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DESIGN GUIDELINES AND OPTIMIZATION OF UHP-FRC BLAST WALLS FOR DIFFERENT SCALED DISTANCES

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Abstract: Ultra High-Performance Fiber Reinforced Concrete UHP-FRC, is the latest generation of structural concrete, having outstanding fresh and hardened properties, this includes the ease of placement and consolidation with ultra-high mechanical properties, as well as toughness, volume stability, durability, higher flexural, tensile strength and ductility. As more research is being focused on it, the material behaviour and characteristics are getting more understood, and the research demand for the special applications of the UHP-FRC is growing higher. One special application that UHP-FRC is thought to have an outstanding performance at is in the field of protective structures, specifically against blast loads. This paper presents part of a study that is concerned with the behaviour and response of UHP-FRC wall panels under blast load. Where a design optimization study of the response of a 200 MPa UHP-FRC under blast loads was conducted using finite element modelling, the parameters being tested were the thickness ranging from 100 mm to 300 mm at 25 mm increments, in addition to the reinforcement ratio of 0%, 0.2%, 1%, 3%, the aspect ratio of 1, 1.5 and 2, and the boundary condition is of 4 edges fixed restrained. The numerical simulation has been performed using an explicate finite element software package. The complete behaviour of UHP-FRC is defined using the concrete damage plasticity model. Concrete constitutive model has been developed considering the contribution of tensile hardening response, fracture energy and crack-band width approaches to accurately represent the tensile behaviour and guarantee mesh independence of results. The blast load is applied using the Conventional Weapons (ConWep) method of the US Army Corps of Engineers (USACE) that is built into the finite element software. The validity of the numerical model used is verified by comparing numerical results to experimental data.

1 INTRODUCTION

UHP-FRC is a special type of concrete having an outstanding fresh and hardened properties, this includes the ease of placement and consolidation with ultra-high early and long term mechanical properties, as well as toughness volume stability, durability, higher flexural and tensile strength and ductility (Kosmata et al. , 2003; Graybeal, 2006; Naaman, 2007; Wille and Naaman, 2010), UHP-FRC material offers a higher potential for outstanding performance in a variety of special and interesting applications.

To achieve these properties coarse aggregate is eliminated, and only fine particles are used; the grain size distribution should be optimized to densify the mix and improve rheology. Moreover, a superplasticizer or high range water reducer should be used to improve rheology while maintaining the W/C as low as 0. 2. Fibres usually steel or synthetic fibres should be added as a volumetric ratio up to 2% to improve ductility and achieve higher tensile and flexural strength and fracture energy.

The high compressive capacity and high flow-ability, as well as low porosity, is achieved by optimizing the particle packing, water content and the use of chemical and mineral admixtures. The durability of the UHP-

FRC is enhanced by the low porosity which makes it suitable for a wide array of applications (Naaman, 2007; Wille and Naaman, 2010). It also allows the construction of sustainable and economical structures with extraordinarily slim designs. Its ultra-high strength and ductility make it the ultimate building material, e. g., For bridge decks, storage halls, thin-wall shell structures, and highly loaded columns.

It has been found out experimentally at Ryerson University that the fracture energy of UHP-FRC is about 100 times that of normal concrete (Wahba and Marzouk 2012).The high-energy absorption capacity of UHP-FRC enables the construction of shield plates that play an important part in protecting existing strategic buildings against extreme loading conditions caused by blast, shock or impact loads (Othman and Marzouk, 2016; Lee, Choi and Kim, 2016; Othman, 2016; Li, Wu and Hao, 2015; Ellis et al. , 2014; Rebentrost and white, 2011;Schleyer et al. , 2010)

On the material behaviour level, the research demand on UHP-FRC is growing higher, the material behaviour and response and how to identify it and capture the actual behaviour as well as the fracture behaviour are of specific interest to researchers over the last decade.

During the past ten years, the German and Japanese codes have started to add new sections to address the different mechanical properties and limitations of this new material. UHP-FRC is used mostly in the construction of bridges and other limited applications for high rise buildings, marine, and offshore structures.

UHP-FRC is still relatively expensive material, thus, it is anticipated that UHP-FRC will find an increasing market as a thin protective cover for reinforced concrete structures in specific zones where the superior properties are needed (Habel and Gauvreau 2008).

