the last two decades, namely structural steel sandwich panels to mitigate the effect of accidental actions. The investigation of stainless steel sandwich panels subjected to extreme loads can be found in [13, 14, 15,16].

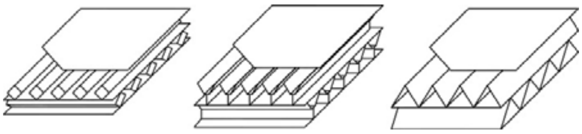
Sandwich panels allow energy to be dissipated through plastic deformation of the core and sheets/plates, making them more efficient than a single sheet [17]. Corrugated plates, honeycomb cores (Fig. 3a)), or with latticed or folders elements (Fig. 3b)), perform well, even for underwater blasts [18]. In [14, 15], the behaviour of these systems is analysed and it is demonstrated that they allow high levels of energy to be dissipated. In [19], the authors studied the effectiveness of orthotropic (Fig. 3c) and honeycomb typologies and the core sandwich panels with orthotropic elements showed great potential when subjected to blast loads. These systems with auxetic material in their core also show good energy absorption capacities and 3D printing can be used to manufacture them easily, where the sheet is printed over the core, avoiding the separation/ detachment [14].



a) Honeycomb core typologies: hexagonal, square and triangular [19].



b) Types with latticed or folded elements in its core [14]



c) Orthotropic types: diamond, Y-shaped and triangular [19].

Figure 3. Examples of different types of sandwich panels systems

In this compilation of the research already done, it is concluded that it is necessary to perform tests to complete and support the knowledge of these structural systems, particularly regarding the optimal configuration under impact or instantaneous loads and the fluid-structure interaction [15]. Complementarily, the explosion behaviour is revealed to have a huge potential, which can be improved through the introduction of alternative composite materials, such as fibre-reinforced polymers and the consideration of dissipative connections of these to the primary structure, [20,21,22].

3. DISCUSSION AND DIRECTION OF THE RESEARCH

3.1. Efficiency of blast walls for protection of soft targets

This item deals with the research focused on the assessment of the blast response of protection walls. The studies developed by the authors in [20,21,22] represent an effort to improve the knowledge on the behavior of blast protection of soft targets by the use of structural blast mitigation solutions already used in oil and gas industrial facilities and in earthquake design.

Here a parametric study is perfomed through numerical modeling. Two common types of pannels (bulkhead and corrugated) with both fixed and pinned boundary conditions are subjected to directly defined presuure loads. Their responses are compared in order to evaluate the effects on the primary steelwork. Reaction forces, displacemnets and energy dissipation is calculated. Possible benefits deriving from typological and geometrical modifications of the local element are also presented.

Numerical modelling

The behavior of the thin two-way elements that are prone to large deformations was analyzed with the software Abaqus. The explicit dynamic solution method was applied due to its computational efficiency. Shell elements S4R with 10 mm of size was chosen. The adopted mesh was according DNV recommendations [23]. The structural steel S355 was adopted. The dynamic non-linear behavior of the material, the strain rate effect, strain hardening and the damage evolution were taken from [21]. In this study the interaction between the load and the element was not considered. The load was defined by specifying the pressure variation, according to DNV [23] and API [24] recommended practices, Figure 4.

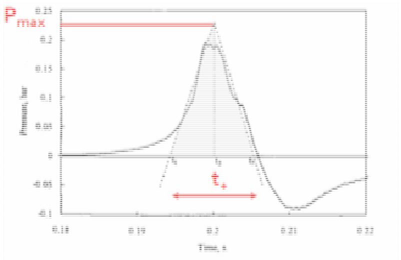


Figure 4. The pressure variation resulting from an explosion, [22]

Results and discussion

The study here developed was conducted in order to identify the most favorable plate type regarding the blast response. The Figure 5 identifies the element sections, which the parameters were analyzed. The displacements in the central node, the factored reaction forces for fixed and pinned plates are given in the Figure 6 and Figure 7, respectively. As the reaction forces are computed in the nodes, the magnitude of these forces depends on the size of the mesh element. For this reason, the value of the reaction force must be factored by the ration of the element size and the length of the support.

