AUTOMATED DESIGN FOR CORRUGATED BLAST WALL PROJECTS

ON WEIGHT SAVINGS AND A PARTITIONING METHOD FOR LARGER NUMBERS OF DESIGN CASES

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Abstract

The design of corrugated blast walls can be challenging but the availability of detailed blast information offers opportunities for economic design. However, for large projects the number of distinct design cases makes it time-consuming to achieve this by manual trial-and-error. Furthermore, it is inefficient to design a different profile for every individual design case. Partitioning the design cases into a small number of groups, each with a distinct blast wall design, strikes the right balance between material cost savings and project complexity. This paper presents a comprehensive design strategy (Figure 5) for these challenging projects, as well as for smaller scale projects.

For projects consisting of a few design cases, profiles can be verified for each case individually. Optimisation for individual design cases is done by brute forcing a large set of profile options and selecting the lightest one that meets all design case requirements calculated using the SATEL model (www.blastresponse.com). In the case of larger projects, the design cases are partitioned using a binary integer programming problem, and an optimised profile is returned per group of design cases by a slightly extended version of the brute force approach. The resulting set of profile designs is verified against specification using explicit Finite Element Analysis.

As an illustration, two individual design cases have been optimised. Compared to previous methods, material cost savings of 10.1% and 31.7% are achieved. Furthermore, partitioning a large scale project using the binary integer programming method resulted in material savings of 14.9%. Altogether, the automated design methods result in safe and verified designs, while allowing significant cost and weight savings for projects of any size and complexity.

1 Introduction

The safety of people and equipment against the effects of explosions depends on reliable blast protection solutions. In the off-shore industry, blast walls form a significant part of this. Improved blast wall design strategies allow for reliable blast protection whilst minimising project cost.

Currently, the main solutions used are steel corrugated profiles (Figure 1) and, more recently, sandwich panels. While sandwich panels come with their own advantages [1], corrugated profiles are preferred by Engineering, Procurement and Commissioning (EPC) contractors, for instance in projects where protection against considerable blast is required. This paper will discuss an optimised design strategy of those blast-resistant corrugated profiles.

Corrugated blast wall projects often are of considerable size and complexity, potentially involving multiple buildings or modules. The end products need to be safe and validated, yet optimised for low cost and weight. Large-scale projects typically pose challenges to EPC-contractors: project requirements are likely to change multiple times and delay is costly. These circumstances demand that technical design decisions are made within a short time frame, based on frequently updated information. At the same time, there is no margin for error.

After setting out the context in which methods for corrugated blast wall design must function, a set of engineering solutions is presented. First a Python-based optimisation for single design cases, built upon a single degree of freedom model, is discussed. This software will allow for considerable weight savings compared to previous corrugated blast wall design methods. Secondly it will be shown that by using a binary integer programming (BIP) method,

Figure 1 A typical corrugated blast panel, consisting of corrugated sheet, top and bottom border plates, and (when applicable) penetration frames. This particular panel features three pipe penetration frames. The material shown here is stainless steel 1.4404 (SS316L). This panel has been successfully tested in fire post-blast (1.2 bar, 80 ms blast loading, EI60 with a hydrocarbon curve)

it is possible to cover a large number of design cases with a small number of distinct wall designs with low impact on total weight. Lastly, the verification strategy of wall designs using explicit finite element analysis (FEA) will be examined. Together these methods allow for highly automated and flexible engineering, delivering safe designs for projects of any size and complexity.

2 The Challenges of Corrugated Blast Wall Projects

Providing blast protection is only one of many tasks in the scope of work of EPC contractors. Usually they are responsible for delivering a fully integrated design of a plant or production facility. Foremost, functional requirements determine the layout of a plant, which is then followed by the design of the modules that protect people and equipment against extreme situations under both operational and accidental conditions.

During the Front-End Engineering Design (FEED) phase, substantial attention is paid to explosion risk management. Once the initial plant design is ready, explosion risk scenarios are studied. These studies are usually done by specialist parties, and result in detailed preliminary blast load specifications. At this stage, possible blast protection suppliers become involved and are asked to submit offers based on those preliminary specifications.