The research demand for the special applications of the UHP-FRC is growing higher, the material behaviour, characteristics are getting more understood as more research is being focused on it. One special application that UHP-FRC is thought to have an outstanding performance in the field of defensive structures, and protective shields, specifically against blast loads, As strong engineering evidence at low speed impact tests done by (H. Othman and Marzouk 2016) on UHP-FRC slabs showed that UHP-FRC has more ductility and energy absorption due to the presence of fibres that bridges the cracks and thus also produces a more ductile failure mode and no fragmentations, than the panels of the same size and geometry made from HSC and NSC.

The aim of this research is to present a better understanding of the influence of the design parameters on the behaviour of UHP-FRC wall panels under blast loads, through conducting a parametric and optimization study using a calibrated finite element numerical simulation. Moreover, to set guidelines and charts for selecting the optimum wall panel for a specific blast load environment and scaled distance, also to set the foundation for further investigation of the response different UHP-FRC wall panel assemblies.

The numerical simulation has been performed using the finite element software package ABAQUS/Explicit (Simula 2016), with a concrete material model which considers the contribution of tensile hardening response, fracture energy and crack-band width approaches to accurately represent the tensile behaviour and guarantee mesh independence of results. The complete behaviour of UHP-FRC is defined using the concrete damage plasticity model. The blast load is applied using the Conventional Weapons (ConWep) method of the US Army Corps of Engineers (USACE, 2017) that is built into the finite element software (Simula 2016). The validity of the numerical model used is verified for drop-impact load against experimental test data (Othman and Marzouk 2018), and for blast loading by comparing numerical results to the available experimental data from research conducted by (Yi et al. 2012).

2 OPTIMIZATION PROCESS

The numerical modelling and optimization process is performed using a complete calibrated model to take advantage of the enhanced post-peak capacity of UHP-FRC. The design optimization of UHP-FRC protective panel is performed considering blast loads up to 420 kg charge mass of TNT at standoff distances 6 m as requested by the client, the choice of this loading scheme, or defined by the FEMA as blast environment follows the blast load environments presented by the FEMA Figure 1, the load was chosen such that it gives a scaled distance value of Z=0.8 $m/kg^{1/3}$ which is higher than the threshold that would result in a structural damage to walls and columns which has a scaled distance of Z=2.37 $m/kg^{1/3}$ as shown in Figure 2.

