1 Introduction

1.1 General

Wind tunnel testing of the finalised Bramley Moore Dock proposals was undertaken by RWDI between September and November 2019 and the results of these tests are reported in the Wind Microclimate ES chapter (Chapter 16, ES Volume II). These tests were the culmination of an extensive programme of wind tunnel tests and Computation Fluid Dynamics (CFD) tests undertaken over a two year period between 2017 and 2019, with wind tunnel testing undertaken by RWDI and CFD tests undertaken by BuroHappold Engineering. In response to these tests, the design of the stadium evolved over this period to achieve a safer and more comfortable wind microclimate.

Key design interventions undertaken during this period that are now incorporated into the final scheme design include:

- The car parking building has been integrated into the main stadium building to create a built form which helps to shelter spectators arriving and leaving the west stand of the stadium from strong down draughts.
- A practical and functional soft and hard landscaping design, which comprises:
    - Trees and vegetation
    - Fixed sculptural forms of visual connectivity and similar language to the stadium façade and materiality. These elements will be unadorned with advertising or other major messaging, but read as contiguous with the stadium architecture
    - Banners and flags, which would be integrated into signage and historical visual language of the club.

This technical appendix provides:

- information on the wind tunnel and CFD tests undertaken prior to the wind tunnel tests reported in the Wind Microclimate ES chapter
- information on the design interventions integrated into the proposals in response to these tests.

1.2 Objectives of the Historic Wind Tunnel and CFD Testing

The objective of the programme of wind microclimate analyses undertaken between 2017 and 2019 was to arrive at a finalised scheme design that provided a safer and more comfortable wind microclimate at the site and in the surrounding area, while also ensure that the design interventions spoke to the stadium architecture, respected the heritage context of the site and integrated with and coordinated with the proposed site circulation.

1.3 Overview of design journey

As part of the design journey, the project team examined the following:

- The optimum assessment and design methodologies for the project, which led the team to employ both wind tunnel testing and CFD;
- The specific nature of wind on the site;
- The relevance and appropriateness of the industry standard comfort and safety criteria (it will be explained why these have been retained later in this report);
- The overall massing and form of the stadium and how this influences wind safety and comfort conditions through wind-structure interactions;
- The optimum location and placing of the stadium on the site;
- Passive localised design intervention measures, including soft and hard landscaping, such as trees, flags and sculptural objects;
- Localised management measures whereby certain balconies or terraces would be closed to access in high winds;
- The potential for larger scale operational management processes for large crowds and whether these could be used to reduce fixed landscaping design intervention. (The chapter will explain why these have proved unfeasible and inappropriate for this type of development).

1.4 Design Method Overview

The iterative approach to the assessment and design evolution process that has been employed is demonstrated in the Figure below: This methodology applies to both the wind tunnel and CFD testing.

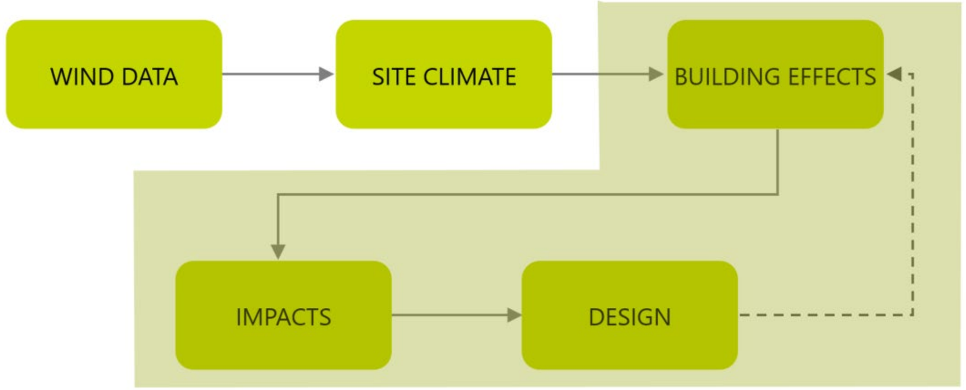


Figure 1—1 Diagram of the wind engineering method, with the iterative design process shown with the shaded area.