The blast protection philosophy is a crucial part of plant hazard risk management. Nevertheless, the blast protection design that expresses this philosophy is subordinate to the plant's functional design: If the plant design changes, which commonly happens during the FEED phase, the design of blast protection systems has

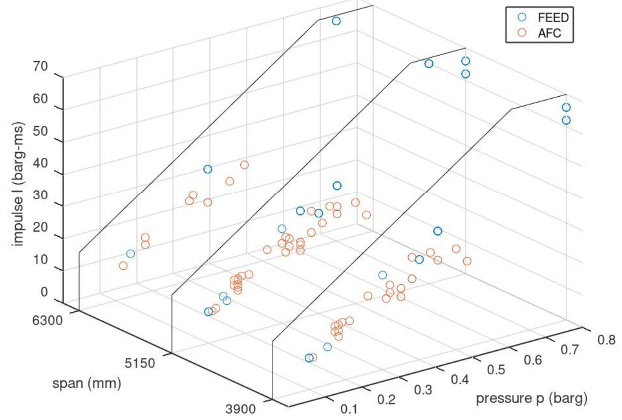

Figure 2 Design cases are determined by three parameters: Wall span, blast pressure and blast impulse. Typical project scopes comprise several spans, with multiple blast loads, resulting in a large number of unique design cases

to be adapted accordingly. This means that blast panel designs may have to be revised over the course of a project. The blast loading on a specific module is strongly influenced by its position in relation to the explosion source. The basic rule is that with less room for distancing, higher-resistant blast walls are required.

In general, blast panel design is largely determined by the maximum bending moment that occurs at mid-span. The three most important parameters that this moment depends upon are the wall span, the blast pressure, and the blast impulse. Other parameters, such as secondary loads due to wind, are accounted for, but generally do not have a decisive influence. Thus, the combination of span, pressure and impulse defines the design case. For a typical project, the number of design cases can be large, and subject to change between the FEED and the AFC (Approved For Construction) phase. All design cases together can be viewed as a cloud of points in a 3D space governed by the three parameters. (Figure 2).

The blast protection envelope usually consists of multiple wall spans, possibly belonging to multiple modules. Blast loadings are often defined with a detail up to the level of explosion pressures and impulses for each wall individually. With information available at such a deep level, it would be a waste of resources to use a single profile design that is able to withstand all design cases. For the minor design cases, this single design will have (much) of its strength left unused, resulting in unnecessary material cost. The opposite, although lean on material use, would also not be feasible: Designing unique panels for every individual design case puts a rather high workload on engineering departments and creates logistical jeopardy. As a result, the total project cost may become unnecessarily high. In between these two extremes exists a middle ground: If the set of design cases is partitioned into groups, a small number of panel designs can be developed, one for each group (Figure 3). With this approach, material cost can be saved, while at the same time the workload is kept manageable.

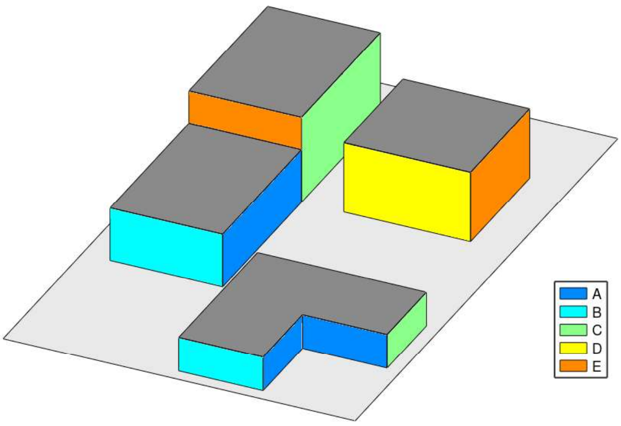

Figure 3 A project consisting of several modules, comprising different wall spans and blast loads. An economical design strategy consists of partitioning the blast protection envelope into groups, using different profile designs (for example A to E shown here) for each group. Profile designs can be shared across multiple design cases, for example as shown here for designs A, B, C, and E.)