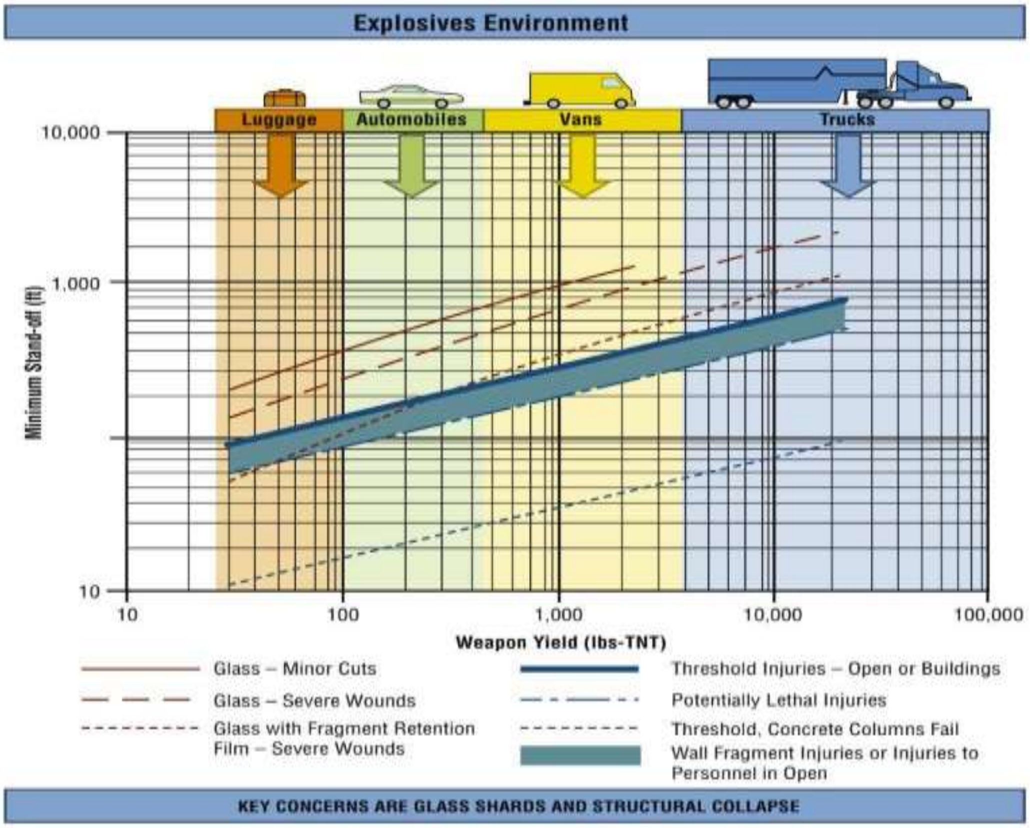

Figure 1 Blast Environment. (FEMA-426, 2003)

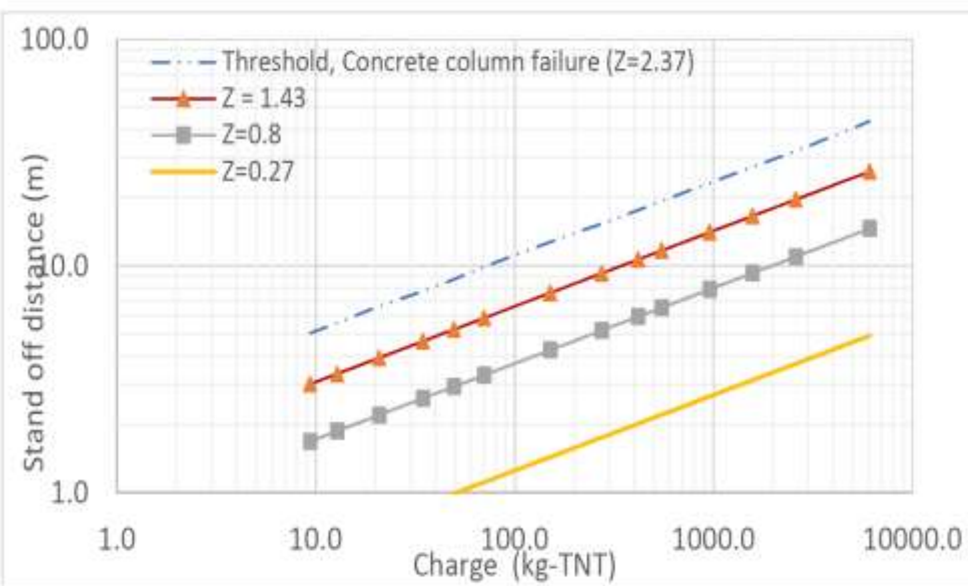

Figure 2 Scaled distance scenarios for the optimization process.

In the current design optimization, in addition to material optimization achieved by using UHP-FRC, shape and size optimization techniques (Tomás and Martí 2010; H. Othman, Tayel, and Marzouk 2015) are combined with the aim of maximizing stiffness, and minimizing the cost while satisfying both the design stresses and construction requirements. The first objective function of maximizing the stiffness is attempted by minimizing the sum of the strain energy of the UHP-FRC panel under the considered blast loads. On the other hand, the second objective function of minimizing the cost will be achieved by minimizing the concrete volume (i.e., Minimizing material usage) and using minimum steel reinforcement ratio. The design variable to be optimized are the wall thickness, the aspect ratio of the panel (i.e., Length/width ratio), and the reinforcement ratio. The optimization design flow is illustrated in Figure 3.