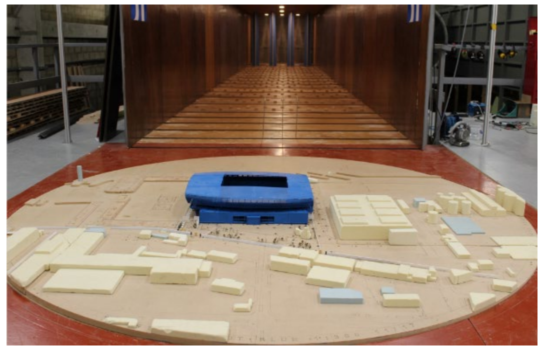
The design method is described in text below:

- Available wind data for the region is established and transposed to the specific project site.
- The nature of the important characteristics of wind climate are examined to understand important parameters such as the prevailing wind directions
- The impact of the wind onto the building is tested (either by wind tunnel or CFD testing) and impacts in terms of safety and comfort determined. Where necessary, the design is revised and testing redone. The iterative assessment and design evolution process continues until .

Wind tunnel testing was considered the primary assessment tool. The CFD was carried out as a design development tool working in parallel to the wind tunnel testing with the CFD model calibrated against the physical wind tunnel test model.

Wind tunnel and CFD have different advantages and disadvantages. Our workflow has been to consider wind tunnel testing as the single consistent way of developing and producing final information as this is the most common method for planning submissions in the UK. CFD is highly effective at certain forms of study and was used predominantly in the project for design development of the west stand massing options.

In both wind tunnel testing and CFD analysis methods, design exploration and testing was at times undertaken with a reduced sub-set of the overall wind regime, focusing on the wind sectors of highest energy. However the final results reported in the Wind Microclimate ES chapter have been generated using the full 360 degree wind analyses from the wind tunnel tests.



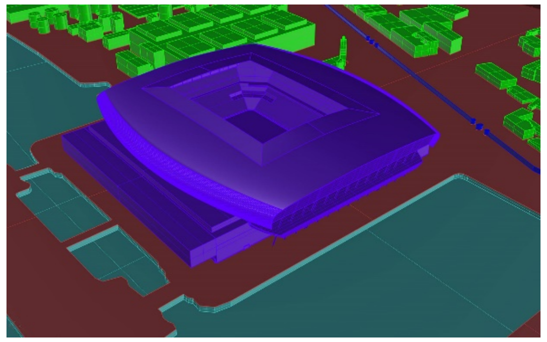


Figure 1—2 Photo on the left of the physical wind tunnel test model in the test laboratory and detailed image on the right of the CFD model used in wind engineering analysis

1.5 Wind at the Site

Source wind data was taken from John Lennon Airport by RWDI and transposed by RWDI, using the industry-recognised methods of the ESDU to create site-specific wind speed data. Further information is provided in the Wind Microclimate ES chapter.

1.6 Assessment Criteria

The Lawson Criteria are guidance only and they are not the only pedestrian wind microclimate assessment criteria that exist, although they are the most prevalent criteria in the UK. The use of alternate criteria was considered. However, to ensure a robust approach and one that is comprehensible to consultees and comparable with other schemes, it was ultimately agreed that the Lawson Criteria would be used.

1.7 Assessment Scenario

Four assessment scenario were considered during the assessment and design evolution process:

- **Configuration 1:** Existing site condition i.e. existing baseline
- **Configuration 2:** Future baseline i.e. Liverpool Waters scheme built out at the application site and on Nelson Dock
- **Configuration 3:** The proposed development (including design interventions) + existing surrounds
- **Configuration 4:** The proposed development (including design interventions) + Liverpool Waters scheme built out on Nelson Dock

The input geometries of the project buildings, site and cumulative designs for the four configurations are addressed elsewhere in the report as are the final RWDI generated deliverables for each of the four scenario.