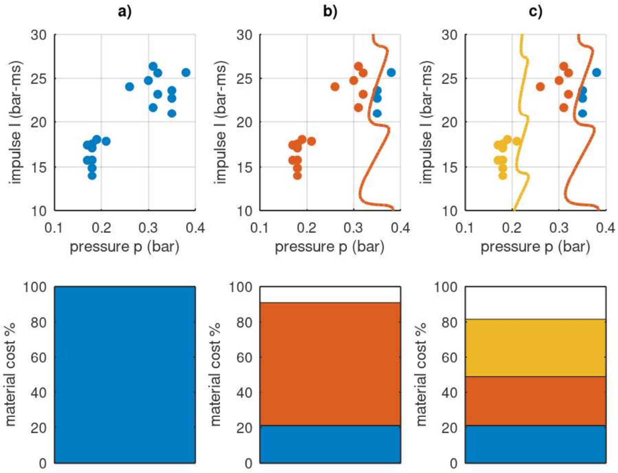

Figure 4 The partitioning visualized. a) Starting point is the situation where all design cases share a heavy initial design (blue). Total material cost serves as a reference. b) First step is to add a new, lighter, design (orange). This design cannot be used for some design cases: The iso-damage curve denotes the boundary that separates those design cases (four in total) from the others. A modest material cost saving is realised. c) Adding yet another design (yellow) splits the set of design cases once more, resulting in further material saving. The process can be repeated until a desired material saving is achieved

2.1 Partitioning of Design Cases

The paradigm of partitioning can be explained on the basis of a thought experiment. In this experiment the pressure and impulse vary and the span is kept fixed for the sake of simplicity. The starting point is the undesirable situation where a single panel design is used throughout the entire set of design cases. This particular panel is designed to (just) withstand the most severe design case, and therefore satisfies all the less severe cases. The first step in the partitioning process is to add another panel design to this existing design. Necessarily, this new design has to be less heavy than the existing panel in order to achieve any material cost reduction. Being lighter, the new design has less strength, and thus can only be applied to a subset of the design cases. The separation between this subset and the other design cases is determined by an iso-damage curve [2-4] that marks those combinations of pressure and impulse for which the damage to the new panel would be on the edge of what is acceptable[1]. Design cases that lie beyond this boundary have to keep the original panel design; design cases within the thus-bounded region can safely make use of the newly added design, resulting in material cost savings. This process can be repeated, each time adding a new design, until a satisfactory reduction is achieved (Figure 4).

The thought experiment may suggest that partitioning can only be done starting from a single initial design. Although nothing prevents the above strategy from being successful, it is important to note that it is not the only strategy possible. In fact, the only essential notion is that the choice of a new panel design automatically determines the location of its iso-damage curve, and thus the separation between design cases for which the panel can be used safely and those cases where it cannot.

Any successful partitioning strategy should bring forward a set of mutually different panel designs that divide the parameter space in such a way that a maximum cost reduction is achieved, while at the same time guaranteeing that the panels fully comply with the project specifications for the design cases they are linked to.

3 Optimised Blast Panel Design

Three concepts will be discussed in this section: design of corrugated panels for individual design cases, the ability to partition design cases for larger project scopes, and verification of designs using FEA. Together these concepts will form a comprehensive design strategy (Figure 5) for blast wall projects of any size and complexity.

To illustrate the successful implementation of these design methods, they will be applied to a typical project consisting of 56 individual design cases. Two design cases (as highlighted in Figure 6) are optimised individually to discuss performance of the method for design of individual design cases. The entire scope of 56 design cases will be optimised using an automated partitioning algorithm, and the results will be presented and compared to results obtained with manual iterations using the calculation rules for corrugated sections as defined in EN1993 [8]. The concept of iso-damage curves will be used to take a closer look at the calculated partitioning and select the profile designs that are verified using FEA.

[1] It is not uncommon to let the iso-damage curve correspond to a predefined ductility ratio. Other choices can be made as well.

