TECHNICAL PAPER
NOVEMBER 2023

BLAST RESISTANT BUILDINGS: CONCRETE OR STEEL?

Written by:
Authors: Alkiviadis John Papadopoulos, MSc, CEng MICE, PMP
Berend Groeneveld, MSc, InterDam, Netherlands

Excel editor: Dinara Tlesheva

Abstract

This paper presents a useful design decision table, including project parameters to assist engineers in decision making at the early stage of the design of land-based blast resistant buildings.
Examples are given in which a series of criteria such as CO2 footprint, installation cost and schedule, performance and other design criteria are discussed.
The case study comparison between steel sandwich panels, corrugated welded steel panels, precast concrete and in-situ casted concrete with incremental blast loads indicate that prefabrication (namely sandwich panels, and precast) has advantages as it minimises onsite labour.

Considering the graphs and the comparison analysis regarding the four blast wall types it can be concluded that:

1. The blast wall comparison table can be a useful tool in FEED phase to take a holistic approach to the basic design of a blast resistant building and include multiple factors in the decision-making part of the design process. It is noted that the weight factors should be applied based on project specific requirements.

2. The CO2 footprint reduction requirements of the design of blast buildings triggers the necessity to look for optimized designs as traditionally higher blast requirements were met with adding mass to a structure.

3. For lower blast rates (op to approximately 0,5 bar overpressure) the case study confirms a bolted sandwich panel is an economically viable option, 33% lower cost in case study at 0,15 bar overpressure, compared to in situ casted concrete.

4. For blast rates over 0,5 bar, pre casted and in situ casted concrete becomes more economically viable than a bolted sandwich panel solution. At 1,0 bar overpressure, 16% lower cost is achieved with precast concrete, compared to steel sandwich panels in the case study.

Key words

blast-resistant buildings, explosion resistance, CO2 footprint, carbon footprint, design procedures, sandwich panels, cost and time efficiency, economic modularisation, precast concrete, in-situ concrete, built-up panels, reduction, absorption, plastic deformation, onshore, offshore, steel, sandwich, concrete, cost, saving, CAPEX.

1. Introduction

Recent developments in the design and testing of blast resistant buildings provide a means to further optimize the design, based on project specific circumstances. Traditionally blast resistant buildings are built either in situ with cast concrete or as a welded corrugated steel box. Nowadays precast concrete elements are used for erecting blast buildings as well as a bolted steel structure complete with prefabricated sandwich panels.

This paper presents a case study of a larger building where these four different building types are compared to each other. Basic knowledge of all four types is assumed. Information on the latest, sandwich panel type, can be found in the EN-14509 [1] and the Databook InterDam-Walls G21 Fire- and Blast Rated [2].
Smaller buildings that can be prefabricated and transported in one piece are not taken into consideration in this paper.

1.1 Concrete walls to resist blast.

In onshore, land based, energy projects where design of blast resistant facilities is required to protect people and/or assets, the traditional method is to use reinforced concrete elements working as diaphragms with sufficient reinforcement steel. Usually, reinforced shear walls are used and foundations are stripped together. Concrete works well under compression and structures tend to be designed as a box or a shell. The design performs well but all work is site-erected, stick-built with significant detailing and predesign for wall penetrations and the labour work at site is intense. In cases where construction is within an existing production facility and/or hazardous gases pose a threat, it is preferable to limit labour hours.

1.2 Steel stiff walls/corrugated sheets.

In the offshore, marine based, sector platforms fabricated in yards with steel is the primary method. Steel panels have traditionally been used, installed at yards and shipped all together as a prefabricated package. Traditionally welded corrugated sheets with insulation installed on the inside are used. Significant man-hours are spent welding the panels in the yard. Penetrations need to be cut prior to coating and erection which becomes the critical path for the completion of the architectural scope of the project.

1.3 Optimizing Building design/take slack out.

As in all areas of engineering both steel and concrete design approaches to blast look for optimisations to meet blast criteria to the ductility limits set. Fully understanding design and performance requirements of the facilities is crucial if the design is to be optimized.

Performance requirements are usually set by the client depending on how much facility damage the client is willing to accept. Damage levels are translated into ductility limits from historical tests and that forms the basis of the design acceptance.
The ASCE describes some ductility limits in relation to performance response criteria requirements. [3]

One would wonder why you would choose medium response or high response for a facility. This general classification refers to a complete structure, but if structure and external walls are viewed separately, further optimisations are possible. The walls can be designed to medium or even higher response while the structural frame remains in the low response level, keeping people and assets out of danger. If the capital cost for replacing the walls after an event is small then the option becomes even more appealing. Consequently, selecting an optimized wall system for either a steel or a concrete building frame would provide a flexible and economic solution where the main structure remains in the low response range while the wall system can absorb blast in a higher response level. In effect the walls are sacrificial to the rest of the building. The main structure, people and equipment could be saved and wall panels replaced at minimal cost and downtime after an event.

In further paragraphs of this paper, the focus will be on the wall systems and not the primary structure. For blast buildings steel structures as well as concrete structures can be used in conjunction with either steel or concrete panels. Some projects are executed with a steel structure and a prefabricated concrete blast wall (figure 2). Other projects are complete preassembled welded steel boxes (figure 3), also steel sandwich panels can be used as façade cladding on steel structures (figure 4).

Figure 1 Precast concrete building, LNG Terminal Botlek

Figure 2 Concrete Firewall | Precast Blast Walls | Precast Concrete Walls Panels | ACP (Concrete) Ltd (thomasarmstrongacpconcrete.co.uk).

Figure 3 Prefabricated blast building with corrugated steel walls by Hertel/InterDam.

