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Response investigation for the replacing of solid walls with RC-sand sandwich walls in RC compartment structures and protective barriers subjected to blast loads

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الملخص العربى :

تهدف هذه الورقة البحثية إلى تقديم شكل جديد من الحوائط في المنشآت المقصورة والحواجز الواقية من الخرسانة المسلحة وذلك عن طريق استبدال حوائط الخرسانة المسلحة المصمتة بحوائط شطائرية من الخرسانة المسلحة والرمل، ومن ثم بحث استجابة هذا الشكل الجديد من الحوائط عندما تتعرض هذه المنشآت لأحمال الانفجارات، وأخيراً تقديم مقارنة شاملة بين سلوك النموذج الجديد مع الشكل الأصلي. تستخدم مقصورات الحماية عادةً لحماية بعض المنشآت المحددة من الانفجارات الداخلية ، كما هو الحال في حالة المباني الصناعية التي تحتوي على أجهزة قد تنفجر في ظروف معينة. تستخدم الحواجز الواقية على نطاق واسع لحماية المنشآت المهمة من الانفجارات الخارجية مثل الهجمات الإرهابية. يركز البحث على أداء استخدام التشكيل الشطائري من الخرسانة المسلحة والرمل بدلاً من الخرسانة المسلحة المصمتة. يتم إجراء تحليل ديناميكي صريح باستخدام نماذج عددية معقدة للحاجز أو المقصورة مع الوسط المحيط والمادة المتفجرة. تم تقديم النتائج ومقارنتها لكلا النموذجين. توضح المناقشة والاستنتاج الخاص بالنتائج كيف تتأثر استجابة المنشأ في كل نموذج.

Abstract:

This paper aims at introducing a new form of walls in RC compartment structures and protective barriers by replacing of RC solid walls with RC-sand sandwich walls, investigating the response of this new form of walls when these structures subjected to blast loads and finally presenting a comprehensive comparison between the behaviour of the new form with the original form. The protective compartments are typically used to protect some specific structures from internal explosions, such as in the case of industrial buildings that contain devices that may explode in certain circumstances. The protective barriers are widely used to protect important structures from external explosions such as terrorist attacks. The paper focuses on the performance of using reinforced concrete-sand sandwich formation instead of solid reinforced concrete. Explicit dynamic analysis is

performed using sophisticated numerical models for the barrier or the compartment with the surrounding medium and the explosive material. The results and their comparison are presented for both forms. Discussion and conclusion for the results illustrate how the response of the structure is affected in each form.
Keywords: Blast loads, protective barriers, protective compartment, RC-sand sandwich walls, nonlinear analysis, explicit dynamic analysis.

Introduction

The worldwide is witnessing an increase in the threats of blast loads in the last years. The blast loads are generated form an explosion and it occurs intentionally as in a terrorist attack or accidentally such as in an explosion in industrial facilities resulted from the explosion of a device due to an error or a mistake in the operation. The explosions can be categorized by different ways; one of that categorization depends on location of the explosion with respect to the structure where in each case the response of the structure is different. In case of the explosion is confined by a structure it is called an internal explosion while in case of it occurs outside the structure it is called an external explosion.

(Kristoffersen, Pettersen, Aune, & Børvik, 2018) Discussed experimentally and numerically the response of RC slab subjected to blast load. (Kong, Zhao, Qu, & Zhang, 2018) Investigated the response of RC slabs repaired with CFRP. Many researchers investigated experimentally various configurations of RC slab (Pantelides, Garfield, Richins, Larson, & Blakeley, 2014) (Thiagarajan, Kadambi, Robert, & Johnson, 2015). Also many researchers discussed experimentally and analytically response of ultra-high performance reinforced concrete under the effect of blast load (Aoude, Dagenais, Burrell, & Saatcioglu, 2016) (Mao, et al., 2015).

When the concrete structures subjected to blast load, there is an interesting feature appears which is known as the strain rate effect. The phenomena of strain rate effect occurs due to subjecting to a rapid dynamic load, where the pressure increases rapidly to its peak value in a very short period then decreases to the negative phase also in a short period then vanishes. Rapid changes in material's strain over time due to this kind of dynamic load, consequently the material strength increases in significant values than its normal strength value in the case of quasi static loads and that significant values depend on the strain rate change over time. There are many researchers investigate the phenomena of strain rate effect (Lu & Li, 2011) (Chen, Fang, Jiang, Ruan, & Hong, 2015), and this effect have been taken into consideration in the presented nonlinear material model.

There are many researches discuss response of structures to blast loads where some of researcher focus on study of columns of building and piers of bridge as it is a key element in any structure to prevent the progressive collapse. (Dua, Braimah, & Kumar, 2019) investigates experimental and numerical performance of different aspect ratio of a concrete rectangular column subjected to different explosive charges and calculate experimentally residual axial capacity of damaged specimens. (Zhuang, et al., 2019) experimentally study response of circular RC columns subjected to underwater explosion with respect to some parameters as charge weight, standoff distance, and detonation depth. (Yang, et al., 2019) discuss numerically response of (square and circular) columns subjected to contact and close range explosion in air and underwater into consideration effect of longitudinal, transferal reinforcement, and concrete compression strengthen to increase blast performance of column.

(Momeni, Hadianfard, Bedon, & Baghlani, 2019) discuss behaviour of various steel columns with similar mechanical properties subjected to blast load taking into consideration two different charges weight at different standoff distances, where the evaluation of the study depends on damage, residual axial capacity, and displacement. (Liu, Yan, & Huang, 2018) Investigate experimentally and analytically the response of reinforced concrete beam and columns subjected to blast loads with respect to various charges weight and standoff distance. (Hu, Chen, Fang, & Xiang, 2018) numerically and experimentally study behaviour of concrete column subjected to close range explosion generated from double end initiation explosive cylinder, where the study including effect of charge shape, diameter to length ratio, scaled distance, and detonation point. (Kyei & Braimah, 2017) numerically and experimentally discuss the response of reinforced columns with various transverse reinforcement spacing subjected to far blast loading where the parametric study are including effect of effect of charge weight, standoff distance, and axial load ratio. (Li J. , Wu, Hao, & Liu, 2017) experimentally investigates response of ultrahigh concrete columns subjected to different quantities of explosive charges at same standoff distance where the study focus on residual axial capacity and damage of the columns. (Codina, Ambrosini, & de Borbón, 2016) numerically and experimentally discuss response of concrete members subjected to near field explosion.