Figure 3 Flow chart of the optimization process

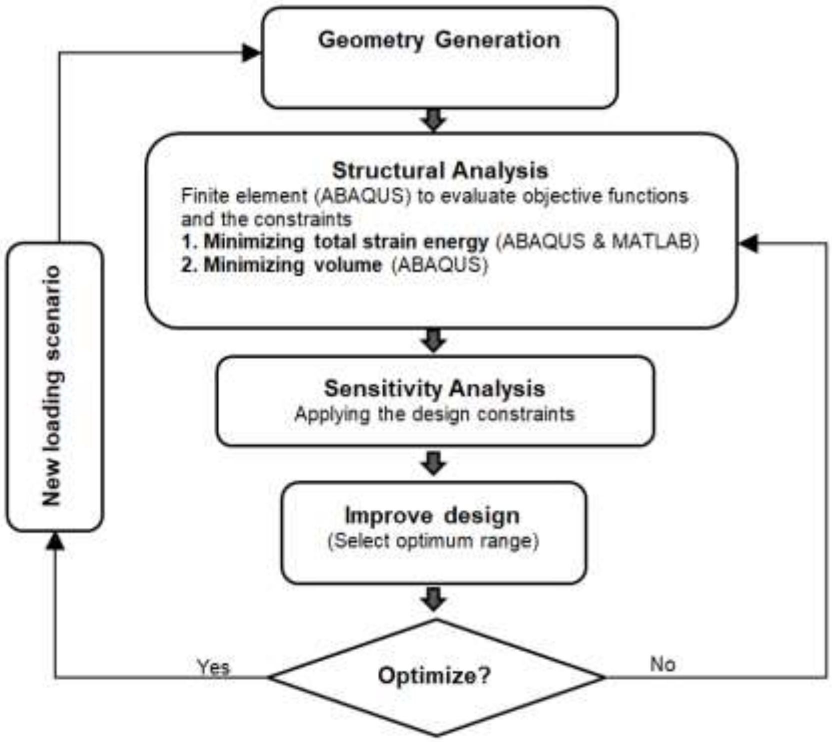

Figure 3 Flow chart of the optimization process (Othman, Sabrah, and Marzouk 2019).

3 OPTIMIZATION PARAMETERS BASED ON BLAST TESTING

The numerical analysis was performed using the calibrated model based on experimental results, the parameters being tested were the thickness ranging from 100 mm to 300 mm at 25 mm increments, in addition to the reinforcement ratio of 0.0%, 0.2%, 1%, 2%, and length to width aspect ratio of 1, 1.25, 1.5,1.75 and 2.

The calibration of UHP-FRC model under blast load is performed such that only the values for material parameters with a significant effect where considered. It was observed in the calibration process, that the influences of material parameters on the impact force and reaction results are generally limited. Therefore, only the results of midpoint displacement, midpoint pressure and acceleration were considered in the calibration (H Othman and Marzouk 2014)

The exact experimental test setup and loading and boundary conditions were modelled in the FEM for UHP-FRC. The results of the calibration for UHP-FRC are shown in Figure 3 and Figure 4. It can be observed that the mid-point displacement and pressure for the FEM model falls within an acceptable range from the experimental results by (Yi et al. 2012).

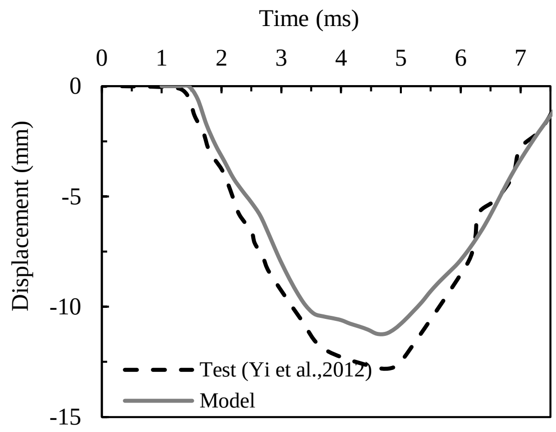

Figure 3 Mid-point displacement for UHP-FRC slab.

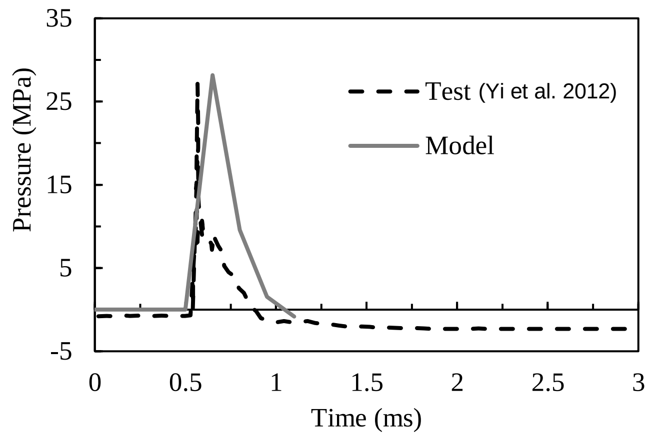

Figure 4 Mid-point incident pressure on the top surface of the UHP-FRC slab.