2 Design Journey

The design journey can be understood in the context of the following diagram:

• **Configuration 1**: Existing site condition *i.e.* existing baseline • **Configuration 2**: Future baseline *i.e.* Liverpool Waters scheme built out at the application site and on Nelson Dock	
• Existing site + stadium design (prior to design interventions being established)	Tests with the stadium on the site provide the first results which show the impact of the stadium on the site and the non-compliant areas.
• Iterative testing and design evolution **Design journey**	Non-compliant areas of the design have been established and the design is then modified. This iterative process continues through 78 different designs
• **Configuration 3**: The proposed development (including design interventions) + existing surrounds • **Configuration 4**: The proposed development (including design interventions) + Liverpool Waters scheme built out on Nelson Dock	A final scheme design is established and the scheme is tested and reported in the Wind Microclimate ES chapter. The results illustrate the improvement in wind comfort and safety conditions from that of the scheme design first tested in December 2017.

The design journey included the following activities:

- Wind tunnel testing, WT1, undertaken by RWDI in December 2017 closely followed by a pre-planned two-day workshop attended by the project team, investigating and evaluating design intervention procedures on 11, 12 January 2018. A total of 14 different design intervention designs were studies and tested in this workshop phase.
- Wind tunnel testing, WT2, undertaken by RWDI in May 2019 with a pre-planned two-day design intervention workshop on 20th and 21st May attended by the project team. A total of 11 different design intervention designs were studies and tested in this workshop phase.
- CFD studies undertaken by BuroHappold with 15 different design intervention designs through July and August 2019.
- Wind tunnel testing, WT3, undertaken by RWDI with 23 different design intervention designs, in August 2019.
- Wind tunnel testing, WT4, undertaken by RWDI, with 15 different design intervention designs carried out in October 2019.

Taken as a whole therefore, the design journey involved a total of 78 different design intervention designs. This fact conveys the high level of scrutiny given to the process.

2.1 The Scheme Design Prior to Design Interventions

The scheme design, prior to the incorporation of design interventions, was tested in December 2017 within the first wind tunnel test, WT1, and the design arrangement is shown in the figure below