Most of researches in the recent years focus on experimentally or numerically performance of concrete filled steel tube columns under contact and close range explosion. (Wang Z. , Wu, Fang, & Wu, 2020) discuss performance of ultra high performance cementitious composite filled steel tube column circular shape subjected to contact explosion of various explosive charges weight where the study depends of calculating experimentally value of residual axial capacity of the damage columns. (Li, et al., 2019) discuss experimentally and numerically response of double steel tube (CFDST) columns circular shape under close range explosion taking into consideration effect of applied axial load on column where the study focus of damage mechanism and energy absorption capacity. (Li, Zong, Liu, & Lou, 2018) study also damage mechanism and energy absorption capacity of (CFDST) bridge column under contact explosion but ignore effect of applied axial load in their research. (Minghong, et al., 2020) experimentally and numerically discuss behaviour of (CFDST) under contact explosion by calculating residual axial capacity of the columns after explosion. The study considered effect of applied axial load and derived an empirical formula to predict the residual axial capacity.

(Zhang, Wu, Zhao, Heidarpour, & Li, Experimental and numerical study of blast resistance of square CFDST columns with steel-fibre reinforced concrete, 2016) Investigate experimentally and numerically mid span deflection of square CFDST columns filled with ultrahigh performance concrete subjected to close range explosion. The previous research also contains a numerical parametric study using a several combination of square and circular columns shape to figure effect of concrete strength, hollow section ratio, inner tube thickness, outer tube thickness, axial load ratio, and cross section geometry. (Zhang, et al., Experimental study of CFDST columns infilled with UHPC under close- range blast loading, 2016) discuss experimentally behaviour of CFDST columns with different shape (square and circular) subjected to close rang explosion, the study discuss effect of column axial load , charge weight, axial load, and hollow section ratio.

Large size of CFST columns had been used by (Wang H. , et al., 2017) to investigate experimentally their blast resistance to close range explosion taken into consideration axial load and experimentally calculates residual axial load capacity of damage specimens. In additional to, the research contains deep parametric study to show effect of charge weight, steel tube thickness, and cross section geometry (square- circular). (Zhang, Wu, Li, & Zhao, 2015) discuss experimentally residual axial capacity of damage specimens of CFDST columns subjected to close range explosion where the columns are filled with ultrahigh performance concrete. The study takes into consideration effect of axial load, charge weight, and hollow section ratio. (Zhang, Wu, Wang, & Zhou, 2015) A deep numerical study had been done to investigate response of different shape of CFST columns (square and circular) subjected to close range explosion, where the study taken into consideration axial load effect and calibrates its result with experimental test. (Ngo, Mohotti, Remennikov, & Uy, 2014) discuss experimentally and numerically response of hollow square concrete filled tube subjected to close range explosion generated from different standoff distance. (Ritchie, Packer, Seica, & Zhao, 2015) shows with experimental test and numerical simulation response of CFST columns with square and circular shape subjected to air blast loading.

(Thai, Pham, & Nguyen, 2019) discuss response of square reinforced concrete column retrofitted by steel jacket plates subjected to different scale distance explosions where the study depends on assessment of damage pattern of the columns after detonation. (Omran & Mollaei, 2017) Compare between several methods to strengthen a square column subjected to close range explosion, where the strengthen methods are used by angles, channels, and plates. (Codina, Ambrosini, & Borbón, 2016) use a steel jacket plate around square concrete column as one of alternative solutions to prevent progressive collapse of concrete structures subjected to close range explosions.

(Yuan, et al., 2019) discuss mechanism of fracture for deep rock which subjected to blast wave generated from two adjacent blast holes exploded with milliseconds delay time between them. (Lu, Li, & Zhou, 2014) Investigated behaviour of concrete dam subjected to under water explosion where the study aims to improve hammer impact methods of the model tests.

The metamaterial is a new research field which aims to develop structures have new properties and unique features to improve its behaviour to resist blast loads (El Sherbiny & Placidi, 2018). Metaconcrete is the new material which is developed to mitigate the effect of the blast on the structure (Kettenbeil & Ravichandran, 2018) (Briccola, Ortiz, & Pandolfi, 2016).

This research aims at investigating the performance of using reinforced concrete-sand sandwich formation instead of solid reinforced concrete wall. A calibrated and sophisticated FE numerical model is introduced in section 2, which also contains the used material properties, geometry, and the dimensions of the model besides a model verification and parameters calibration. The commercial program software is used in this research is Autodyn (Ansys, 2020). In Section 3 and 4, the response of the new proposed form of the compartment and the barrier, respectively, and a comparison with the original form consisting of RC sand sandwich model instead of the solid RC model is introduced. Finally, section 6 contains overall results, conclusions and recommendations for future works.

This research aims at investigating the performance of the new form of walls, using reinforced concrete-sand sandwich formation instead of solid reinforced concrete. To achieve this goal, a calibrated and sophisticated FE numerical model is introduced in section 2, the proposed material properties, geometry, and the dimensions of the model besides a model verification and parameters calibration are also presented in section 2. Autodyn (Ansys, 2020) software commercial program is used to carry out the analysis. In Section 3 and 4, response of a new proposed form of the model compartment and barrier respectively consisting of RC sand sandwich model instead of the solid RC model is investigated. Finally, conclusions and recommendations for future works are presented in section 6.

Analytical technique and numerical model

The proposed model and analytical technique

There are two cases study in that research, the first one is a reinforced concrete compartment subjected to an internal blast wave, generated from accidental explosion of a device in an industrial facility. While the second case study is a reinforced concrete barrier subjected to blast load caused by an external explosion resulted from a terrorist attack. The model consists of the reinforced structure, the surrounding medium and the explosive material. An explicit dynamic analysis with full interaction between all parts is used in the analytical models. Autodyn software is used to carry out the analysis.

Four materials have been used in the proposed models. The materials are concrete, steel, air and explosive material TNT where each one has its constitutive material model. Every model requires some input parameters to simulate the real behaviour of the presented material. The numerical models used in this research have been verified in previous work carried out by M G El Sherbiny in his PhD thesis, (El Sherbiny, 2012). In additional to that, the material input parameters have been addressed in Autodyn (Ansys, 2020) program help and manual. The calibrated parameters of the material models are presented from Table 13 to

Table **16**, which have been calibrated before in (El Sherbiny, 2012) and will be verified in the next subsection 2.2.

RHT concrete model is used in the analysis to represent the material nonlinearity, which takes into account the strain rate effect. Table 13 presents the properties of RHT concrete model. The properties of steel reinforcement liner model is used and are shown in Table 14.

Table **15** shows the input parameters of material model used to present the surrounding medium of the structure which is the Air. Finally,

Table **16** shows the properties of the material model used to present the explosive material TNT.