4 MODEL GEOMETRY AND BOUNDARY CONDITIONS

The blast wall panels were modelled as being rigidly fixed on all four edges using steel channels that are rigid and non-deformable. Such supporting system was used as the effect of the boundary condition is not part of this study. The load was applied on the blast panels using the ABAQUS built in ConWep module, the charge was defined at a reference point located at the specified standoff distance from the center of the panels.

5 ANALYSIS RESULTS.

The optimization process started with optimizing the thickness through running the analysis for wall panels having an aspect ratio of L/W = 1.00 and 1.50 as presented in Table 1 and Table 2 respectively, this yielded an optimum range of 150 mm to 225 mm for L/W = 1.00 as shown in Figure 5 and the range narrowed down to 150 mm to 200 mm for L/W = 1.50 as shown in Figure 6. As for the other two groups having an aspect ratio of L/W = 1.25 and L/W = 1.75 the analysis was carried out for the panels within the pre-determined optimum range of 150 mm to 200 mm as presented in Table 3 and Table 4 respectively.

Analysis of Panels with aspect ratio L/W = 1.00 revealed that the thickness had a greater influence on improving the response and midspan displacement. Table 1 shows the maximum displacement experienced by each wall panel. Moreover, the reinforcement ratios of 0.2% and 1% were not significant in improving the performance nor in reducing the midspan displacement. The optimum thickness rage reached in this group was 150 mm to 225 mm.

Table 1 Maximum displacement for slabs of aspect ratio L/W = 1.0

Reinforcement ratio	Thickness (mm)	100	125	150	175	200	225	250	275	300
	Thickness /Area (m^{-1})	0.031	0.038	0.044	0.050	0.056	0.063	0.069	0.075	0.031
0	maximum displacement (mm)	69.28	29.12	15.86	11.00	7.09	5.62	4.35	3.04	2.64
0.2		66.13	28.15	15.45	10.59	7.78	5.28	4.31	3.07	2.59
1		56.33	27.12	14.23	7.81	6.13	4.56	3.41	2.86	2.44

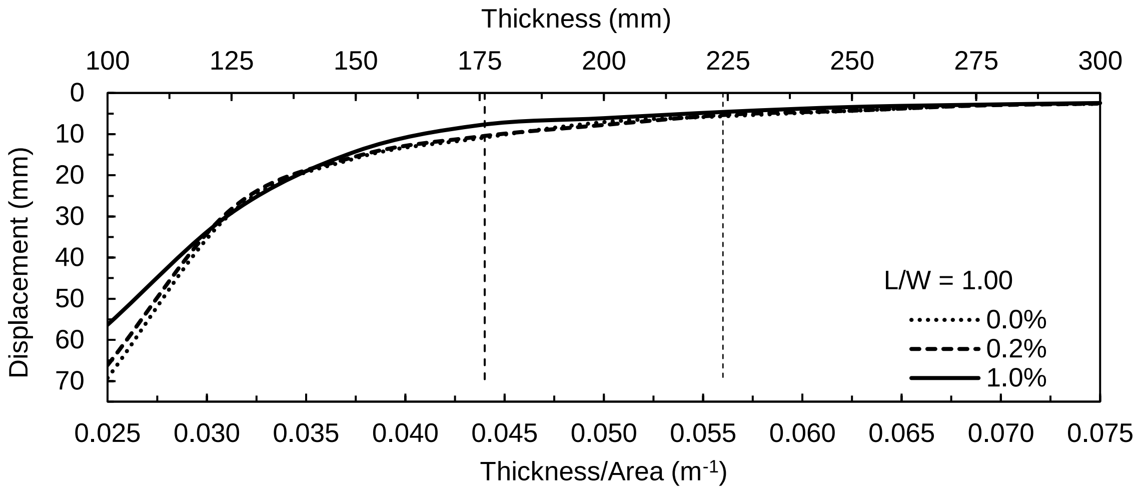

Figure 5 The ratio of thickness to area versus maximum displacement for an aspect ratio of L/W= 1.00 for different reinforcement ratios.