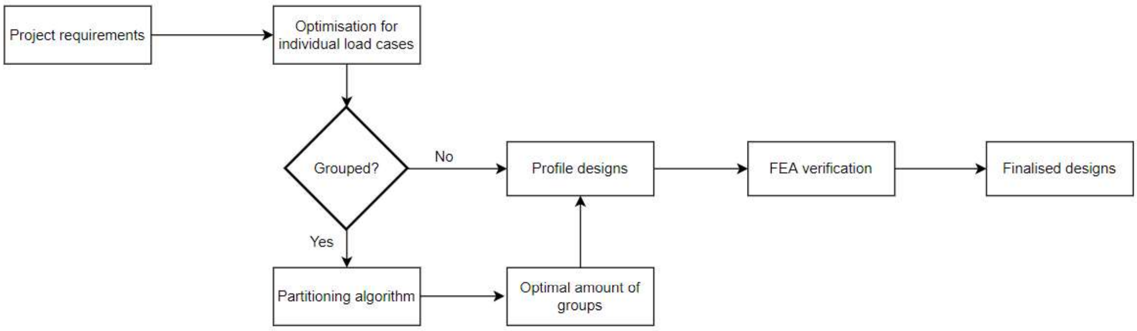

Figure 5 A comprehensive design strategy for blast wall projects.

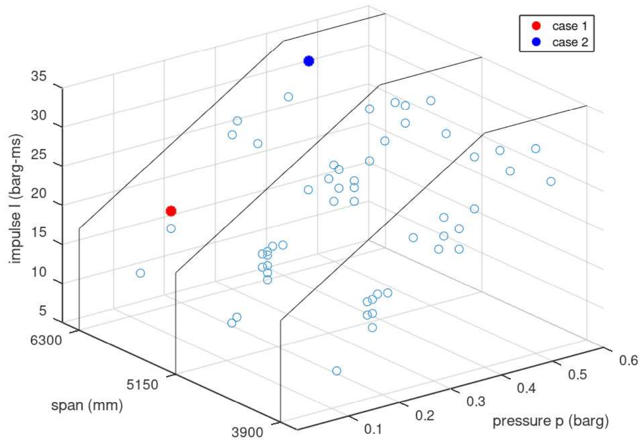

Figure 6 Project consisting of 56 design cases, of which two individual cases as well as the entire scope will be used as example of optimisation using the new methods.

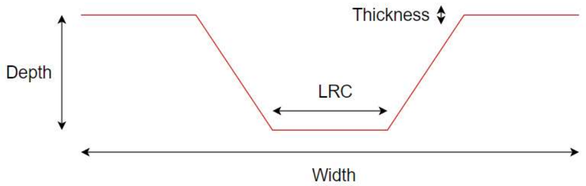

Figure 7 Panel geometry parameters, which will be used as variables to optimize profile design

3.1 *Design Methodology for Single Design Cases*

An established calculation method of corrugated panel response to blast loading is the SATEL model [5,6], an improvement on the Biggs' single-degree-of-freedom (SDOF) model [7]. The SATEL model is used as a basis for a program that determines the lightest possible profile given a certain design case.

Four variables determine the panel geometry: the corrugation depth, width, thickness and the horizontal distance between the lower radius centres (LRC), as displayed in Figure 7. The values for each of these geometry variables are bounded above and below, possibly due to project requirements such as a maximum allowed profile depth, after which the sets of values are discretized where necessary. By listing every possible combination of the discretised geometry variables, a set of profile designs (~500.000) is created, which are all[2] evaluated using the SATEL model, after which the lightest design that meets ductility and deflection requirements is selected. Those designs that are selected are then verified using finite element analysis.

A schematic presentation of this optimisation for single design cases can be found in Figure 8. The material properties are regarded as input for the design optimisation, but different materials can of course be considered.