Table 13: Nonlinear properties of concrete model

Parameter	Value
Equation of state	**P alpha**
Bulk Modulus A1	35.27 (GPa)
Reference density	2.75 (t/m^3)
Strength model	**RHT Concrete**
Shear Modulus	16.7 (GPa)
Compressive Strength	35 (MPa)
Failure	**RHT Concrete**
Damage Constant, D1	0.040 (none)
Damage Constant, D2	1.00 (none)
Erosion	**Failure**

Table 14: Properties of steel reinforcement model

Parameter	Value
Equation of State	Linear
Reference density	7.83 (g/cm^3)
Bulk Modulus	159 (GPa)
Strength	Elastic
Shear Modulus	77.74 (GPa)
Failure	None
Erosion	None

Table 15: Air properties

Parameter	Value
Equation of state	**Ideal gas**
Gamma	1.40 (none)
ReferenceTemperature	288.20 (K)
Specific Heat	717.60 (J/KgK)
Strength	None
Failure	None
Erosion	None

Table 16: Explosive material (TNT) properties

Parameter	Value
Equation of state	**JWL**
Reference density	1.63 (g/cm^3)
Parameter A	373.8 (GPa)
Parameter B	3.74 (GPa)
Parameter R1	4.15 (none)
Parameter R2	0.90 (none)
Parameter W	0.35 (none)
Strength	None
Failure	None
Erosion	None

Generally, any model consists of two main parts. The first one is Lagrange part which is used to represent the structure's part. While the second one is Euler part and it used to represent the air and TNT where TNT is located in air. When the TNT detonates the analysis starts, the blast generates a pressure wave travels through the air until it reaches the structure. The interaction between the blast wave and the structure generates internal forces, stresses, and deformations in the structure. The time of the analysis is 100 ms which starts from the detonation start instant.

The first case study is the compartment structure which is a fortified room. The dimensions of the compartment are (2.6×3.6×6.0m) (width, tall, and height respectively). The compartment consists of walls and base but there is no roof ceiling. The thickness of walls and base is 40 cm and the wall reinforcement is 5Φ16/ m vertical and 5Φ12/ m horizontal each side, while the base reinforcement is mesh 5Φ16/ m top & bottom. A cube mesh is used in RC elements, air, and TNT where size of RC mesh is 50mm, while size for air and TNT is 100mm. There are four supports at the corners of the compartment. Figure 24-a shows geometry and supports of the compartment and Figure 24-b shows the whole analytical model which includes the compartment (concrete and steel reinforcement), air and TNT. Finally, Figure 25 shows the details of steel reinforcement of the compartment.

The second case study is a reinforced concrete barrier. The barrier model is 5m width, 6 m height and 40 cm thickness, the barrier reinforcement is 5Φ16/ m vertical and 5Φ12/ m horizontal each side. The barrier is modeled as a cantilever wall fixed at its bottom. A cube mesh is used in RC elements, air, and TNT where size of RC mesh is 50mm, while size for air and TNT is 100mm. The whole model representing the geometry of the barrier and TNT are shown in Figure 26.

(a) (b)

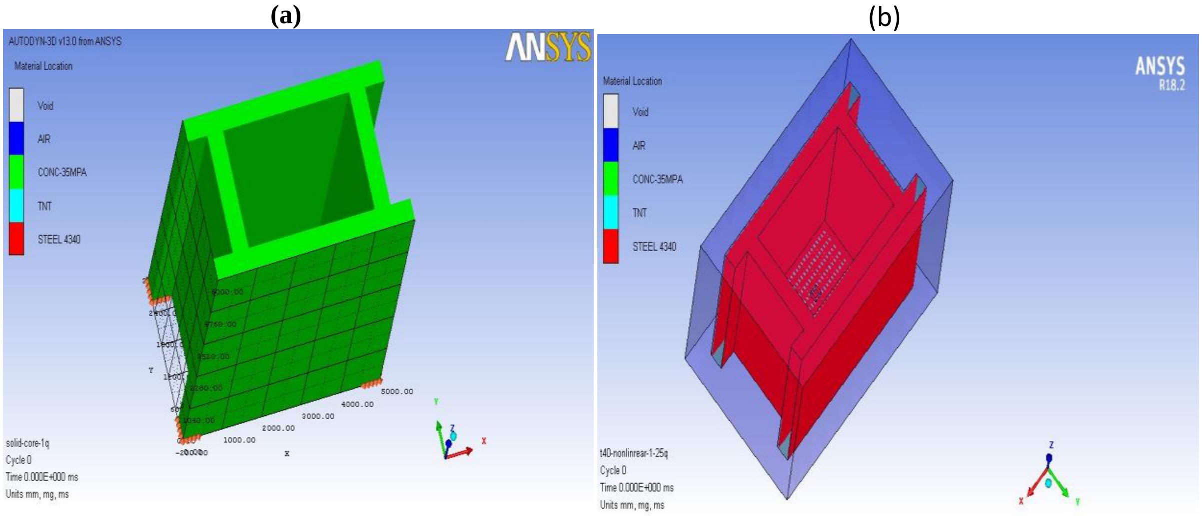

Figure 24: (a) Compartment's geometry, (b) The F. E. model for concrete, steel reinforcement, air and TNT

(a) (b)

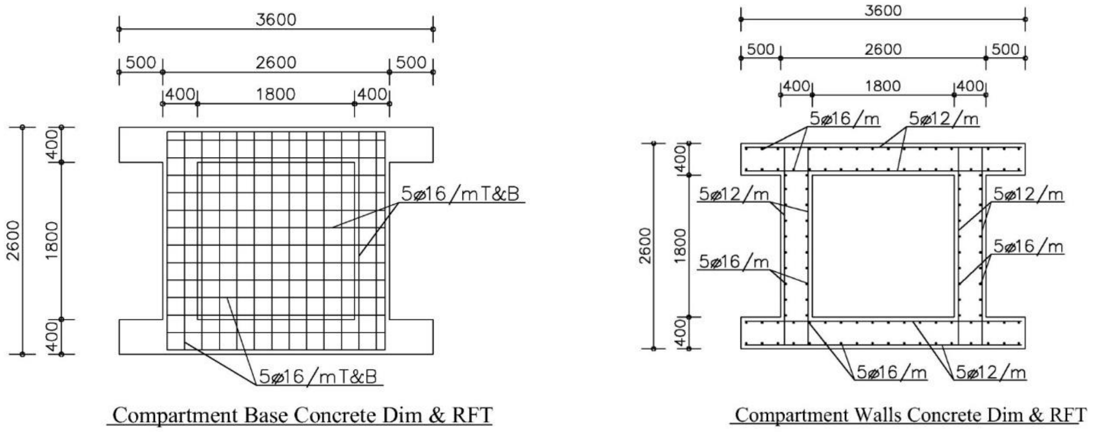

Figure 25: Reinforcement in the compartment's (a) base and (b) wall.