On the other hand, Panels of aspect ratio L/W = 1.50 narrowed down the that for walls in this group the thickness had a greater influence on improving the response and midspan displacement. Table 2 shows the maximum displacement experienced by each wall panel. Moreover, it is still obvious that the reinforcement ration is not significant in improving the performance nor in reducing the midspan displacement. The optimum thickness rage reached in this group was 150 mm to 200 mm as shown from in Figure 6 At this point it was determined that the optimum panel thickness for the specified scaled distance of Z=0.8 m/kg$^{1/3}$ would be around 150 mm or a more general term, the optimum wall panel thickness would be of a thickness to surface area ratio of 0.044 m^{-1}.

Table 2 Maximum displacement for slabs of aspect ratio L/W = 1.5

Reinforcement ratio (ρ, %)	Thickness (mm)	100	125	150	175	200	225	250	275	300
	Thickness/Area (m^{-1})	0.031	0.038	0.044	0.050	0.056	0.063	0.069	0.075	0.031
0	Maximum displacement (mm)	45.3	20.9	12.0	8.9	5.9	4.4	3.9	3.1	2.4
0.2		42.0	20.2	11.8	8.4	5.5	4.3	3.6	2.6	2.1
1		40.2	19.0	11.3	7.6	5.1	3.8	3.4	2.7	2.3

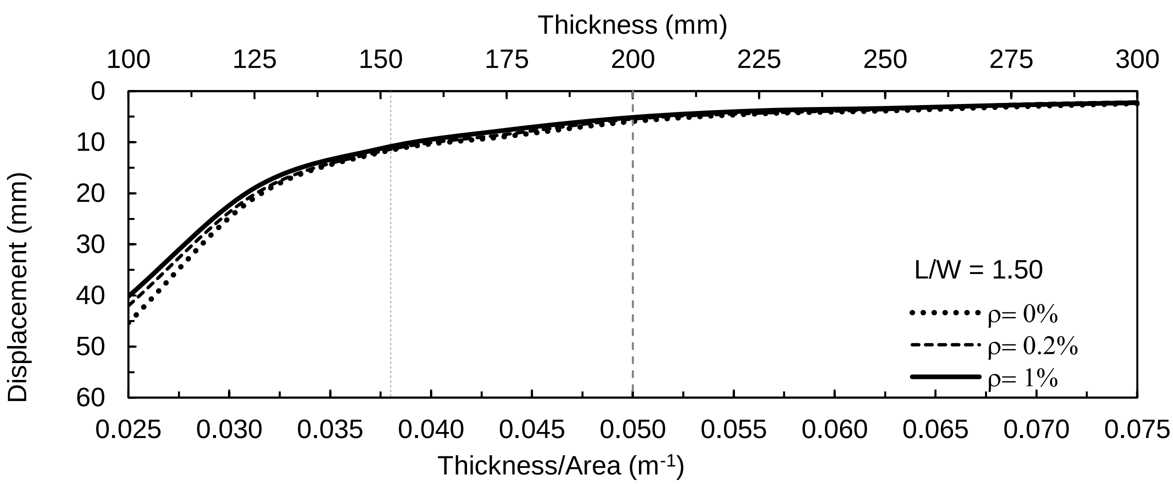

Figure 6 The ratio of thickness to area versus maximum displacement for an aspect ratio of L/W= 1.5 for different reinforcement ratios.

Two more rounds of analysis were carried out to obtain the optimum aspect ratio, for aspect ratios of L/W =1.25 and 1.75, for each aspect ratio panels of thickness 150 mm, 175 mm, and 200 mm was each having reinforcement ratio 0%, 0.2%, 1%, and 2%. Maximum displacement results for the two sets are presented in Table 3 and Table 4 and Figure 7 and Figure 8. it was observed that as the aspect ratio increases the maximum displacement decreases, moreover, the effect of the reinforcement ratio on reducing the maximum displacement was almost negligible as shown by Table 3 and Table 4. The optimum range for thickness remained between 150 mm and 200 mm for a scaled distance of Z=0.08 m/kg$^{1/3}$, or within thickness to surface area ratio of 0.038 to 0.05 respectively. The optimum thickness chosen is 150 mm for cost-effectiveness purposes.