Figure 4 Ineos control building with steel fire- and blast resistant sandwich panels.

1.4 Plastic deformation.

Similar to car bumper design, structures can be allowed to deform plastically to provide a protective zone against blast. Due to the improved calculation capabilities since the early '80s and a growing series of field tests, steel wall behaviour during an event has become more predictable [4]

Seismic design requirements should be implemented when building in seismic prone areas [5]. Considerable data is available on the behavior of all types of wall systems during a seismic event. Steel structures behavior under seismic loading however has long been regarded as very efficient due to the material ductility, construction lightweight, and structural systems versatility [6].

1.5 Economy of Scale.

Today's better understanding of blast wall design with any material gives the opportunity for standardisation and rationalisation in order to select from a basket of vendor tested and proven materials for any structural type (steel or concrete) or arrangement. Commonly used and economic materials like cladding panels, that can be easily installed and are replaceable, can be selected simply from catalogue data. This poses an opportunity for vendors to create catalogue data of product performance in relation to blast resistance, absorption and response limits. Lighter wall systems could be prefabricated and transported and installed with less effort, thuswise saving cost.

1.6 Optimization of materials, Composite ''light weight'' walls.

It is apparent that onshore and offshore projects have different construction requirements and hence there has been a divergence in design solutions between them although blast conditions could be similar.
As the understanding of the material properties and performance has evolved to consider composite actions during an event, there is a current trend of convergence for both Onshore and Offshore projects with regards to providing similar blast resistant wall solutions Construction companies that are specialised in building blast resistant buildings are continuously looking for improved and verified solutions that minimise erection time with safe installation and reduced labour man-hour especially within hazardous areas.

Composite concrete walls cover a broad spectrum of solutions, but share the commonality of optimized design by combining 2 or more materials and their properties into an enhanced result. Exotic materials such as carbon fibre and bubble aluminium are being used, or steel honeycomb sandwich blast walls [7].
These types of walls are quite labour intensive to produce and are made of exotic, expensive materials and need to be avoided if low CAPEX is a requirement. Carbon fibre, honeycomb, blast resistant concrete etcetera are not taken into consideration as this paper focuses on minimizing CAPEX.

To minimize CAPEX a steel-stone wool-steel sandwich composite could be considered. This wall system can be produced on an automated production line and utilizes the combination of properties of low cost, easy to recycle materials: steel and lava stone fibres [8].

1.7 Carbon footprint

Due to recent environmental laws, acts and multinational agreements to combat climate change, more and more countries have implemented building laws that demand or reward lowering the carbon footprint of buildings. A building's carbon footprint refers to all the carbon released into the atmosphere during the design, construction, operation and removal of the project.
Shadow costs is a methodology used in The Netherlands that presents the environmental costs of a building in monetary value. The NIBE shadow cost app contains a rapidly growing database of shadow cost per unit per material, including the cost for steel sandwich panels and reinforced concrete can be found at NIBE Milieuclassificaties [9].

Some countries are further ahead than others regarding the enforcement of building with low carbon footprint, but in general it is evident that the direction of legislation is strongly moving towards enforcing rapidly lowering the carbon footprint of buildings. Buildings can be designed based on their Environmental Cost Indicator (ECI). In the Netherlands, currently the ECI is a mandatory criterium to use at more and more buildings. Current ECI of a building should be lower than 1.0 EURO per m2 useable surface per year.

Generally buildings designed in steel have a better CO2 footprint than buildings designed in concrete: "*By replacing Portland cement and using other carbon-reducing strategies, the team was able to cut the embodied carbon of the proposed Mexico City Airport project by 130 million kilograms*" [10].

2 Types of available solutions of blast resistant walls

This chapter focuses on 4 types of blast walls. These types are offset against each other based on several criteria.

In industrial structures, common practice has for decades been to use bunker type concrete buildings to protect people and equipment against explosions. To increase the blast resistance, simply add mass, by adding concrete and rebar steel. This in situ casted concrete still can be a viable solution but has some cons that should be taken into account at the FEED (Front End Engineering and Design) design stage of a project. In order to optimize the design of structures subject to blast, the engineer should firstly ask the following questions, resulting in a preferred design strategy in order to minimize cost and risk during construction (CAPEX):

- Does the climate allow for year-round casting and painting? If not, prefabricated modules/materials to be considered.
- Does the jobsite have installation time constraints? If yes, prefabricated modules/materials could be considered.
- Does the jobsite allow for the transport and installation of modularized buildings? If yes, prefabricated steel modules could be considered.
- Is the building to be removed after use with ease or is that no concern (life cycle analysis)?

What foundations are required in order to prevent the structure from overturning during a blast? If the soil is light, additional, potentially costly, foundations have to be considered or offset against a wall structure able to absorb part of the blast.

- Is weight of the total structure an issue for the projects?

The four generic types of wall systems that can practically be used for blast resistant buildings with pro's and con's are shown in table 1.