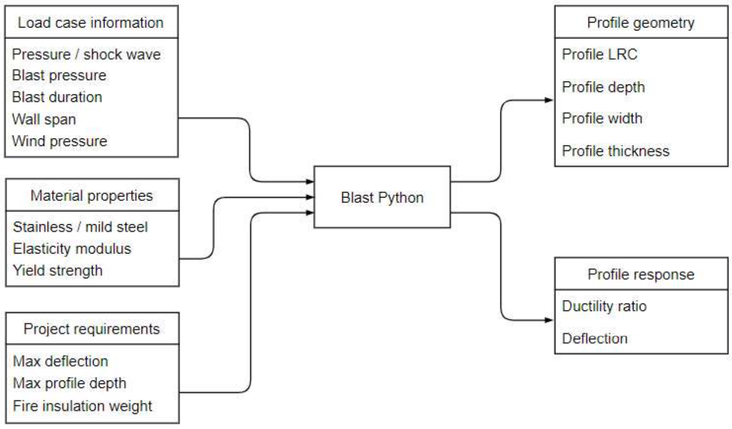

Figure 8 Schematic showing in- and output for profile design optimisation

[2] In practice, to reduce computation time, the profiles are first sorted by increasing mass and the algorithm is stopped as soon as a profile that fulfills all requirements is found.

This automated design method, a brute force over a discretised parameter space, is preferable over previously used design methods. Previous methods involve extensive manual trial-and-error and more easily result in mistakes, while these risks are minimised when the brute force method is used.

To illustrate the weight saving on profile design this brute force method offers, two examples (Figure 6) are shown in Table 1. For design case 1 and 2, if individually optimised, the new design method returns profile designs 10.1% and 31.7% lighter, respectively, while still meeting all requirements. In comparison with designs verified using EN1993 rules [8], the new profiles are lighter which demonstrates a level of conservatism in EN1993. The weight reduction is significant, and it is concluded that the brute force optimising method, combined with verification by finite element analysis of the cases that pass the brute force optimisation leads to more economic designs for single design cases and smaller projects.

3.2 *Optimisation of Large Project Scope*

The partitioning of design cases into a predefined number of groups is done by translating[3] the results from optimisation for the individual design cases into a binary integer programming (BIP) problem [9]. This translation yields as objective function an estimated total mass for the entire project[4] (thus is weighted by wall area per design case), which is to be minimised under compliance with the partitioning constraints. These constraints are the "rules" that define partitions: each design case must be an element of exactly one group, and there must be exactly as many groups as predefined. The BIP model partitions the design cases, after which for each group the lightest profile design is calculated that meets the project requirements for all design cases of its group. Using a slight extension of the brute force method for individual cases, this is not difficult: Instead of checking the profiles against a single design case, they must meet the requirements for all design cases in the group. Again, the lightest possible profile is returned.

The previously used manual partitioning method is applied to the 56 design cases in Figure 6, dividing them into eight groups. This method is time-consuming to such an extent that repeating the process for a different number of groups is not desirable. However, the BIP approach is fast and highly automated, which allows not only for a solution set for eight groups to be calculated, but for any number of groups deemed relevant. The results of this can be viewed in Figure 9. It is with considerable margin that the BIP partitioning method outperforms the previously used method. For example, the total reduction for 8 groups (15%) is the result of optimised profile designs combined with partitioning. Optimising the profile designs while keeping the old partitioning in place would result in a reduction of 10%. Hence, 10 percentage points are due to the panel design optimisation and 5 percentage points as a result of the BIP partitioning method.

CASE	WIDTH [mm]	DEPTH [mm]	THICKNESS [mm]	LRC [mm]	MASS [kg/m²]
1 - Old method	750	220	4	230.0	44.6
1 - New method	1000	455	3	175.1	40.1
2 - Old method	900	320	8	230.0	95.1
2 - New method	1360	585	5	259.9	65.0

Table 1 Profile designs for two design cases, calculated with the old and new method. The mass per m² includes the relative mass of the border plates. The profiles meet all project requirements (such as maximum allowed wall zone)

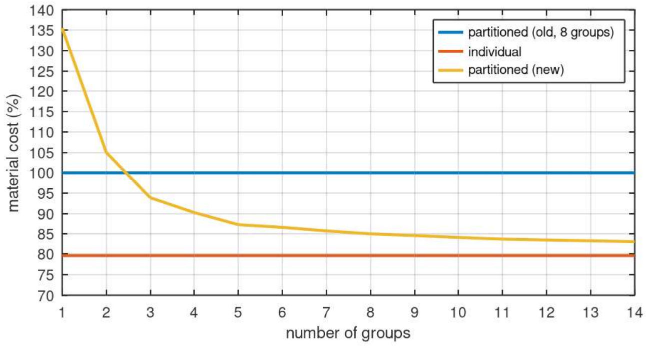

Figure 9 Material cost for a project consisting of 56 design cases. The old partitioning has been chosen as reference. Border plate cost has been included