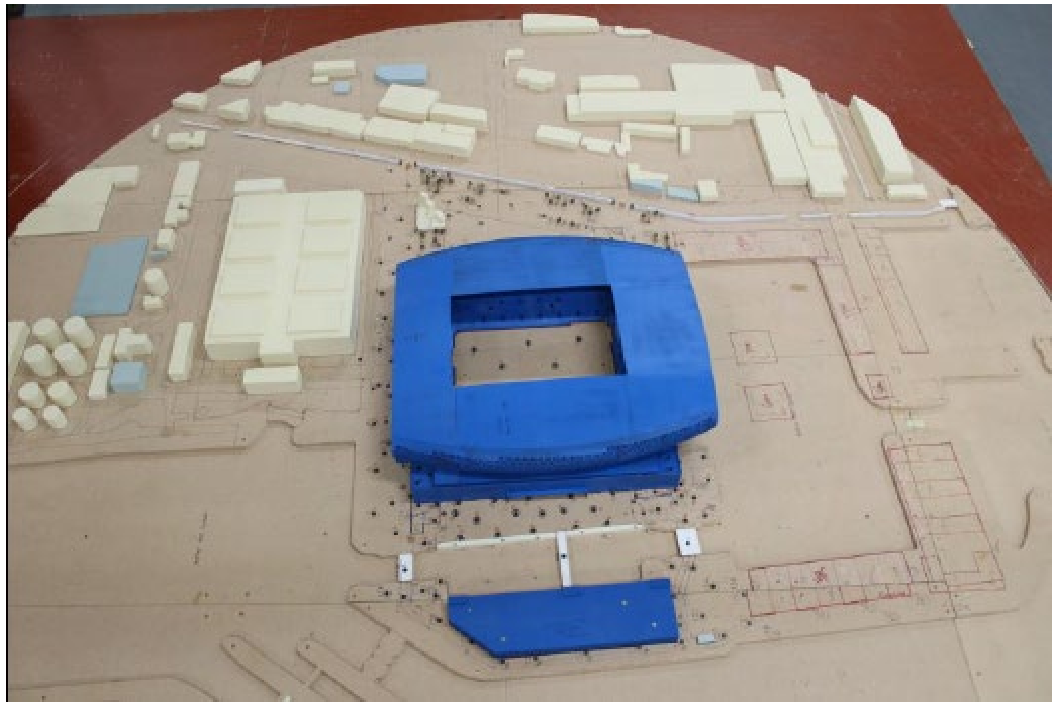


Figure 2—1 Wind Tunnel Test 1, Photo (Pre-mitigated design)

A full range of wind plots from WT1 were generated by RWDI. The safety condition wind plot are presented below, which convey succinctly the nature of design challenge:

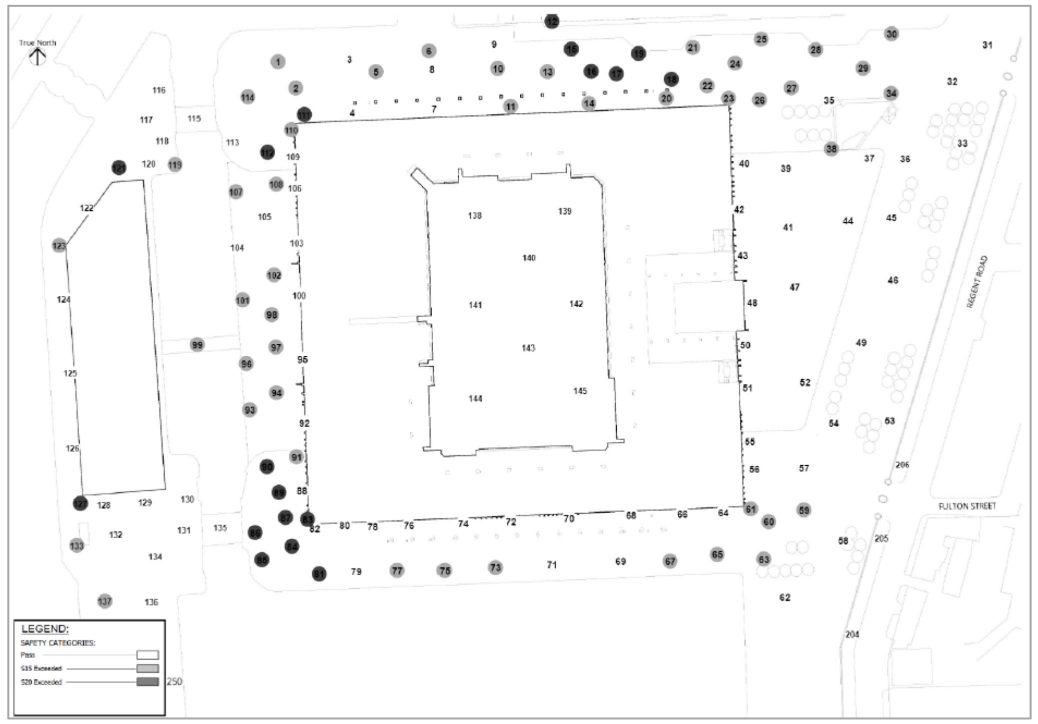


Figure 2—2 Wind Tunnel Test 1, Results

The pre-design intervention wind tunnel test results showed sixty six S15 failures and eighteen S20 failures. The causes of the wind exceedances was examined through the following methods:

- detailed assessment of the numeric data from RWDI which can be broken down to show contributions of wind exceedance according to wind direction;
- smoke visualisations in the wind tunnel test;
- CFD (configuration M1 was chosen as a test case for calibration);

3 CFD Methodology

The wind tunnel testing methodology is reported in the Wind Microclimate ES chapter. The CFD testing methodology is described in the sections below.