	In situ casted concrete	Precast concrete	Welded corrugated steel	Bolted sandwich panels
PRO'S	• Proven blast performance. • Low tech materials available in most countries. • Reuse abilities of materials although on site demolition is time intensive. • Low materials cost.	• Proven blast performance. • Reuse abilities of materials, although on site demolition is time intensive. • Low materials cost. • Fit in modular or prefabrication design. • Low erection time.	• Prefabrication possibilities. • Proven blast performance. • Reuse abilities of materials. • Fit in modular or prefabrication design. • Proven fire post blast resistance.	• Prefabrication possibilities. • Proven blast performance. • Behavior onder seismic loading. • Reuse abilities of materials. • Fit in modular or prefabrication design. • Proven fire post blast resistance. • Useable in cold climates, for both installation and operation. • Penetration cut out after installation of panels gives maximum flexibility. • Fit in standardized and modularized design. • Automated prefabrication allows for economies of scale. • Bolted construction allows for minimal on-site installation time. • Material cost is considerable, but labour cost is minimal for production and installation.
CON'S	• Time consuming to erect. • No proven fire post blast resistance. • Considerable material transport required for construction. • Not easy to install in cold climates and added insulation required for comfortable occupancy. • All penetrations to be finalized prior to casting. • No fit in modular or prefabrication design. • Limited economy of scale, considerable manual labour required. • Time consuming to disassemble. • Carbon footprint. • Insulation and finishing are labour intensive applications.	• Limited proven fire post blast resistance. • Considerable material transport of heavy prefabricated materials required for construction. • Not easy to install in cold climates and added insulation required for comfortable occupancy. • All penetrations to be finalized prior to factory casting. • Economy of scale possible, provided nearby production location is available to optimize logistics.	• All penetration locations to be finalized prior to production of steel panels. • Onsite installation time is laborious due to considerable welding and insulation activities. • Economy of scale only possible for factory production of larger parts, on site welded assembly of these parts is still time consuming on site.	• Limited application for higher blast loads and low response requirements. • High cost of materials.

Table 1 The four generic types of wall systems that can practically be used for blast resistant buildings with pro's and con's

2.1 Blast wall comparision table

The earlier mentioned pro's and con's can be used as a relative value and inserted in a table where the four blast wall types are discussed and valued for 13 different criteria. A project based weight factor is added to come to a project based valuation Table 2.

Criteria\Wall Type	In situ casted concrete	pre casted concrete	Welded (corrugated) steel	bolted sandwich panel	Example of weight factor (project based)
CO_2 footprint	1	1	2	3	3
Reuse ability of materials	1	2	2	3	1
Prefabrication possibilities	1	3	2	3	2
Allowed plastic deformation	1	1	2	3	0
Blast absorption possibilities	1	1	3	3	1
Earthquake resistance	2	2	2	3	0
Proven blast resistance performance	3	3	3	3	2
Proven fire post blast resistance	1	1	3	3	0
Useability in cold climates	1	2	2	3	2
Simplicity for wall penetrations, allowance for late design changes	1	1	2	3	1,5
Fit in standardized and modularized design	1	3	2	3	2
Economy of scale	1	3	2	3	1
Minimization of onsite installation time	1	3	1	3	2
Total CAPEX cost including installation	1	2	1	3	2
Weighted value per wall type	23,5	42,5	38	58,5	

(1 = poor, 2 = average, 3 = good)

Table 2 Blast wall comparison table for 0,3 bar peak reflected overpressure, project with prefabrication preference due to desire to minimize disruptive site installation time on brownfield development. No fire post blast requirement. Please note: To use this table for your project, please fill in your own specific weight factors.

Another way to look at the four different types of blast walls is to compare their weight per m2, per blast strength. Basically, the higher the weight, the higher the associated costs such as logistics and cost of removal after use, as well as the carbon footprint of a building.

Blast wall comparison table Weight					
Over pressure (80msec)	Wall type: Weight kg/m²	In situ casted concrete	Pre casted concrete	Welded (corrugated) steel	Bolted sandwich panel
0,15 bar		600	570	65	45
0,30 bar		720	685	80	60
0,50 bar		840	800	80	70
0,70 bar		840	800	90	100
1,0 bar		960	910	125	140

Table 3 Blast wall comparison table - weight including architectural substructure, based on case yy

2.2 Interpretation

Based on the comparison tables in this chapter, there are significant differences with respect to weight, prefabrication possibilities, blast absorption possibilities and modularization as well as minimization of installation time. In order to advise on the best fit for purpose blast wall solution, a project-based decision-making model should be made in an early design stage, taken into account the criteria mentioned in the tables. To support this decision making, a case study offsetting the 4 different wall times will be discussed.

3 Case Study

To understand the efficiency of the sandwich panels in relation to other blast wall types we compared compatible structural systems and their performance for various loads keeping the building geometry constant. Geometry changes would create another variable but could be extrapolated.

The case study constrains the geometry size to a building of 50m length x 25m width x 6 height. The roof is assumed flat (less than 6 degrees).

3.1 Input Parameters

The structural systems is set with columns table 4:

Frame System	Wall system
Steel Frame @6.25m c/c and 6m c/c	Steel Sandwich Panel
Steel Frame @6.25m c/c and 6m c/c	Built-up Steel Cladding Panels
Concrete Box with internal central columns@6.25m c/c	In-situ reinforced concrete
Concrete Box with internal central columns@6.25m c/c	Precast reinforced concrete

Table 4 The structural system.

The steel frame solution is based on rigid frames at every 6.25m as shown in figure 5.

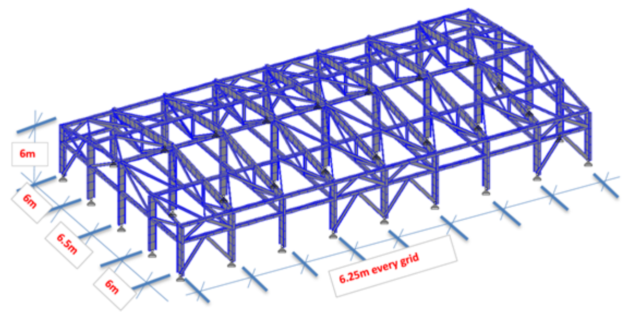


Figure 5 Structural Steel System for Analysis

The equivalent concrete box solution is designed with internal central columns and a roof as a solid slab. The solid roof slab could also represent an equivalent grillage beam system. The arrangement is shown below:

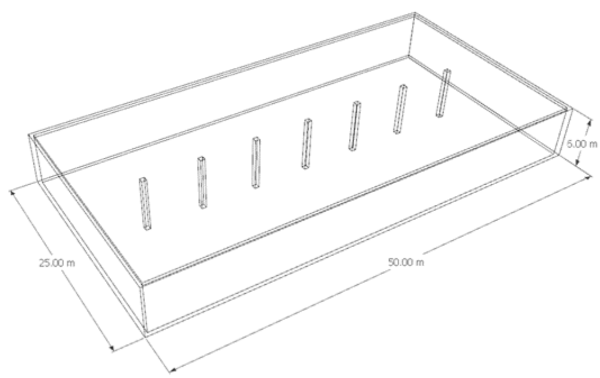


Figure 6 Concrete System for Analysis

The shock front of blast load is considered in the long direction of the building and therefore as a front face and has been investigated for the following blast parameters in increments, table 5.

Peak Incident Side-On Overpressure Pso	Duration of the Positive phase td
15 kpa	80 msec
30 kpa	80 msec
50 kpa	80 msec
70 kpa	80 msec
100 kpa (1bar)	80 msec

Table 5 Blast parameters in increments

A typical time duration 80 msec was considered which represents a short impulse.

The analysis for the steel structure was conducted using STAAD Pro time-history loading method.

Blast resistant structures were designed in accordance with the ASCE blast load combination.
$U(t) = a * D + b*L+B(t)$

- $U(t)$ = total applied time-dependent load or its effect.
- D = static dead load.
- $B(t)$ = time-dependent blast load or its effect (horizontal and vertical).
- L = conventional static live load (roof live load may be taken as zero).
- a = reduction factor applied to static dead load. Factor is to be taken as 0.9 when the dead load counteracts the blast load, otherwise to be taken as 1.0.
- b = reduction factor applied to conventional live loads to reflect the portion of live load expected to occur simultaneously with the blast load. Zero shall be used for the reduction factor if doing so will result in a more severe condition.

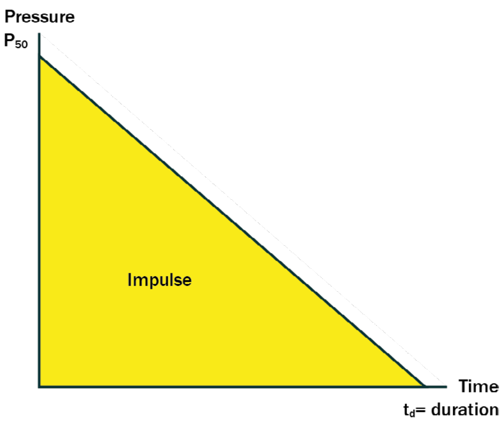


Figure 7 Impulse pressure simplification over time.

The loads were applied on all sides as per ASCE design guideline for blast resistant buildings [3].

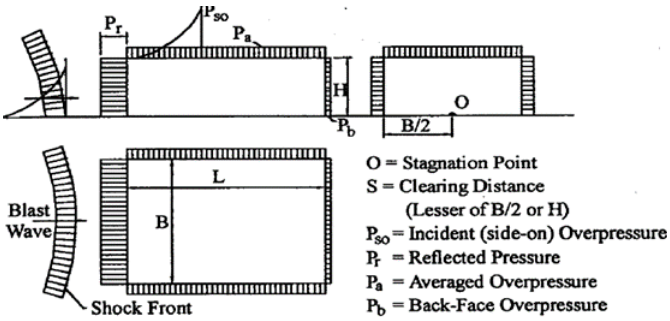


Figure 8 Blast defenition

3.2 Methodology

3.2.1 Structural Steel Frame Analysis

For the steel diaphragm buildings, the resistance factor (Φ) was set to 1.0 for load combinations which include blast loads. Design of the overall structural-framing system included analysis of global response including sidesway, overturning, and sliding. Sidesway analysis was performed with and without leeward side (rear wall) blast loads but took into account the time lag where relevant. Individual frame members also met their response limits of ductility and rotation. Column base plates were designed to develop the peak dynamic member reactions applied as a static load. In accordance with Blast Design the calculations were performed and these calculations are available upon request. Please send your inquiry to info@InterDam.com.

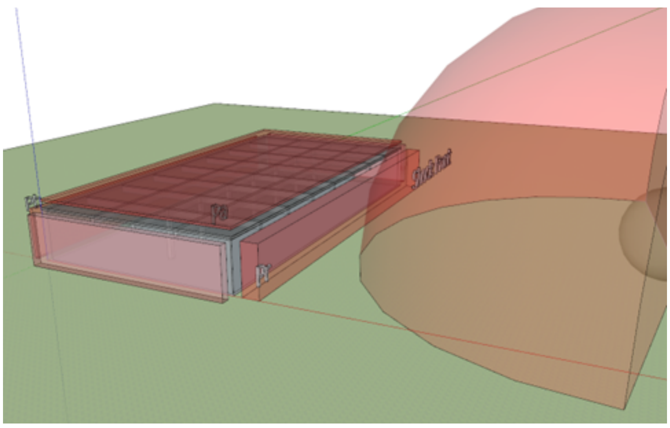


Figure 9 Blast wave orientation and setup

4.2.1 Concrete Box Analysis

For the concrete buildings iterative method was used to establish the optimum wall reinforcement and thickness in order to satisfy the dynamic ultimate shear and bending capacity of the sections. For the sake of simplicity all walls were assumed to have uniform top and bottom reinforcement with the roof to have a fraction of the reinforcement.

Sample calculation for the concrete box reinforcement is available upon request. Please send your inquiry to info@InterDam.com.