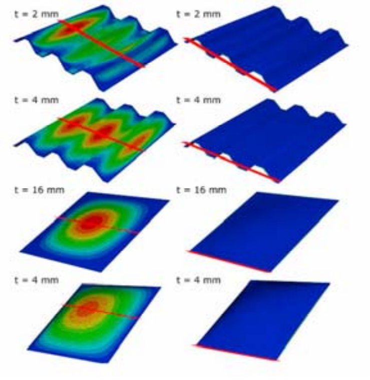


Figure 5. Sections in which the results were analyzed: Displacements (left) and reactions (right) [21]

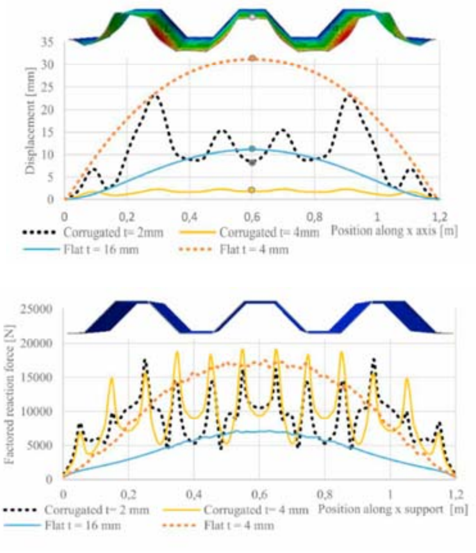


Figure 6. Displacments and factored reaction forces in fxed plates. [21]

The results from the FEM analysis demonstrate it is more economical to use corrugated plates instead of bulkheads if the deflection of the element is the relevant design criterion. In this case, it appears to be more reasonable to allow some flexibility in the edges since the overall response of the plate would be more favourable due to the much higher energy dissipation. On the other hand, even though much heavier, the thick bulkhead seems to perform better if the magnitude of the reaction forces is the primary design criterion. Using this approach, it is possible to trace the plastic deformation of elements in time, distribution of stresses and to measure the energy dissipation for different solutions. This results demonstrate the importance of geometry and boundary conditions, even for the safe design of supporting structure. This research also emphasised the importance of having a precise blast load in order to obtain a more adequate blast resistant wall protection design.

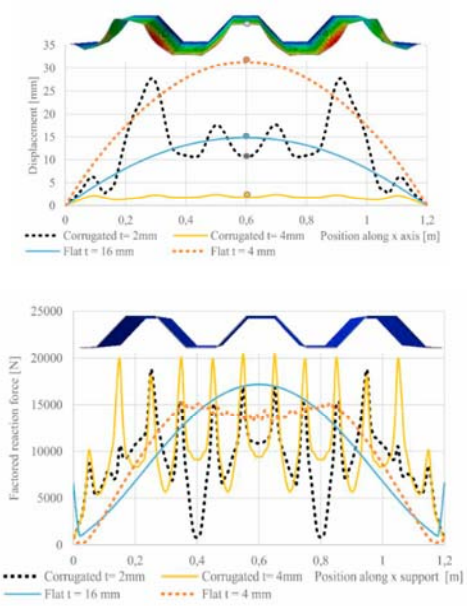


Figure 7. Displacments and factored reaction forces in pinned plates.

3.2. Explosive blasting resistance metal foil using Autodyn simulation

Confined underwater blast wave generators (WBG), consisting of an explosive charge inside of a water tank, generate a wide range of the produced blast impulses and surface area distribution, avoiding the generation of high velocity fragments and reducing atmospheric sound wave, leading to a more precise blast wall design. Air and underwater explosions (UNDEX) are important for design of not only the warships and submarines, but also for offshore platforms and infrastructures for fuel transportation, such as pipelines [25].

The study already developed [18], presents the 2D simulations of WBG, using Ansys Autodyn ©, projecting water against a thin stainless steel plate as a function of water tank size and for different values of stand-off distances. The phenomenological transmission of the shock, through the multi-material domain, is presented and discussed.

The basics of the shock physics necessary for understanding of detonation front formation and propagation as well as the fundamental equations of expansion of detonation products can be found in the literature [26-28]. More information about the material modelling and dynamic simulations in Autodyn are available in [29] and [30]. The following chapters provide basic assumptions for material modelling and dynamic simulations applied in the current study.

Numerical modelling

For the material characterization, in general, is necessary the equation of state, material strength model and material failure model. For the inert materials such as metals and liquids, the equation of state is commonly given by the form of Mie-Gruneisen equation of state combined with experimental shock velocity-particle velocity relation [31]. In the case of products of explosive materials used in this study, Autodyn offers Jones-Wilkins-Lee (JWL) Equation of State (EOS) [30]. Concerning the strength model, the Piecewise JC model available in Autodyn was used [32]. The failure mode of materials defined in this study was erosion criteria.

Before the implementation of the experimental case study a mesh sensitivity (the mesh element size of 0,1 mm was the most promising), computational demand, critical length of explosive, particularities of different discretization methods and overall performance of the model with emphasis on distribution of pressure and velocities through defined domain was done.