BuroHappold has extensive experience of using CFD analysis to assess wind environment issues. As part of the overall engineering study, BuroHappold worked closely with the stadium architects and landscape architects in integrating the findings of the wind studies with other aspects of the site and stadium engineering. The aim of this was to develop a stadium solution that not only mitigated the wind safety and comfort issues, but also provided a holistic approach for access, egress, car parking, concourse arrangements.

3.1 Prevailing winds

The strongest prevailing winds on the site are from the west, southwest, northwest and southeast and these are the winds that contribute significantly to the comfort and safety values. The aim of the CFD study was very much to develop the design and utilise comparative assessments of different designs to establish an optimised single design. As such, in order to progress the design effectively, without unnecessary computer runtime, the design methodology was to seek results only from the governing important wind directions.

The wind directions used in the CFD design development studies were generally from the following six most important directions: 157.5 degrees, 247.5 degrees, 270.0 degrees, 292.5 degrees, 315.0 degrees and 337.5 degrees.

Full 360 degree wind input was not used in the CFD, but carried out in the knowledge that the final wind tunnel tests, used to establish final results, would be undertaken for all wind directions.

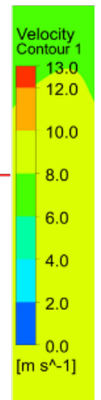
3.2 CFD Methodology: Industry standard comfort and safety criteria

The basis of study is to establish areas of comfort appropriate to use and of safety following the industry standard criteria. The figure below shows the comfort and safety scales for pedestrians in wind environments.

The CFD analysis delivers its results as contour maps showing wind speed at 1.1m above ground whereas the wind tunnel test delivers its results as wind speeds at probe locations. There is a good basis of correlation between the wind values from the tunnel test and the speeds in the CFD analysis and to the information delivered via the probes.

Comfort Scales		
Wind Speed Category	Wind Speed Range (m/s)	Tolerable Activity
A	0 – 4	Pedestrian sitting for extended periods, in the vicinity of entrance doors
B	4 – 6	Pedestrian standing i.e. standing/sitting for a short time
C	6 – 8	Pedestrian walking i.e. Strolling
D	8 – 10	Business walking (walk through – i.e. walking from A to B), Includes cyclists

above this level safety issues likely



Comfort & Safety Criteria		
Criteria	Frequency of Wind Speed Occurrences	Activity
Comfort	< 5%	All pedestrian activities
Safety	< 0.025%	All pedestrian activities

Figure 3—1 Base Design CFD 292.5 degrees

Initial CFD analyses were run to compare the CFD results with the results of the Wind Tunnel tests carried out by RWDI for WT1 and WT2 ###. Good agreement was achieved in the results from the two different engineering analysis methods.

Design Intervention cases M01 and M02 from the first wind tunnel test [WT1] of RWDI were chosen for comparison with the CFD simulations. The details and results of the particular wind tunnel test case summary can be found below and figure 3-2report. The key aspects of the model in the wind tunnel test M01 were:

- The proposed stadium development with the existing surroundings;
- The proposed landscaping scheme: a 50/50 mixture of evergreen and deciduous trees of height 6m was used;

The key aspects of the model in the wind tunnel test M02 were:

- The proposed stadium development with the existing surroundings;
- The proposed landscaping scheme: a 50/50 mixture of evergreen and deciduous trees of height 6m was used;
- Additional landscaping design intervention elements:
    - 3m tall solid parapets along the north and south ends of the thoroughfare at the western side of the stadium;
    - A 3m tall, 50% porous fence along the west edge of the river wall along the thoroughfare to the west of the stadium
    - A 3m tall, 50% porous cover on the bridge between the car park and the western side of the stadium;
    - A full height 50% porous wall at the northern façade;
    - Planters of 1.2m height at the southeast corner of the stadium;

The CFD results showed good agreement and trends to those observed with the wind tunnel. The figure below shows thumbnails of the CFD plots for a selection of wind directions and the safety plot developed by RWDI corresponding to the same design and design intervention configuration.