ID	Construction ID	Construction Type	Blast Load	Region ID	Region
PC15CH	PC	Precast Concrete	15	CH	China
PC15EU	PC	Precast Concrete	15	EU	Western Europe
PC15ME	PC	Precast Concrete	15	ME	Middle East
RC15CH	RC	Reinforced Concrete	15	CH	China
RC15EU	RC	Reinforced Concrete	15	EU	Western Europe
RC15ME	RC	Reinforced Concrete	15	ME	Middle East
SW15EU	SW	Steel Sandwich Panel	15	EU	Western Europe
SW15CH	SW	Steel Sandwich Panel	15	CH	China
SW15ME	SW	Steel Sandwich Panel	15	ME	Middle East
BCP15EU	BCP	Built-up Cladding Panel	15	EU	Western Europe
BCP15CH	BCP	Built-up Cladding Panel	15	CH	China
BCP15ME	BCP	Built-up Cladding Panel	15	ME	Middle East

Table 6 Example of design ID setup

ID	Construction	Construction Type	Blast Load	Region ID	Region	Length (m)	Width (m)	Height (m)	Wall thk (m)	Roof Thk (m)	Insulation Thickness (m)	Total Length of Columns	Av Size of Columns (m2)	Total Length of Beams	Av Size of Beams (m2)	Wall Area (m2)	Roof Slab Area (m2)	Av. Wall Reinf Area (m2)	Av. Roof Reinf Area	Sum VolofWalls (m3)	Sum Weight ofWalls (kg)	Sum VolofRoof (m3)	Sum Weightof Roof (kg)	Sum VolofCol (m3)	Sum VolofBeams (m3)	Sum Weight ofCol (kg)	Sum VolofInsul (m3)	Sum Weight ofInsul (kg)
PC15EU	PC	Precast Concrete	15	EU	Western Europe	50	25	6	0.25	0.25	0.1	208	0.2	417	0.3025	900	1250	0.00268	0.001	225	540,000	312.5	750,000	42	126	101250	215	21,500
RC15EU	RC	Reinforced Concrete	15	EU	Western Europe	50	25	6	0.25	0.25	0.1	208	0.2	417	0.3025	900	1250	0.00268	0.001	225	540,000	312.5	750,000	42	126	101250	215	21,500
PC30EU	PC	Precast Concrete	30	EU	Western Europe	50	25	6	0.3	0.3	0.1	208	0.3	417	0.36	900	1250	0.00419	0.002	270	648,000	375	900,000	52	150	125000	215	21,500
RC30EU	RC	Reinforced Concrete	30	EU	Western Europe	50	25	6	0.3	0.3	0.1	208	0.3	417	0.36	900	1250	0.00268	0.001	270	648,000	375	900,000	52	150	125000	215	21,500
SW15EU	SW	Steel Sandwich Panel	15	EU	Western Europe	50	25	6	0.1	0.1						900	1500											
SW30EU	SW	Steel Sandwich Panel	30	EU	Western Europe	50	25	6	0.15	0.15						900	1500											
SW50EU	SW	Steel Sandwich Panel	50	EU	Western Europe	50	25	6	0.172	0.172						900	1500											
SW70EU	SW	Steel Sandwich Panel	70	EU	Western Europe	50	25	6	0.2	0.2						900	1500											
SW100EU	SW	Steel Sandwich Panel	100	EU	Western Europe	50	25	6	0.2	0.2						900	1500											
PC50EU	PC	Precast Concrete	50	EU	Western Europe	50	25	6	0.35	0.35	0.1	208	0.3	417	0.4225	900	1250	0.00419	0.002	315	756,000	437.5	1,050,000	63	176	151250	215	21,500
RC50EU	RC	Reinforced Concrete	50	EU	Western Europe	50	25	6	0.35	0.35	0.1	208	0.3	417	0.4225	900	1250	0.00419	0.002	315	756,000	437.5	1,050,000	63	176	151250	215	21,500
PC70EU	PC	Precast Concrete	70	EU	Western Europe	50	25	6	0.35	0.35	0.1	208	0.3	417	0.4225	900	1250	0.00654	0.003	315	756,000	437.5	1,050,000	63	176	151250	215	21,500
RC70EU	RC	Reinforced Concrete	70	EU	Western Europe	50	25	6	0.35	0.35	0.1	208	0.3	417	0.4225	900	1250	0.00654	0.003	315	756,000	437.5	1,050,000	63	176	151250	215	21,500
PC100EU	PC	Precast Concrete	100	EU	Western Europe	50	25	6	0.4	0.4	0.1	208	0.4	417	0.49	900	1250	0.01414	0.007	360	864,000	500	1,200,000	75	204	180000	215	21,500
RC100EU	RC	Reinforced Concrete	100	EU	Western Europe	50	25	6	0.4	0.4	0.1	208	0.4	417	0.49	900	1250	0.01414	0.007	360	864,000	500	1,200,000	75	204	180000	215	21,500
BCP15EU	BCP	Built-up Cladding Pane	15	EU	Western Europe	50	25	6	0.1	0.1						900	1500											
BCP30EU	BCP	Built-up Cladding Pane	30	EU	Western Europe	50	25	6	0.15	0.15						900	1500											
BCP50EU	BCP	Built-up Cladding Pane	50	EU	Western Europe	50	25	6	0.172	0.172						900	1500											
BCP70EU	BCP	Built-up Cladding Pane	70	EU	Western Europe	50	25	6	0.2	0.2						900	1500											
BCP100EU	BCP	Built-up Cladding Pane	100	EU	Western Europe	50	25	6	0.2	0.2						900	1500											

3.3 Material Take-Off

Using the same geometry with the blast increments (15, 30, 50, 70 and 100 Kpa) and upgrading the steel members as well as the reinforcement and wall thickness to meet ductility limits for low response, an MTO table was compiled with all combinations.