Particular cases: results and discussion

This group of simulations is performed to study transmission of the shock through multi-material domain, assess the use of WBG for experimental study of thin plates and to help de-sign appropriate experimental samples.

The models for the assessment of the thin plate's kinetic energy and impulse in y direction (Figure 8) was created with Eulerian solver as explained in [18]. Particular simulation cases have their dimensions varied, where "wg" stands for water gap (representing the height of water above pbx: 7,5, 15 and 30 mm), "sd" represents the stand-off distance (3,75, 7,5 and 15 mm) and "ag" represents the air behind the stainless steel plate. Here is presented three models MP1(wg=7,5 mm; sd=0 mm), MP2 (wg=7,5 mm; sd=3,75 mm), and MP3 (wg=7,5 mm; sd=7,5 mm).

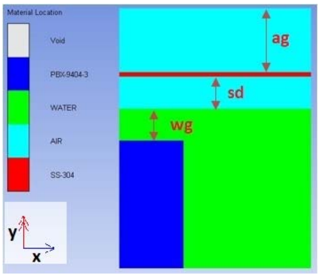


Figure 8. Layout of the particular cases models

The curves of the Figure 9 show that the kinetic energy of the stainless steel thin plate can be controlled by the water gap and stand-off distance. For the constant water gap, the kinetic energy reduces with increase of the stand-off distance. The overlap and the comparison of the thin stainless steel plates position for these three cases (MP1, MP2 and MP3) is shown in the Figure 10. These show that for the constant water gap, the increase of stand-off distance leads to lower movements of the plate.

The expansion of detonation products and the pressure transmission through water and air was observed for models with Lagrangian solver. An example of pressure transmission through these different material zones and expansion of detonation products is shown in the Figure 11 for model MP11(wg=7,5 mm; sd=7,5 mm).

The left image (a) shows the pressure at the end of the PBX 9304-3 material zone, whereas the central (b) and the right (c) image show the pressures at the end of water (wg) and air (sd) zone.

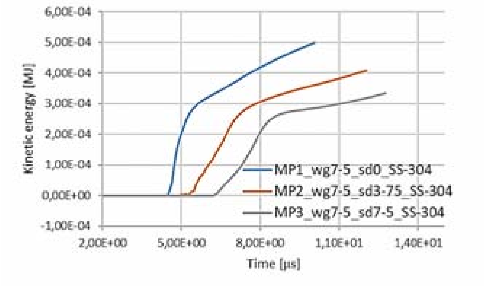


Figure 9. Kinetic energy for models with water gap of 7,5 mm

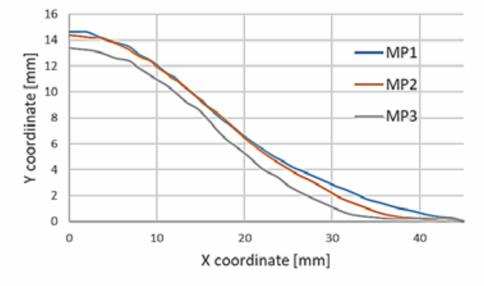


Figure 10. Comparison of the stainless steel position for the case of MP1, MP2 and MP3

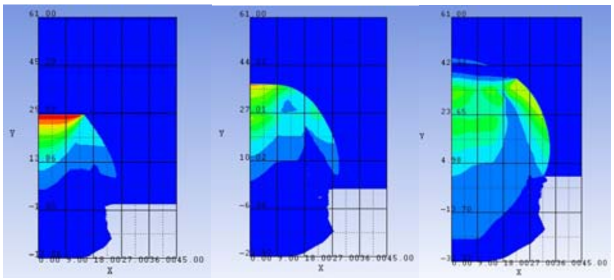


Figure 11. Pressure transmission and expansion of detonation products for the model MP11 (wg=7,5 mm; sd=7,5 mm)

The main conclusions of the work are: 1. WBG can be used effectively for small scale blast test of plates. The kinetic energy of the element can be controlled by the size of the water tank and the stand-off distance; 2. The increase of the water tank size and of the stand-off distance will in both cases lead to a reduction of the kinetic energy and of the impulse in the thin plate; 3. The increase of the stand-off distance will slightly delay the response of the plate and affect the size of the impacted area.