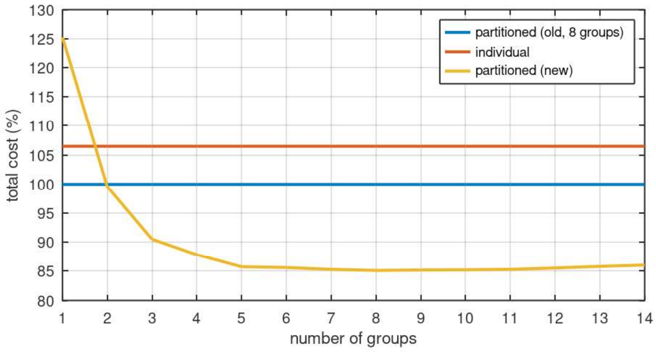

Figure 10 Cost for a project consisting of 56 design cases. The old partitioning has been chosen as reference. Included are all material costs (Figure 9), and estimated project costs for engineering, work preparation, project management, production and logistics. In this particular project, the optimum lies around 8 groups. Beyond 10 groups the decrease in material cost is outweighed by the increasing other project costs

[3] This is done using PuLP [10], a linear programming modeler written in Python.

[4] Some complexities have been omitted. For reasons of computational feasibility, the total mass is *estimated*. The fact that it differs slightly from the *true* total mass has no or minimal impact on the partitioning found.

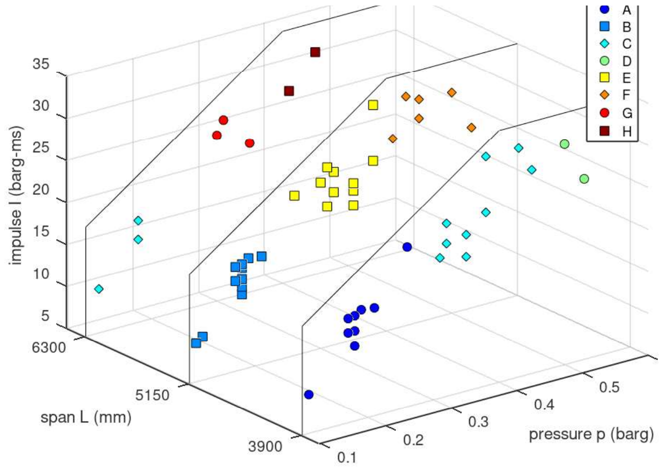

Figure 11 The partitioning into eight groups using the old method (manually)