Table 3 Maximum displacement for slabs of aspect ratio L/W = 1.25

Reinforcement ratio (ρ, %)	Thickness (mm) Thickness/Area (m^{-1})	150 0.0375	175 0.04375	200 0.05
0.0	maximum displacement (mm)	13.9	10.0	6.3
0.2		13.6	9.9	6.2
1.0		11.8	8.2	5.2
2.0		10.2	6.6	4.4

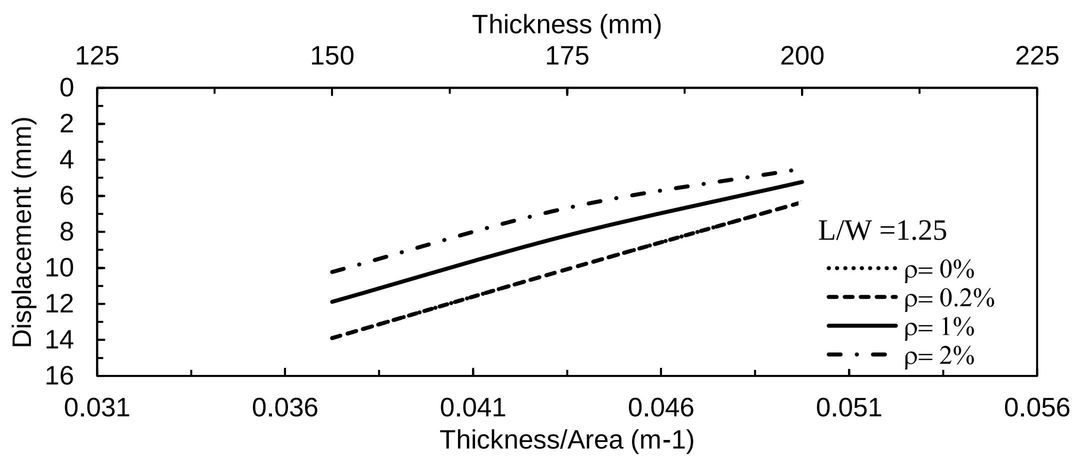

Figure 7 The ratio of thickness to area versus maximum displacement for an aspect ratio of L/W= 1.25 for different reinforcement ratios.

Table 4 Maximum displacements for slabs of aspect ratio L/W = 1.75

Reinforcement ratio (ρ, %)	Thickness (mm) Thickness/Area (m^{-1})	150 0.038	175 0.044	200 0.050
0.0	maximum displacement (mm)	8.922	6.618	4.467
0.2		8.663	5.957	4.265
1.0		7.576	5.389	4.431

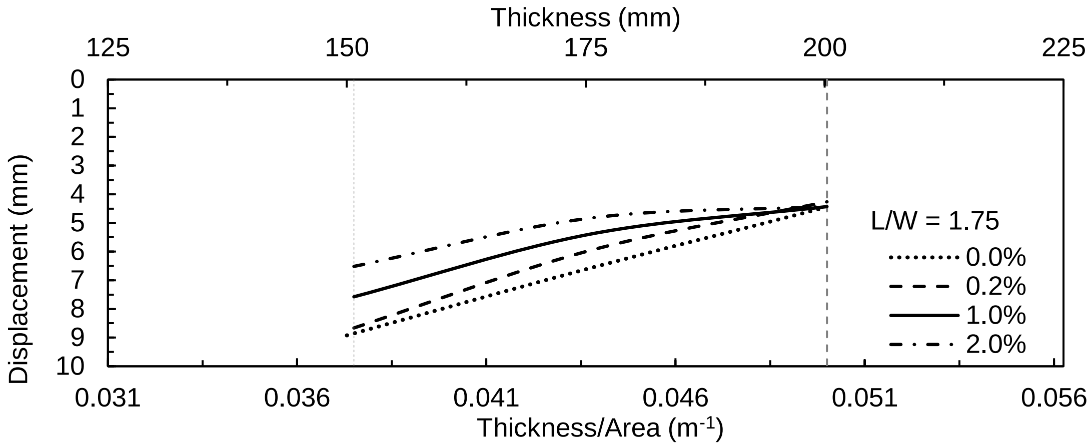

Figure 8 The ratio of thickness to area versus maximum displacement for an aspect ratio of L/W= 1.75 for different reinforcement ratios.

Further processing of the simulation data showed that the optimum aspect ratio of the panel is L/W =1.75 as shown in Figure 8, moreover, it revealed that the reinforcement is not much significant in improving the displacement, thus a minimum reinforcement ratio of 0.2% should be sufficient.