4. FINAL REMARKS AND FUTURE RESEARCH

Due to the research already developed it can be conclude that the design of new kind of lightweight multi-layer sandwich structure with improved mechanical properties and high blast resistance requires an accurate blast information. This demands the validation of model and constants by the correlation, with experimental results, of water blast and stainless steel plate deformation, showing the role of the resistant blast wave wall. The research under development will take the following steps:

1. Definition of JWL parameters (EOS) for emulsion explosive in Autodyn based on theoretical calculations performed by THOR Code;

2. Propose new coefficients in existing empirical equations of Sadovsky and Zamyshlyaev for blast properties of emulsion explosive;

3. Validate the numerical model concerning propagation of the blast wave through the non-reacted emulsion and water domain with experimental results already existent.

4.With the numerical procedure validated for emulsion and water domain the attention will be focused on the experimental response of the plated elements, which include the following configurations: a. Single steel plate; b. Double steel plate; c. Steel sandwich panels with aramid honeycomb core; d. Steel sandwich panels with aluminum foam; e. Sandwich panels with aramid sheets and fabric honeycomb core;

Acknowledgement

This work was supported by the Portuguese Ministry of Science, Technology and Higher Education (Ministério da Ciência, Tecnologia e Ensino Superior) under the individual contract [Grant SFRH/BD/146533/2019]

References

[1] IPCC Special Report on the Ocean and Cryosphere (SROCC), Published 05 Nov 2019 https://www.ipcc.ch/srocc/download-report/

[2] United Nations. Sustainable Development Goals (SDGs) - United Nations. 2015. https://sdgs.un.org/goals.

[3] Schoonees, T., Gijón Mancheño, A., Scheres, B. et al.. Hard Structures for Coastal Protection, Towards Greener Designs. Estuaries and Coasts 42, 1709–1729. 2019. https://doi.org/10.1007/s12237-019-00551-z

[4] Titus Manohar, C.R. Suribabu, G. Murali, M.P. Salaimanimagudam. A novel steel-PAFRC composite fender for bridge pier protection under low velocity vessel impacts, structures, volume 26, 765-777, 2020. https://doi.org/10.1016/j.istruc.2020.05.005

[5] Wei Fana, Wei Guo, Yang Sun, Baisheng Chen, Xudong Shao. Experimental and numerical investigations of a novel steel-UHPFRC composite fender for bridge protection in vessel collisions, Ocean Engineering, volume 165, 1-21. 2018. https://doi.org/10.1016/j.oceaneng.2018.07.028.

[6] AASHTO. Guide specification and commentary for vessel collision design of highway bridges, 2nd ed., 2009. Washington, DC.

[7] Constança Rigueiro, João Ribeiro, Aldina Santiago. Numerical assessment of the behaviour of a fixed offshore platform subjected to ship collision, X International Conference on Structural Dynamics, EURODYN 2017, September 2017, Roma, Italy. Journal Procedia Engineering, No. 199, pp. 2494-2499. https://doi.org/10.1016/j.proeng.2017.09.415

[8] D. Balkan i Z. Mecitoğlu. Nonlinear dynamic behavior of viscoelastic sandwich composite plates under non-uniform blast load: Theory and experiment, International Journal of Impact Engineering, t. 72, pp. 85-104. 2014.

[9] M. Grujicic, B. Pandurangan i B. d'Entremont. The role of adhesive in the ballistic/structural performance of ceramic/polymer–matrix composite hybrid armor, Materials & Design, t. 41, pp. 380-393. 2012.

[10] J. Godzimirski, J. Janiszewski, M. Rośkowicz i Z. Surma. 2015. Ballistic resistance tests of multi-layer protective panels, Eksploatacja i Niezawodnosc - Maintenance and Reliability, t. 17, br. 3, pp. 416-421, 2015.

[11] S. Signetti, F. Bosia, S. Ryu i N. M. Pugno. A combined experimental/numerical study on the scaling of impact strength and toughness in composite laminates for ballistic applications, Composites Part B: Engineering, V. 195, p. 108090. 2020. https://doi.org/10.1016/j.compositesb.2020.108090

[12] Y. Gao, W. Zhang, P. Xu, X. Cai i Z. Fan. Influence of epoxy adhesive layer on impact performance of TiB2-B4C composites armor backed by aluminum plate, International Journal of Impact Engineering, t. 122, pp. 60-72. 2018.