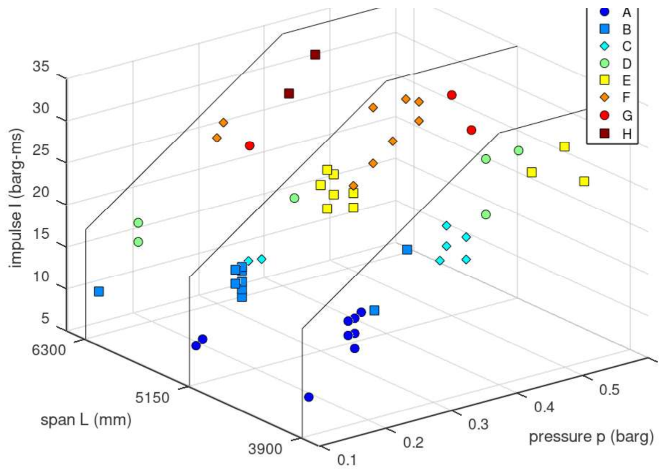

Figure 12 The partitioning into eight groups using the automated BIP method

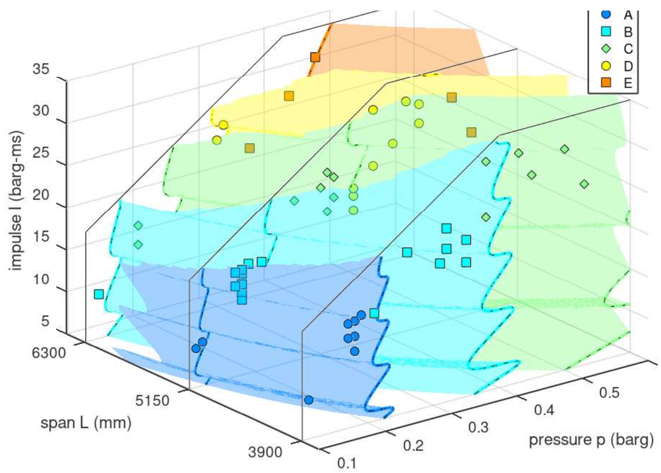

Figure 13 Partitioning into five groups using the BIP method, with the iso-surfaces for each of the group profiles

If the design cases are partitioned into enough groups (5 or more), partitioning does not come at a significant increase in material cost compared to optimising all design cases on an individual basis. However, the latter option would lead to an increase in other project costs, such as engineering, work preparation, production, logistics, and project management. In general, more groups lead to a lower material cost but higher other project costs. An estimation of that payoff has been made (Figure 10). In conclusion, the new design optimisation methods offer considerable savings on project cost and weight.

A closer look at some of the partitions is in order, as to understand why the new algorithm yields better results. As seen in Figure 9, the new partitioning into eight groups has significantly improved compared to the old one, but where do they differ? The old and new partitions are visualized in Figure 11 and Figure 12, respectively. The most notable difference using the new partitioning method is that design cases from different spans are more often grouped together. For instance, in the manual partitioning only design "C" is used across two different spans, whereas in the automated partitioning designs "A", "B", "D", "E", "F" and "G" are used across multiple spans. The BIP method is better suited to take all design case variables into account and to partition accordingly.

Figure 12 visualises the way in which the design cases are partitioned but provides no information on the profiles designed for the groups. In section 2 the notion of an iso-damage curve has been introduced (Figure 4). This 2D representation can be extended to 3D if the additional variable of wall span is considered. If this variable is added, an iso-damage surface is obtained and these iso-damage surfaces can be plotted for every group profile, for instance for the partitioning into five groups (Figure 13). The iso-damage surfaces partition the parameter space and lie as close as possible to (but "outside"!) the design cases linked to them. This notion of distance from the iso-damage surface to its design cases will be used to determine which cases will be verified using FEA.

3.3 Verification of Design Cases

The SATEL model estimates panel responses at a low computational cost, making it ideal for optimisation purposes. However, for the purpose of verification, SATEL is not able to provide the necessary level of detail. For example, the influence of perturbations (for example wall penetrations), local buckling effects [11], and the possible interaction between perturbations and buckling cannot be captured by this single-degree-of-freedom approach. Numerical analysis, for example using the finite element method, can provide such insights (Figure 14).

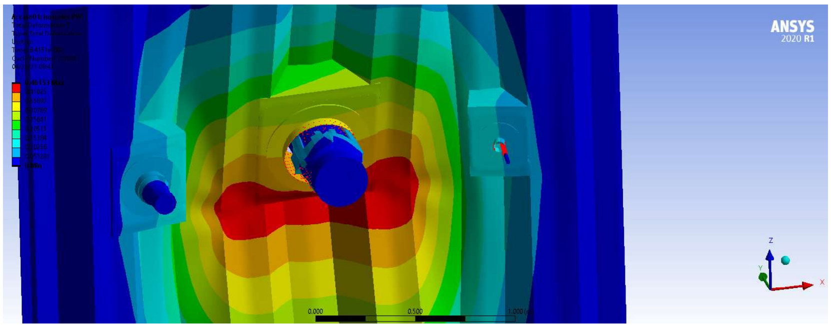

Figure 14 Numerical analysis can accurately capture the interaction between the panel and perturbations such as penetration frames, possibly resulting in buckling. In this case, Ansys Explicit Dynamics [12] is used, a finite element code that is specialised for fast dynamics, such as blast