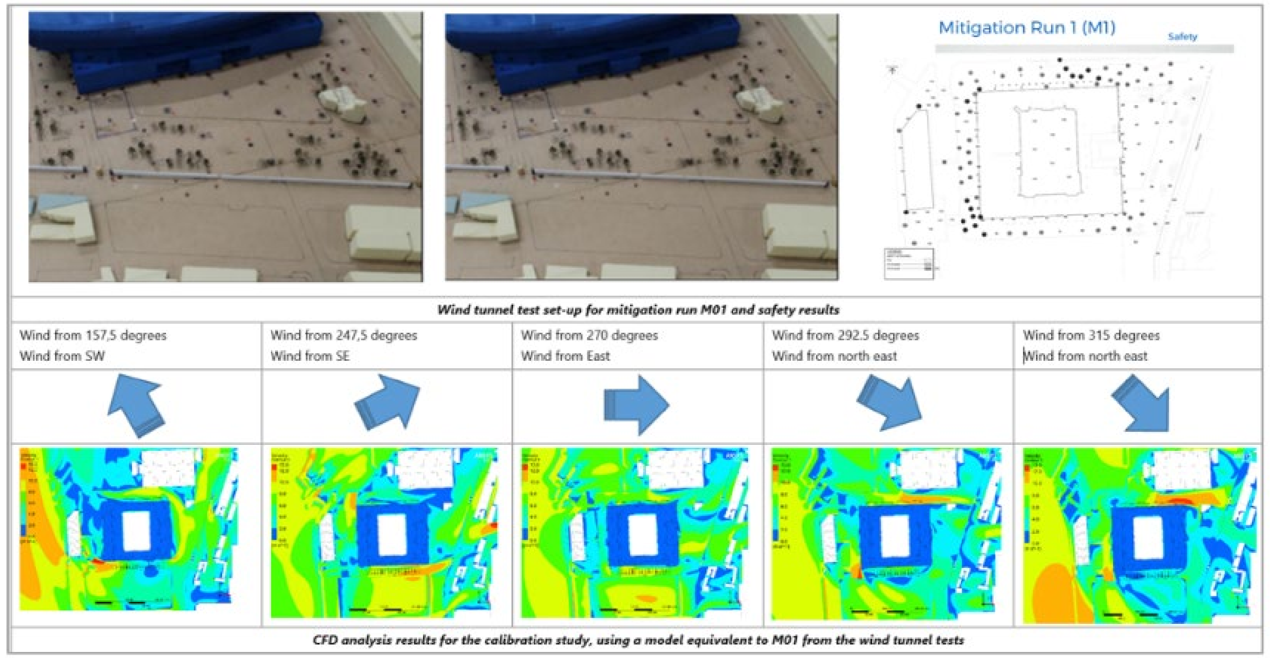


Figure 3—2 Representative images of the calibration analysis showing wind tunnel test model, wind tunnel test results and CFD analysis plots for the same design

The CFD model and analysis was calibrated to the wind tunnel test model and analysis in order that design development studies could proceed with the CFD model. A representative analysis image from the CFD is shown below for wind input from 292.5 degrees and it shows windiness in west and north areas as the wind tunnel test found.