(a) (b)

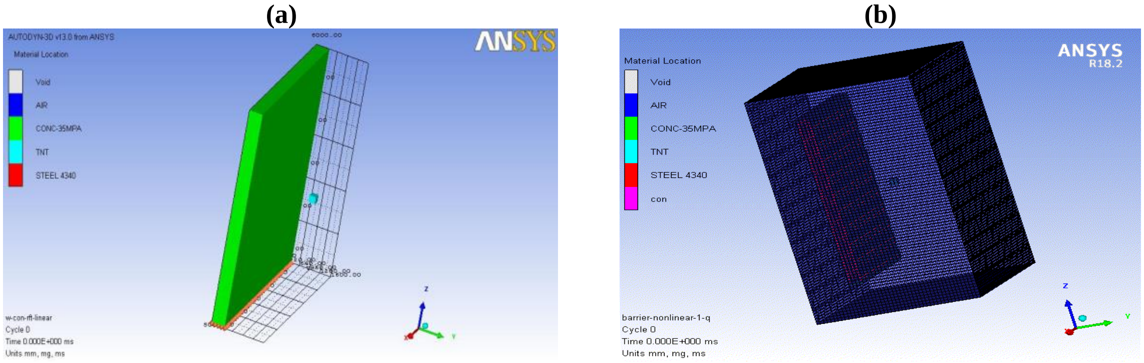

Figure 26: (a) The barrier's geometry, (b) The F. E. model for concrete, steel rebar, TNT and Air

Model verification and calibration of parameters

(Li, Wu, & Hao, 2020) Discuss experimentally behaviour of normal strength concrete slab under blast wave generated from contact 1kg TNT charge. The test specimen slab dimensions are (200,100, and 10cm) (long, width, and thickness respectively) as shown in Figure 27. There are two reinforcement mesh for upper and lower, where diameter of bar used in mesh 12mm and spacing at longitudinal and transversal directions 100, 200 mm respectively. The specimen slab is simply supported at its transversal edges and slab has compression strength 39.5 MPa. Figure 28 shows the real damage shape of upper and lower surfaces of the slab specimen after exploding the TNT charge. Slab concrete spall is one of the explosion results, where average diameter of spall is 390 mm as shown in Figure 28.

By using Autodyn software, a numerical FE model is simulated to calibrate the model. All the technique and the material parameters presented in the previous sub section 2.1 are used in this FE model. Strength of the concrete is 39.5 MPa instead of 35 MPa to match with specimen slab concrete strength. Solid elements are used to represent slab with concrete nonlinear material properties, while beam elements are used to represent steel reinforcement with linear steel material properties. Both of concrete and reinforcement elements are contacted and they present the Lagrange part in the model as shown in Figure

29. Euler solid elements are used to represent the explosive charge (TNT) and the air, which extends around the slab from all directions. An enough space is made to allow the interaction between the Lagrange parts and the Euler parts, which have fully coupled interaction.

The evolution of model after detonation is depends on damage pattern and the deformation of the slab. The detonation generates spall of slab concrete and the dimension of the spall part about 370 mm as shown in Figure 30. The damage pattern of the top and the bottom faces of the slab are shown in Figure 31.

By comparing the both results of the experiment test and the Autodyn model simulation, it is found that there is very good agreement, where the results of damages pattern and dimension of the concrete spall are very close. Therefore, the pervious analytical technique and parameter values have accepted degree of confidence and can be used to discuss the behaviour of such structures subjected to blast loading.

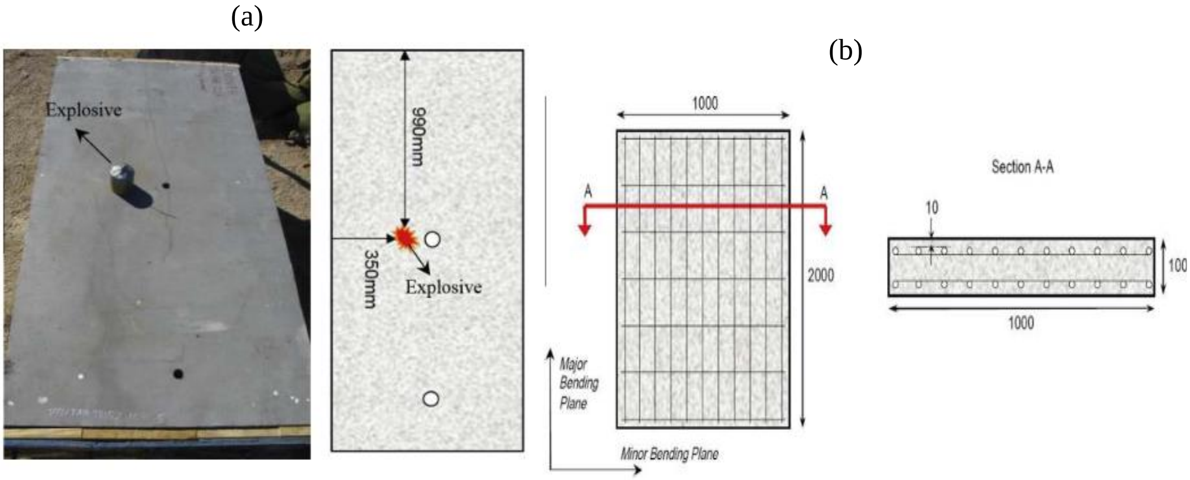

Figure 27: (a) Slab subjected to contact explosion and (b) slab geometry and reinforcement *(Li, Wu, & Hao, 2020)*

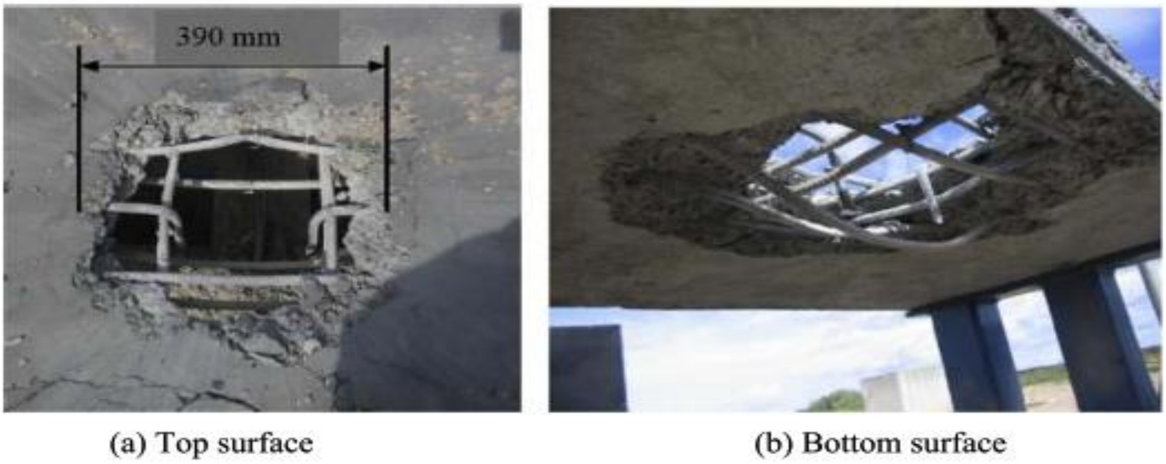

Figure 28: (a) Top and (b) bottom face of the slab after explosion *(Li, Wu, & Hao, 2020)*