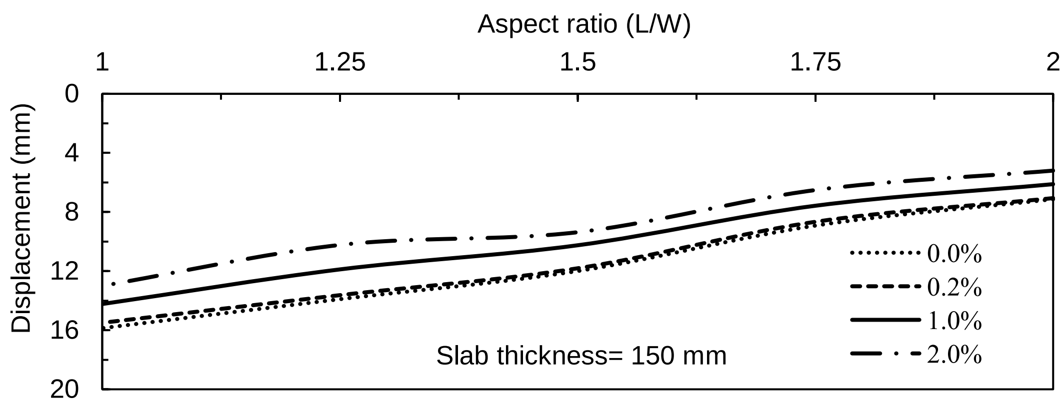

Figure 9 The aspect ratio versus maximum displacement for a slab thickness of 150 mm at different reinforcement ratios.

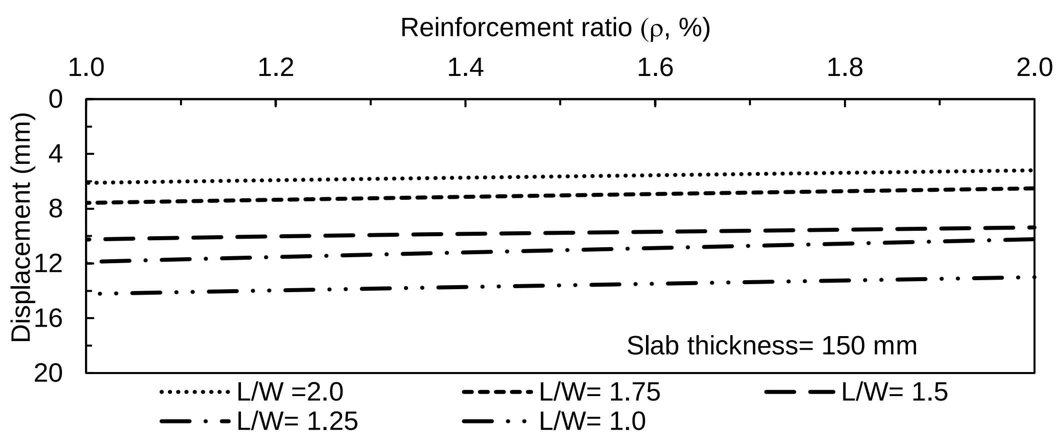

Figure 10 The reinforcement ratio versus maximum displacement for a slab thickness of 150 mm at different aspect ratios.

6 CONCLUSIONS

The shape and size optimization techniques were combined in the current report, by minimizing maximum displacement and cost. The proposed technique of optimization can be considered as a valuable tool for the blast-resistant design to set a proper value range of different dimensions of different types of protective panels at a different scaled distance. From the results obtained in the current study, the following aspects can be highlighted:

1. For blast wall panels subject to blast loads of a scaled distance Z = 0.80 kg/m$^{1/3}$ the optimum range of thickness is between 150 mm and 200 mm, or within the thickness to surface area ratio of 0.038 to 0.05. The optimum thickness recommended is 150 mm for cost-effectiveness purposes under the considered loading environment and a panel surface area of 4 m^2.

2. The optimum shape of the blast shield wall panel should be rectangular with a side length aspect ratio of L/W=1.75.

3. The effect of reinforcement ratio up to 2% showed to be insignificant to the overall performance of UHP-FRC panels under blast load under the considered conditions herein, however, it has been recommended by other researchers that the reinforcement ratio should go up to 5%.

4. As the aspect ratio increases the maximum displacement decreases, moreover, the effect of the reinforcement ratio on reducing the maximum displacement was almost negligible

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