The MTO design combinations were coded and given an ID based on Construction Type, Blast and Region. Examples of unique design IDs are as table 6.

By creating unique IDs based on construction type, blast load and region we were then able to populate a spreadsheet creating a database for cost and duration analysis.

Sum ALL Areas	Sum WeightofReinf (kg)	Sum Volumeof ALL Concrete	Sum WeightofMainSteel (kg)	Sum WeightofSteel Railing (kg) HE20	Sum WeightofALL Steel (kg)	EQUIPMENT UNIT COST
2,823	32,093	706				0
2,823	32,093	706				0
2,958	50,145	847				0
2,958	32,093	847				0
2,400			114,000	19,043	133,043	0
2,400			175,872	26,660	202,532	0
2,400			237,000	44,433	281,433	0
2,400			273,716	55,542	329,258	0
2,400			283,000	74,056	357,056	0
3,106	50,145	992				0
3,106	50,145	992				0
3,106	78,352	992				0
3,106	78,352	992				0
3,267	169,240	1,139				0
3,267	169,240	1,139				0
2,400			114,000	19,043	133,043	0
2,400			175,872	26,660	202,532	0
2,400			237,000	44,433	281,433	0
2,400			273,716	55,542	329,258	0
2,400			283,000	74,056	357,056	0

Table 7 Example of design ID setup

3.4 Unit Rates

A unit rate database was created for both cost and time for all different types of construction and regions. Similar ID codes were used in order to link the MTO and the Unit rate database together. Extract of the unit rate database is as table 8.

Seri	CONST	CONSTRU	WORK TYPE	CAT1	Description	Cost Units	EU	CH	ME	EU-MH	CH-MH	ME-MH	Notes
1	BCP	BCP15	MATERIAL	MATERIALS (primary)	Cladding Panel (15mbar)	USD/M2	45	45	45				same all regions, all blast (req
1	PC	PC15	LABOUR	OFFSITE	factory boxing	USD/M2	20.42	7.86	5.25				same all regions, all blast
1	PC	PC15	LABOUR	OFFSITE	factory unboxing	USD/M2	4.084	1.572	1.05				same all regions, all blast
1	BCP	BCP15	TRANSPORT	MATERIALS (non primary)	all-in transport to site BCP	USD/M2	20	20	20				same all regions, all blast
1	RC	RC15	TRANSPORT	MATERIALS (non primary)	all-in transport to site RC	USD/M2	12	12	12				same all regions, all blast
1	SW	SW15	TRANSPORT	MATERIALS (non primary)	all-in transport to site SW	USD/M2	10	10	10				same all regions, all blast
1	RC	RC15	LABOUR	ONSITE	applying insulation	USD/M2	28.588	11.004	7.35				same all regions, all blast
1	RC	RC15	LABOUR	ONSITE	applying insulation	MH/M2				0.7	2.1	2.1	same all regions, all blast
1	RC	RC15	LABOUR	ONSITE	boxing (forming)	USD/M2	40.84	15.72	10.5				same all regions, all blast
1	RC	RC15	MATERIAL	MATERIALS (non primary)	boxing (forming) RC	USD/M2	25	25	25				same all regions, all blast
1	RC	RC15	LABOUR	ONSITE	boxing (forming)	MH/M2				1	3	3	same all regions, all blast
1	SW	SW15	MATERIAL	MATERIALS (primary)	Cladding Sandw. Panel (100 mm thk, 15 kpa blast)	USD/M2	95	95	95				Per Blast , Same per Region
1	RC	RC15	MATERIAL	MATERIALS (primary)	Concrete Materials (usd/m3)	USD/M3	99	99	99				Quantity Dependent
1	RC	RC15	LABOUR	ONSITE	concrete pouring	USD/M2	12.252	4.716	3.15				same all regions, all blast
1	RC	RC15	MATERIAL	MATERIALS (non primary)	concrete pouring	USD/M2	12.252	4.716	3.15				same all regions, all blast
1	RC	RC15	LABOUR	ONSITE	concrete pouring	MH/M2				0.3	0.9	0.9	same all regions, all blast
1	RC	RC15	LABOUR	ONSITE	Cost of ONSITE for blue collar technicians (usd/hour)	USD/MH	40.84	5.24	3.5				MH dependent

Table 8 Unit rates extract

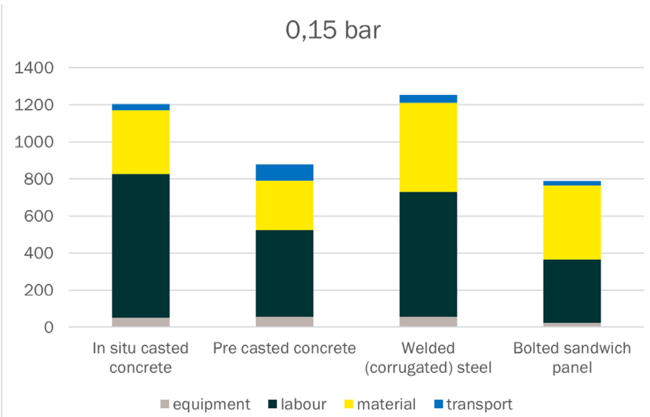
The unit rates are based on information provided in Turner and Townsend as well as Arcadis construction cost handbooks and market surveys for 2019.

3.5 Cost and Time Comparison.

By linking the two databases together, a dynamic link and extract some useful graphs, comparison data, trends, and conclusions can be drawn.