(a)

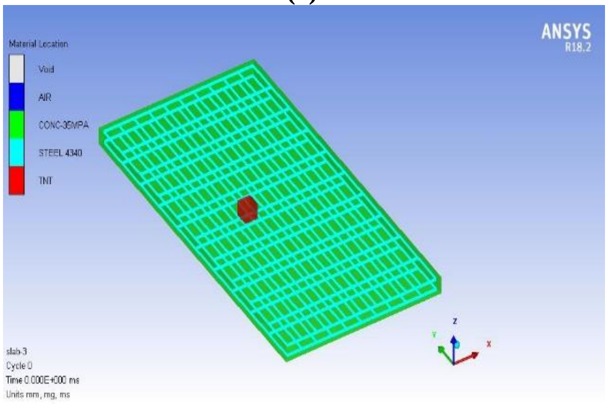

Figure 29: F. E. model of the tested slab

(b)

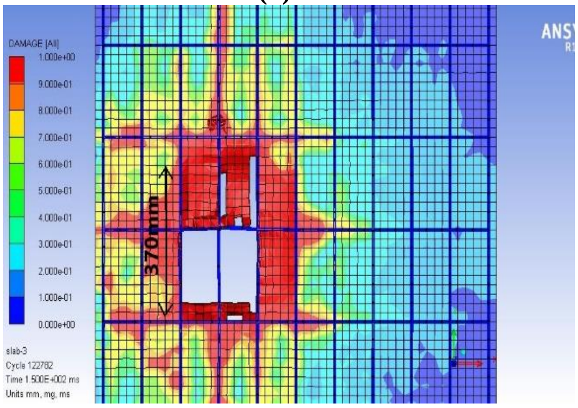

Figure 30: Concrete spall at the top face of the F. E. model after the explosion

(a) (b)

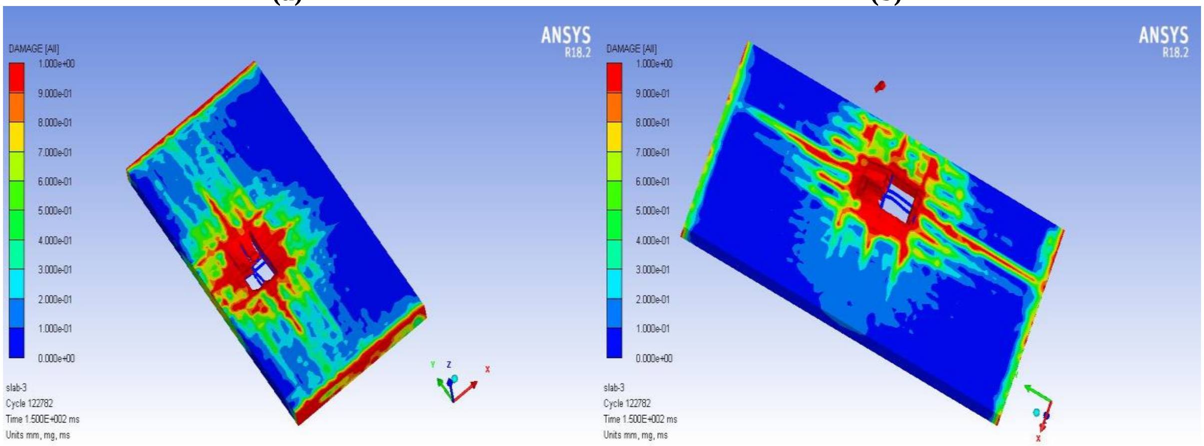

Figure 31: (a) Top and (b) bottom damage face of the numerical model after the explosion

The compartment model

The behaviour of a new form of the wall and base instead of the solid RC is investigated in this section. New model based on the original model dimensions presented in section 2 is created by replacing the solid concrete wall and base with a multilayer consists of 15 cm RC concrete layer followed by 10 cm sand layer followed by 15 cm RC concrete layer with a total thickness of 40 cm similar to the thickness of the original model. The two RC walls are connected together by RC ribs every 100 cm as shown in Figure 32. The model is subjected to the explosion of a medium explosive charge equals 13 Kg of TNT, located at the center of the compartment at height 1.5 m above the base. The damage index for the concrete sand model and solid concrete model are illustrated in Figure 33 and Figure 34 respectively.

It can be seen in Figure 33 that the damage index reached 1 in some locations and some areas started to erode, after about 6 ms since the detonation started, which means that the model had been failed in these areas. This model showed weakness in resisting the blast load especially at the edges.