[13] Damjan Čekerevac, Constança Rigueiro, Eduardo Pereira. Characterization of accidental scenarios for offshore structures, Special Issue: Proceedings of Eurosteel 2017, Volume1, Is-sue2-3, 4341-4350. 2017. https://doi.org/10.1002/cepa.493

[14] Tarlochan, F.. Sandwich Structures for Energy Absorption Applications: A Review. Materials, 14, 4731. 2021. https://doi.org/10.3390/ma14164731

[15] Z. Xue and J. W. Hutchinson. A comparative study of impulse-resistant metal sandwich plates, International Journal of Impact Engineering, vol. 30, Issue 10, 1283-1305. 2004. https://doi.org/10.1016/j.ijimpeng.2003.08.007

[16] J. W. Hutchinson and Z. Xue. Metal sandwich plates optimized for pressure impulses, Inter-national Journal of Mechanical Sciences, vol. 47. 2005. https://doi.org/10.1016/j.ijmecsci.2004.10.012

[17] V. Rubino, V. S. Deshpande and N. A. Fleck. The dynamic response of end-clamped sandwich beams with a Y-frame or corrugated core, International Journal of Impact Engineering, vol. 35, 829-844. 2008. https://doi.org/10.1016/j.ijimpeng.2007.10.006

[18] Damjan Čekerevac, Constança Rigueiro, Eduardo Pereira and José Campos. Explosive blasting resistant metal foil using autodyn simulation, XII Congresso de Construção Metálica e Mista, Coimbra, Portugal, 2019.

[19] R. Alberdi, J. Przywara and K. Khandelwal. Performance evaluation of sandwich panel systems for blast mitigation, Engineering Structures, vol. 56. 2013. https://doi.org/10.1016/j.engstruct.2013.08.021

[20] Damjan Čekerevac, Constança Rigueiro, Eduardo Pereira. Measures for Soft Target Protection Inspired in Other Blast Vulnerable Structures, In: Hofreiter L., Berezutskyi V., Figuli L., Zva-ková Z. (eds) Soft Target Protection. NATO Science for Peace and Security Series C: Environmental Security. Springer, Dordrecht. 2020. https://doi.org/10.1007/978-94-024-1755-5_6

[21] Damjan Čekerevac, Constança Rigueiro, Eduardo Pereira. Efficiency of blast walls for primary steelwork protection of soft targets, Transportation Research Procedia, Vol. 40, 16-23. 2019. https://doi.org/10.1016/j.trpro.2019.07.004

[22] Damjan Čekerevac, Constança Rigueiro, Eduardo Pereira. Performance of Structural Blast Mitigation Measure for Oil and Gas Industrial Facilities, Key Engineering Materials 812, 92-99, 2019. https://doi.org/10.4028/www.scientific.net/KEM.812.92

[23] DNV, 2010. DNV-RP-C204: Design against accidental loads, s.l.: Det Norske Veritas.

[24] API, 2006. Recommended Practice for the Design of Offshore Facilities Against Fire and Blast Loading, s.l.: American Petroleum Institute.

[25] Z. Wang, X. Liang, A. S. Fallah, G. Liu, L. A. Louca and L. Wang, "A novel efficient method to evaluate the dynamic response of laminated plates subjected to underwater shock," Journal of Sound and Vibration, vol. 332, no. 21, pp. 5618-5634, 2013.

[26] D. B. Hayes, "Introduction to Stress Wave Phenomena," Sandia Laboratories, Albuquerque, 1976.

[27] Z.-Y. Liu, "Overdriven detonation phenomenon and its applications to ultra-high pressure generation," Kumamoto University, Kumamoto, Japan, 2001.

[28] H. Hamashima, Y. Kato, Y. Nadamitsu and S. Itoh, "Determination of JWL parameters from underwater explosion test for ideal and non-ideal explosives," Science and Technology of Energetic Materials, vol. 64, no. 6, pp. 248-253, 2003.

[29] ANSYS, Autodyn User's Manual, Canonsburg: ANSYS, Inc., 2013.

[30] J. Ambrósio, R. Ferreira, R. Mendes, J. Campos, P. M. S. Santos, B. P. M. Duarte, N. Oliveira, J. Pereira and P. B. Lourenco, "Prediction and Experimental Results of Confined Underwater Blasting Generators," in 44th International Conference of the Fraunhofer ICT, Germany, 2013.

[31] P. Harris and L. Avrami, "Technical report No. 4423: Some Physics of the Gruneisen Parameter," Picatinny Arsenal, Dover, New Jersey, 1972.

[32] E. L. Lee, H. C. Hornig and J. W. Kury, "Adiabatic expansion of high explosive detonation products," Lawrence Radiation Laboratory University of California, Livermore, 1968.

[33] G. Johnson and W. Cook, "A Constitutive Model and Data for Metals Subjected to Large Strains, High Strain Rates, and High Temperatures," in Proceedings 7th International Symposium on Ballistics, Hague, 1983.