3.5.1 Construction Type Breakdown Cost

In this set of graphs, we have extracted the cost between blast loads and construction type with an additional breakdown to better understand the cost variations (i.e. labour, material, transportation, equipment. Total external envelope structure including secondary support and a thermal insulation value of Rc 3 m2K/W, but excluding foundation works, assuming structural openings are equal with all solutions and not taken into account).

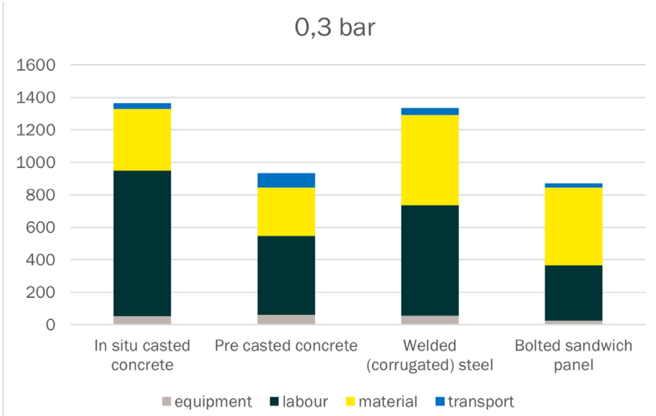


Graphic 1 0,15 bar

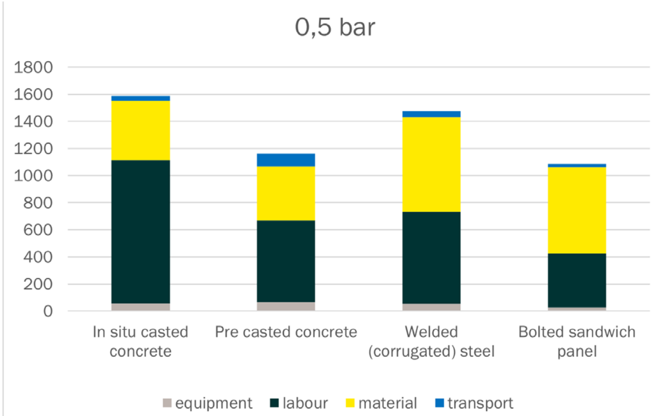
Graphic 1 to 5 are showing cost trends per construction type with blast increments demonstrating the trend discussed above relating to cost efficiency of sandwich panels with blast increase.

Vertical axis: total cost of insulated blast resistant façade including secondary support structure per m2 floorspace in EURO.

Labour cost is reducing from Europe to China to the Middle East

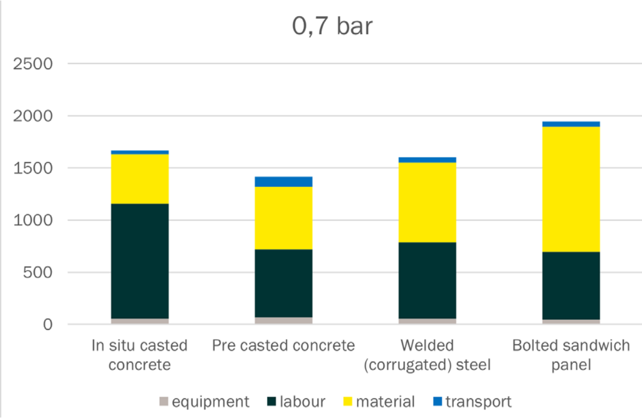


Graphic 2 0,3 bar

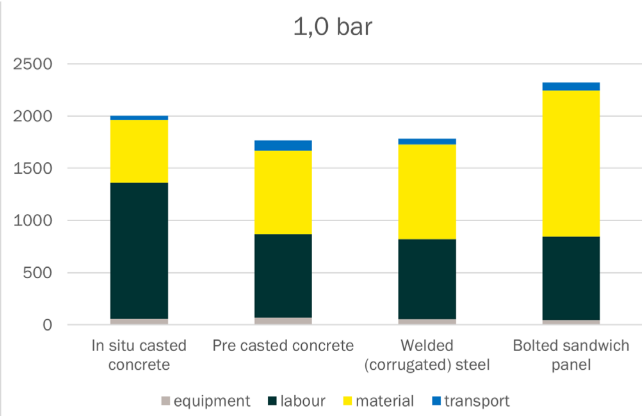


Graphic 3 0,5 bar

consistently between blast loads while material cost remains constant within margins. Reviewing the average percentage cost difference between sandwich panels with the other construction methods, we see that material cost is higher by an average of 35% to Precast and Reinforcement but cheaper in labour, equipment



Graphic 4 0,7 bar



Graphic 5 1,0 bar

and transport by an average of 74%. This explains why with higher blasts which require more materials the sandwich panel cost efficiency is reduced.

3.5.2 Durations Onsite and Offsite

Looking at the manhour duration of on-site and off-site construction we also see the following, based on 0,3 bar design:

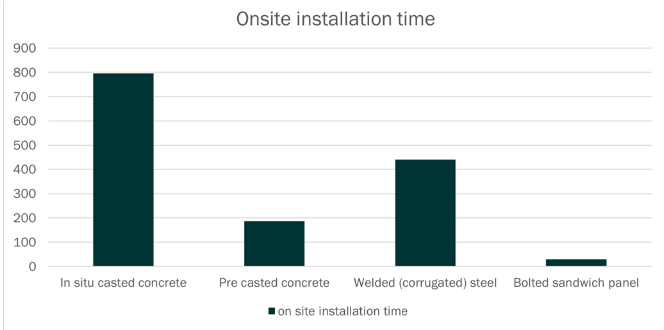
Graphic 6 and 7 onsite and offsite manhour duration for case study options of walls, 0,3 bar overpressure.