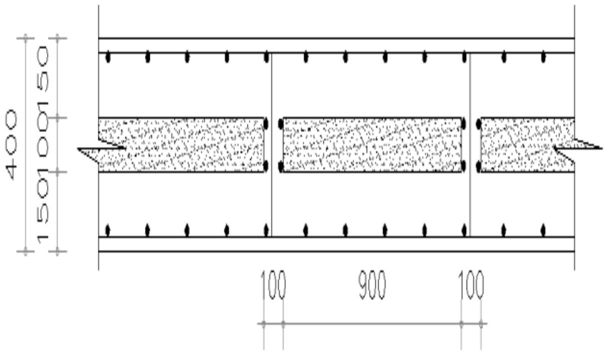

Figure 32: Cross section of the concrete sand sandwich model

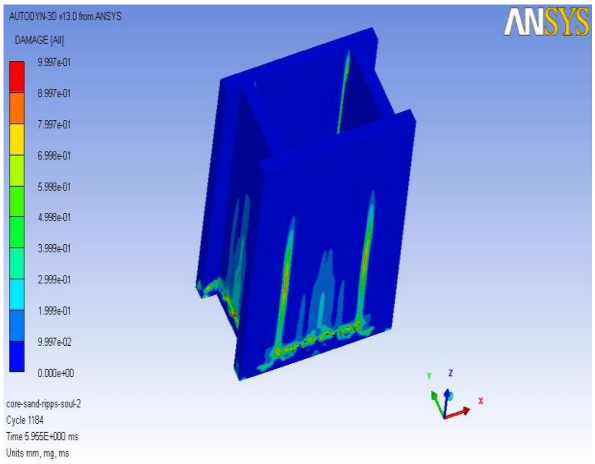

Figure 33: The damage index for concrete sand sandwich model

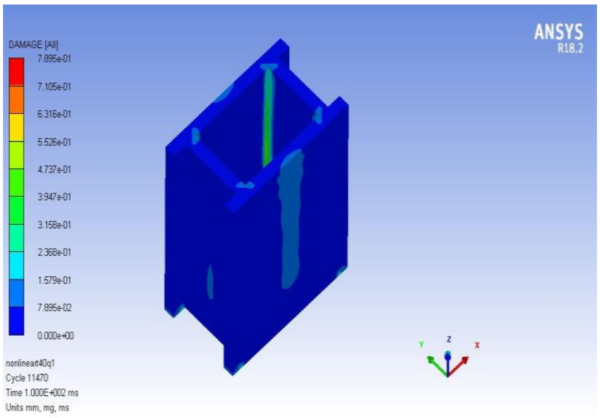

Figure 34: The damage index for solid concrete model

The barrier model

A new form of the barrier has been developed and investigated in this section. The new model is a multilayer flat barrier model consists of 15 cm RC concrete layer followed by 10 cm sand layer followed by 15 cm RC concrete layer with a total thickness of 40 cm, which is the same thickness of the solid RC flat barrier model presented in section 2. Three proposed models of this form have been developed, the first one is as explained earlier with no connections between the RC layers, the second one is connecting the two RC walls together by RC ribs every 100 cm and the third is connecting the two RC walls together by RC ribs every 50 cm as shown in Figure 35. All models are subjected to the explosion of a medium explosive charge equals 13 Kg of TNT, and is located at a stand-off distance equals 1.5 m in front of the center face of the barrier. The output of the selected results are presented in the following figures.

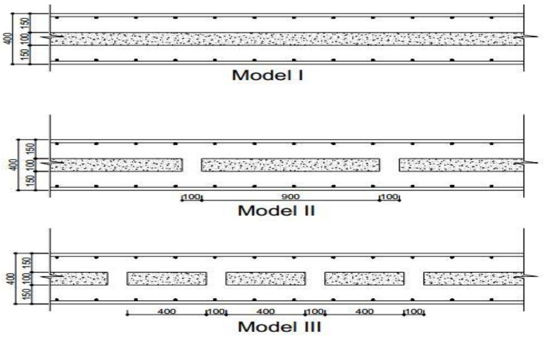

Figure 35: Cross section of the sandwich barrier models.

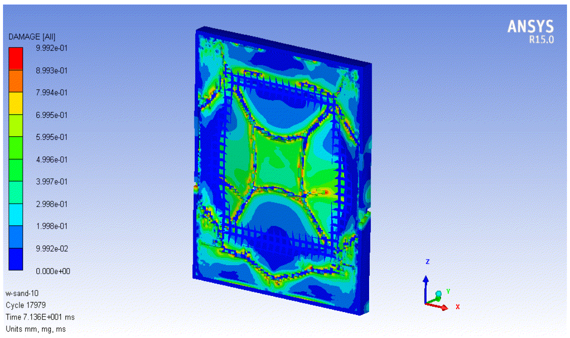

Figure 36: The front face of damage index of sandwich barrier model I due to 13 kg.

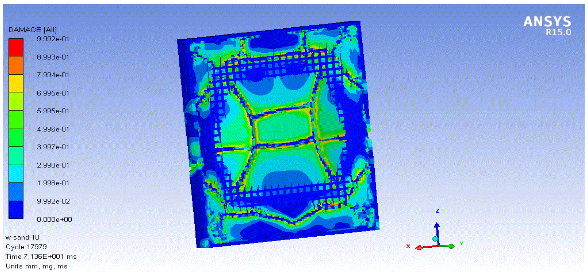

Figure 37: The back face of damage index of sandwich barrier model I due to 13.

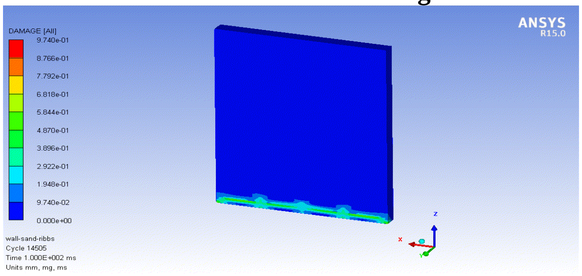

Figure 38: The front face of damage index of sandwich barrier model II due to 13 kg.

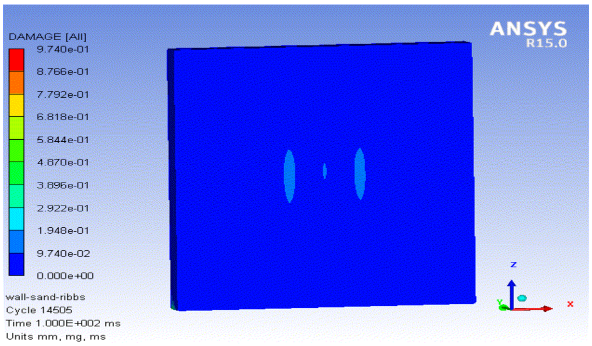

Figure 39: The back face of damage index of sandwich barrier model II due to 13 kg.

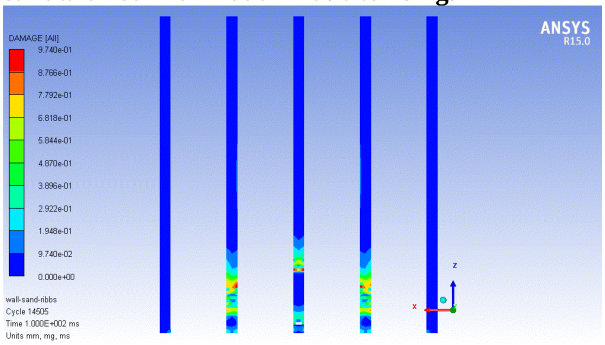

Figure 40: The front face of damage index of internal ribs of sandwich barrier model II due to 13 kg.

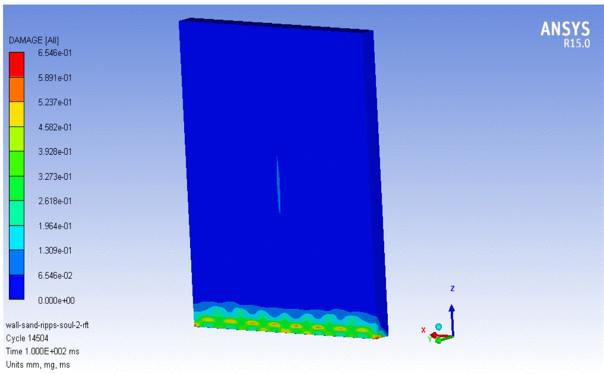

Figure 41: The front face of damage index of sandwich barrier model III due to 13 kg.