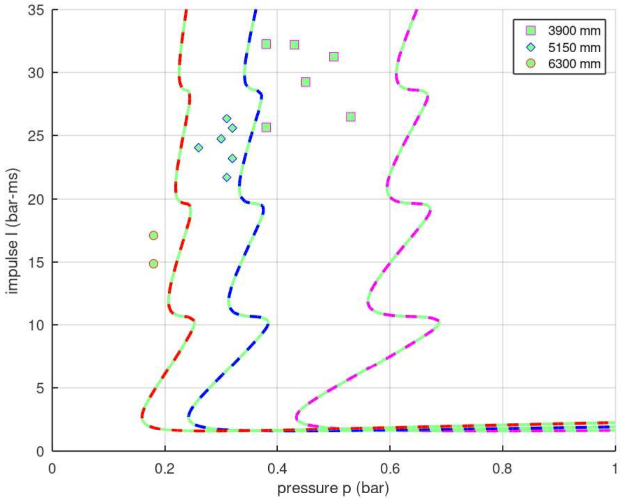

Figure 15 Iso-lines for design C, based on an optimisation using 5 groups. The design case which has the shortest distance to the iso-damage curve is selected for numerical analysis. This is done on a per span-basis

Finite element analysis of the rapid transients that are typical to blast requires specialised explicit time integration solvers to accurately solve for the equations of motion as a function of time [11]. In the particular case of blast wall problems, time steps as small as a tenth of a microsecond (1e^{-7} s) are sometimes necessary. With such small time steps, traditional *implicit* finite element solvers are usually too slow to be computationally feasible. Imposing a larger time step, as is sometimes mistakenly done to speed up computation with an implicit solver (for example when expensive explicit solvers are not available), often violates the Courant-Friedrichs-Lewy condition [13-15], yielding simulation results that are not trustworthy.[5]

Even when the faster explicit solvers are employed, the computational cost can be serious: It is not uncommon for a single blast wall problem to take more than a day to finish on an average workstation![6] From this it becomes apparent that when confronted with a large number of design cases, choices have to be made regarding which cases to analyse.

The partitioning into 5 groups (Figure 13) shows that for each of the three spans, there are multiple design cases that belong to design "C". Cross sections of this panel's iso-damage surface can be plotted in 2D for every span (Figure 15). The design cases belonging to each span can be plotted alongside of their corresponding iso-curve. The design case that is the closest to the iso-curve experiences the highest level of damage among its peers, which is why it is selected for numerical analysis. In this example, this means three design cases are selected, instead of the total of 14 that belong to this group.

Even though iso-damage curves constitute a practical way to assess design cases, they are not the only criterion on which the choice of design cases is based. In practice, a certain degree of heuristics also contributes to the selection. For instance, a design case that is the closest to the iso-damage curve can be a blind, unperturbed panel, whereas the design case that comes just after this can be perturbed by a large HVAC-penetration. In such situations the selected cases from other preliminary analyses are amended with cases selected using the iso-damage curves.

4 Conclusions

Corrugated blast wall projects vary in size, ranging from one, a few, to dozens of design cases. A brute force method based on the SATEL model to design a separate profile for each design case has been presented. This method results in substantially leaner designs for individual design cases. However, for larger projects an individual profile design for each design case would lead to high project complexity and cost. As a solution, an automated partitioning method in which a binary integer programming (BIP) problem is solved has been presented. This method yields improved results over previously used manual partitioning methods. Compared to optimising for each individual design case, partitioning does not come at a significant increase in material cost, and leads to a significant reduction in total project cost. A selected subset of the

[5] In practice, this time step depends on the wave propagation speed in the steel material, and the chosen mesh element size.
[6] A Microsoft Windows 10 Pro workstation with an Intel Xeon 3.50 GHz CPU and 32 GB of RAM.

designed profiles (or for smaller projects, the entire set) is verified against project specifications using numerical analysis, which can achieve a level of detail a SDOF-model cannot.

With the presented methods the design of corrugated blast walls is automated. A significant material cost and weight reduction is achieved, while the protection of people and equipment against blast is ensured. This comprehensive design strategy provides a flexible approach to optimisation of blast walls from the FEED phase of a project, until and including the as- built verification.

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