Sandwich panels on steel support structure are the most time efficient solution for onsite work. For offsite work due to the automation of sandwich panel manufacturing the manhour reduction is significant.

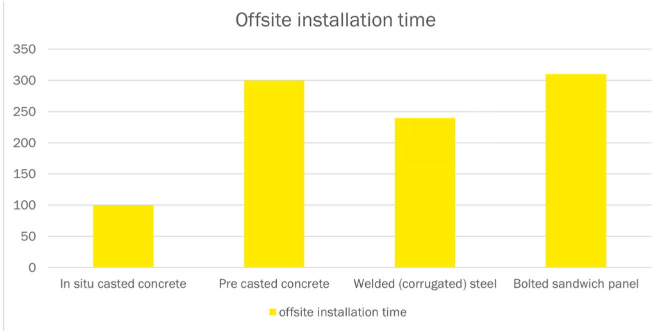
3.6 Carbon footprint, Shadow cost.

According to the tables in the NIBE shadow cost app, the following shadow cost can be found based on standard, non-blast rated façade options:

Functional unit: 1m2 façade materials, support over 75 years, including support structure



Graphic 6 Onsite installation time



Graphic 7 Offsite installation time

Sandwich panels flat, steel+stonewool, coated 2b, EUR 5,48
Steel support structure, galvanized and coated 3a, EUR 1,88
total EUR 7,36

Concrete, strengthened, glasswool, concrete 2x EUR 12,27 [9]

In this case a lower value in EUR of the shadow cost is better. Based on the currently available lists, the carbon footprint of a sandwich panel building is considerable lower, thus better than a steel enforced, insulated concrete building.

4. Conclusions and recommendations

The case study comparison between steel sandwich panels, corrugated welded steel panels, precast concrete and in-situ concrete with incremental blast loads has indicated that prefabrication (i.e sandwich panels, and precast) has clear advantages as it minimises onsite labour.
Looking at the graphs and the comparison analysis between the 4 types of wall systems, it can be concluded that:

1. The blast wall comparison table can be a useful tool in FEED phase to take a holistic approach to the basic design of a blast resistant building and include multiple factors in the decision-making part of the design process. It is noted that the weight factors should be applied based on project specific requirements.

2. The carbon footprint reduction requirements of the design of blast buildings triggers the necessity to look for optimized designs as traditionally higher blast requirements were met with adding mass to a structure.

3. For lower blast rates (op to approximately 0,5 bar overpressure) the case study confirms a bolted sandwich panel is an economically viable option, 33% lower cost compared to in situ casted concrete, in case study at 0,15 bar overpressure.

4. For blast rates over 0,5 bar, pre casted and in situ casted concrete becomes more economically viable than a bolted sandwich panel solution. At 1,0 bar overpressure,16% lower cost is achieved with precast concrete, compared to steel sandwich panels in the case study.

4.1 Limitations

Region:
The case study and comparison are based on construction in 'western, high labour rate countries. In countries where a considerably lower labour rate is applicable, the cost comparison outcome could switch to the more labour-intensive solution, like in situ cast concrete.

Finishing:
The case study and comparison are based on a building including thermal insulation and clean finishing on the inside. Steel sandwich panels already have this insulation and clean finishing incorporated in a prefabricated/automated production line. If a project does not require thermal insulation and clean finishing, in situ cast concrete will be more competitive, regarding the cost and installation time.

Fire resistance:
Fire resistance is not discussed in this paper, although thermal insulation is and all types of discussed blast resistant walls can be supplied as fire and blast resistant walls. Some solutions are even tested and certified on fire resistance after a blast [11] .

Cost:
In the paragraphs considering cost of the various blast resistant wall types, the possible gain of the absorption of part of the blast wave by a ductile wall structure, thus lowering the reaction forces to the foundations are note taken into consideration.

Carbon footprint:
In the near future the carbon footprint of both steel and concrete production will change with the wider availability of green steel. Green steel is produced using renewable energy and has minimum slag, as slag mainly comes from coal. This means that the concrete industry also has to look for an alternative supply chain for their raw materials of which steel slag was a big contributor to lower the carbon footprint of concrete production.

5. References:

[1] EN-14509 Self supporting double skin metal faced insulating panels. Factory made products, Specifications, CEN Brussels.
[2] Databook InterDam-Walls G21 Fire- and Blast Rated
[3] Design of Blast-Resistant Buildings in Petrochemical Facilities, Second Edition, Task Committee on Blast-Resistant Design, ASCE
[4] https://www.fabig.com/publications-and-videos/technical-guidance/technical-note-05/
[5] ASCE/SEI 7-22. Minimum Design Loads and Associated Criteria for Buildings and Other Structures.
[6] (PDF) State of the Art Report on Past Performance of Steel Moment-Frame Buildings in Earthquakes (researchgate.net)
[7] https://www.sciencedirect.com/science/article/abs/pii/S0020740318309391
[8] https://www.onepetro.org/conference-paper/OTC-26908-MS
[9] NIBE Environment classifications app, Nederlands Instituut for Bouwbiologie en ecologie app,.NIBE Milieuclassificaties (nibe-sustainability-experts.com).
[10] The Urgency of Embodied Carbon and What You Can Do about It | BuildingGreen. https://www.buildinggreen.com/feature/urgency-embodied-carbon-and-what-you-can-do-about-it
[11] Video Fire Post Blast: https://www.youtube.com/watch?v=nWXc6PlsQ5E6.

For further information, please contact:

InterDam
Your shield in the field.

Klompenmakerstraat 12
2984 BB Ridderkerk
The Netherlands

T: +31 (0) 180 470 030
E: info@interdam.com
W: www.interdam.com