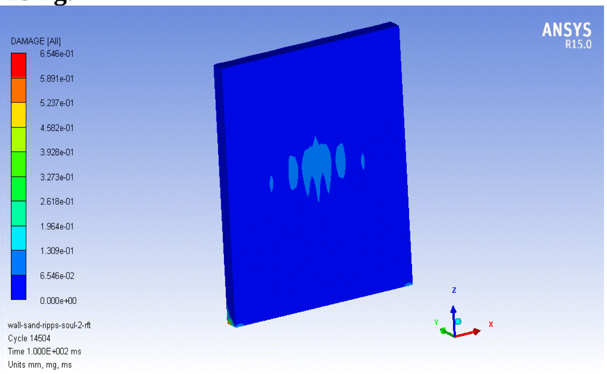

Figure 42: The back face of damage index of sandwich barrier model III due to 13 kg.

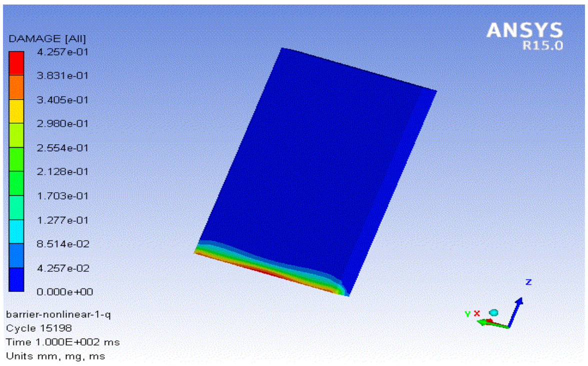

Figure 43: The front face of damage index of original model due to 13 kg located.

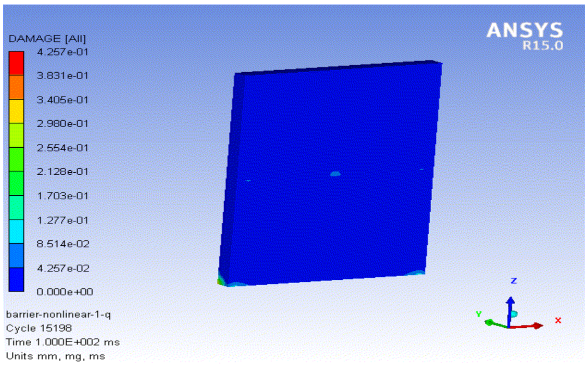

Figure 44: The back face of damage index of original model due to 13 kg.

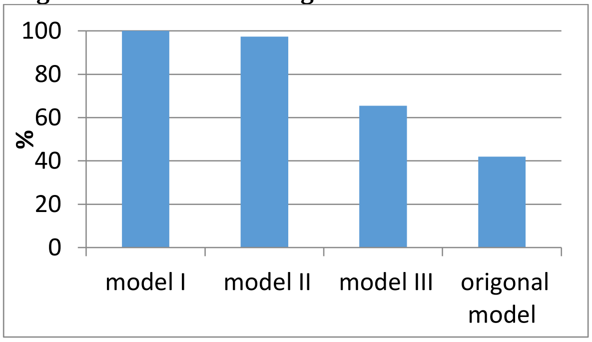

Figure 45: Comparison of damage index for models (I, II, III, original model) due to an explosive charge 13 kg TNT which is located at 1.50m standoff distance from center of the barrier.

By investigating figures from Figure 36 to Figure 45, the following notes are remarked:

Model I shows obvious weakness in resisting the blast load. The damage index of the model reached about 100%, and many elements had been eroded and the whole model failed to resist this load. The model showed total damage in both RC walls. This can be explained that each RC wall resists the load separately without any rigid interaction between them, as the sand layer can transfer compression forces only between the walls, and consequently the model's strength had been degraded too much than the original model.

Model II shows a little bit better performance than model I. The damage index for model II reached about 97%. This indicates that the ribs between the RC walls enhanced slightly the performance of the model. A remarkable observation is that the maximum damage index occurs at the lower part of the middle ribs, and the damage index at the walls is remarkably lower than the maximum value at the ribs.

Model III shows significant improvement and much better performance than model I & II. The damage index for model III is about 65%. That means when the ribs become closer, the performance have been improved.

The original model shows the best performance in the proposed models. It has damage index about 43%.

Model II & III is more economic than the original model regarding the material's cost.

For model II and model III, the damage is concentrated in the lower part of the front face of the barrier, while the rest of the front face is almost free of damage, also the back face is almost free of damage, very small value of the damage index have been reported in the center of both walls.
The previous observation leads to a great improvement for the performance of model II & III, this improvement can be achieved by altering the lower part of the model by completely solid RC part, this alteration can be made for about 50 cm, where this region has stress concentration and maximum damage.

Conclusions

This research introduced a new form of walls by the replacing of solid walls with RC-sand sandwich walls in RC compartment structures and protective barriers. The behaviour and response of this new form have been investigated under the effect of blast loads and remarkable conclusions have been concluded.
The use of RC-sand sandwich compartment walls instead of solid ones showed weakness in resisting the blast load especially at the edges.
The RC-sand sandwich barrier wall has been shown to offer a great improvement in the barrier performance and regarding to its cost, when altering the lower part of the model by completely solid RC part, this alteration can be made for about 50 cm, where this region has the most stress concentration and maximum damage.
It is suggested for future research to looking for new forms for the walls, new materials and investigating the use of metamaterials with new features to improve the behaviour of the protective barriers and compartments under the effect of blast loads.
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References:

Ansys. (2020). Ansys Help. Autodyn User's Manual . Ansys.

Aoude, H., Dagenais, F., Burrell, R., & Saatcioglu, M. (2016). Behaviour of ultra high performance fibre reinforced concrete columns subjected to blast loading. Engineering Structures, 118, 97-107.

Briccola, D., Ortiz, M., & Pandolfi, A. (2016). Experimental Validation of Metaconcrete Blast Mitigation Properties. Journal of Applied Mechanics, 84.

Chen, L., Fang, Q., Jiang, X., Ruan, Z., & Hong, J. (2015, December). Combined effects of high temperature and high strain rate on normal weight concrete. International Journal of Impact Engineering, 86, 40-56.

Codina, R., Ambrosini, D., & Borbón, F. (2016). Alternative to prevent the failure of RC members under close in blast loading. Engineering failure analysis, 60, 96-106.

Codina, R., Ambrosini, D., & de Borbón, F. (2016). Experimental and numerical study of a RC member under a close- in blast loading. Engineering Structures, 127, 145-158.

Dua, A., Braimah, A., & Kumar, M. (2019). Experimental and numerical investigation of rectangular reinforced concrete columns under contact explosion effects. Engineering Structures, 205.

El Sherbiny, M. G. (2012). Response of buildings to blast loads. PhD Thesis. Cairo, Egypt: Ain Shams University, Faculty of Engineering, Structural Department.

El Sherbiny, M. G., & Placidi, L. (2018, October). Discrete and continuous aspects of some metamaterial elastic structures with band gaps. Arch Appl Mech, 88(10), 1725-1742. doi:https://doi.org/10.1007/s00419-018-1399-1

Hu, Y., Chen, L., Fang, Q., & Xiang, H. (2018). Blast loading of the RC column under close-in explosion induced by the double-end-initiation explosive cylinder. Engineering Structures, 175, 304-321.

Kettenbeil, C., & Ravichandran, G. (2018). Experimental investigation of the dynamic behavior of metaconcrete. International Journal of Impact Engineering, 111, 199-207.

Kong, X., Zhao, Q., Qu, Y., & Zhang, W. (2018). Blast Response of Cracked Reinforced Concrete Slabs Repaired with CFRP Composite Patch. KSCE Journal of Civil Engineering, 22, 1214-1224.

Kristoffersen, M., Pettersen, J., Aune, V., & Børvik, T. (2018). Experimental and numerical studies on the structural response of normal strength concrete slabs subjected to blast loading. Engineering Structures, 174, 242-255.

Kyei, C., & Braimah, A. (2017). Effects of transverse reinforcement spacing on the response of reinforced concrete columns subjected to blast loading. Engineering Structures, 142, 148-164.

Li, J., Wu, C., & Hao, H. (2020). Investigation of ultra – high performance concrete slab and normal strength concrete slab under contact explosion. Journal of Engineering structures, 102, 395 – 408.

Li, J., Wu, C., Hao, H., & Liu, Z. (2017). Post – blast capacity of ultra-high performance concrete columns. Engineering Structures, 134, 289-302.

Li, M., Zong, Z., Hao, H., Zhang, X., Lin, J., & Xie, G. (2019). Experimental and numerical study on the behavior of CFDST columns subjected to close-in blast loading. Engineering Structures, 185, 203-220.

Li, M., Zong, Z., Liu, L., & Lou, F. (2018). Experimental and numerical study on damage mechanism of CFDST bridge columns subjected to contact explosion. Engineering Structures, 159, 265-276.

Liu, Y., Yan, J.-b., & Huang, F.-l. (2018). Behavior of reinforced concrete beams and columns subjected to blast loading. Defence Technology, 14, 550-559.

Lu, L., Li, X., & Zhou, J. (2014). Study of damage to a high concrete dam subjected to underwater shock waves. Earthquake Engineering and Engineering Vibration, 13, 337–346.

Lu, Y., & Li, Q. (2011, April). About the dynamic uniaxial tensile strength of concrete-like materials. International Journal of Impact Engineering, 38(4), 171-180.

Mao, L., Barnett, S., Tyas, A., Warren, J., Schleyer, G., & Zaini, S. (2015). Response of small scale ultra high performance fibre reinforced concrete slabs to blast loading. Construction and Building Materials, 93, 822-830.

Minghong, L., Zong, Z., Hao, H., Zhang, X., Lin, J., & Yuchen, L. (2020). Post- blast performance and residual capacity of CFDST columns subjected to contact explosions. Journal of Constructional Steel Research, 167.

Momeni, M., Hadianfard, M., Bedon, C., & Baghlani, A. (2019). Numerical damage evaluation assessment of blast loaded steel columns with similar section properties. Structures, 20, 189-203.

Ngo, T., Mohotti, D., Remennikov, A., & Uy, B. (2014). Numerical simulation of response of tubular steel beams to close-range explosions. Journal of Constructional Steel Research, 105, 151-163.

Omran, M., & Mollaei, S. (2017). Investigation of Axial Strengthened Reinforced Concrete Columns under Lateral Blast Loading. Shock and vibration, 2017, 1-18.

Pantelides, C., Garfield, T., Richins, W., Larson, T., & Blakeley, J. (2014). Reinforced concrete and fiber reinforced concrete panels subjected to blast detonations and post-blast static tests. Engineering Structures, 76, 24-33.

Ritchie, C., Packer, J., Seica, M., & Zhao, X. (2015). Behaviour and analysis of concrete-filled rectangular hollow sections subject to blast loading. Construction and Building Materials, 147, 340-359.

Thai, D.-K., Pham, T.-H., & Nguyen, D.-L. (2019). Damage assessment of reinforced concrete columns retrofitted by steel jacket under blast loading. Struct Design Tall Spec Build, 29. doi:10.1002

Thiagarajan, G., Kadambi, A., Robert, S., & Johnson, C. (2015). Experimental and finite element analysis of doubly reinforced concrete slabs subjected to blast loads. International Journal of Impact Engineering, 75, 162-173.

Wang, H., Wu, C., Zhang, F., Fang, Q., Xiang, H., Li, P., . . . Li, J. (2017). Experimental study of large – sized concrete filled steel tube columns under blast load. Construction and Building Materials, 134, 131-141.

Wang, Z., Wu, H., Fang, Q., & Wu, J. (2020). Experimental study on the residual axial capacity of ultra high performance cementitious composite filled steel tube (UHPCC-FST) column under contact explosion. Thin- Walled Structures, 153.

Yang, G., Wang, G., Lu, W., Zhao, X., Yan, P., & Chen, M. (2019). Cross section shape effects on anti-knock performance of RC columns subjected to air and underwater explosions. Ocean Engineering, 181, 252-266.

Yuan, W., Liu, S., Wang, W., Su, X., Li, Z., Li, J., . . . Sun, X. (2019). Numerical study on the fracturing mechanism of shock wave interactions between two adjacent blast holes in deep rock blasting. Earthquake Engineering and Engineering Vibration, 18, 735–746.

Zhang, F., Wu, C., Li, Z.-X., & Zhao, X.-L. (2015). Residual axial capacity of CFDST columns infilled with UHPFRC after close- range blast loading. Thin- Walled Structures, 96, 314-327.

Zhang, F., Wu, C., Wang, H., & Zhou, Y. (2015). Numerical simulation of concrete filled steel tube columns against blast loads. Thin- Walled Structures, 92.

Zhang, F., Wu, C., Zhao, X.-L., Heidarpour, A., & Li, Z. (2016). Experimental and numerical study of blast resistance of square CFDST columns with steel-fibre reinforced concrete. Engineering Structures, 149, 50-63.

Zhang, F., Wu, C., Zhao, X.-L., Xiang, H., Li, Z.-X., Fang, Q., . . . Packer, J. (2016). Experimental study of CFDST columns infilled with UHPC under close- range blast loading. International Journal of Impact Engineering, 93, 184-195.

Zhuang, T., Wang, M., Wu, J., Yang, C., Zhang, T., & Gao, C. (2019). Experimental investigation on dynamic response and damage models of circular RC columns subjected to underwater explosions. Defence Technology, 16, 856-875.