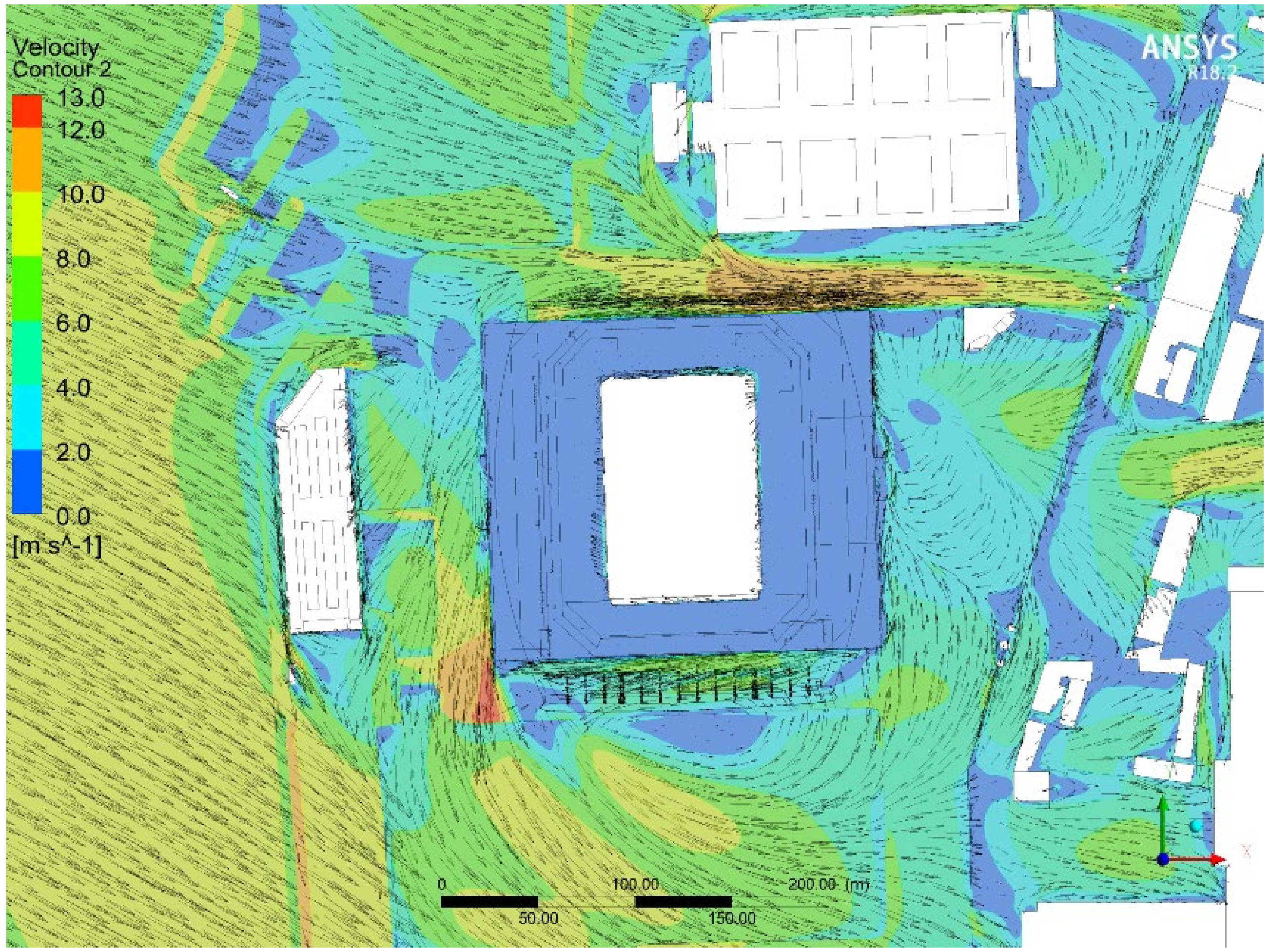


Figure 3—3 Base Design (pre-Design Intervention) CFD 292.5 degrees

The test and analysis results showed there were a number of important wind effects that would need to be mitigated, broadly fitting into types listed below and as shown in the figure below:

- Ground level wind speed exceedance on the site, on the west side of the west stand generated by westerly winds;
- Ground level wind speed exceedance on the site, on the north side of the north stand generated by north-westerly winds;
- Ground level wind speed exceedance on the site, on the south side of the south stand generated by winds from the southerly sector;

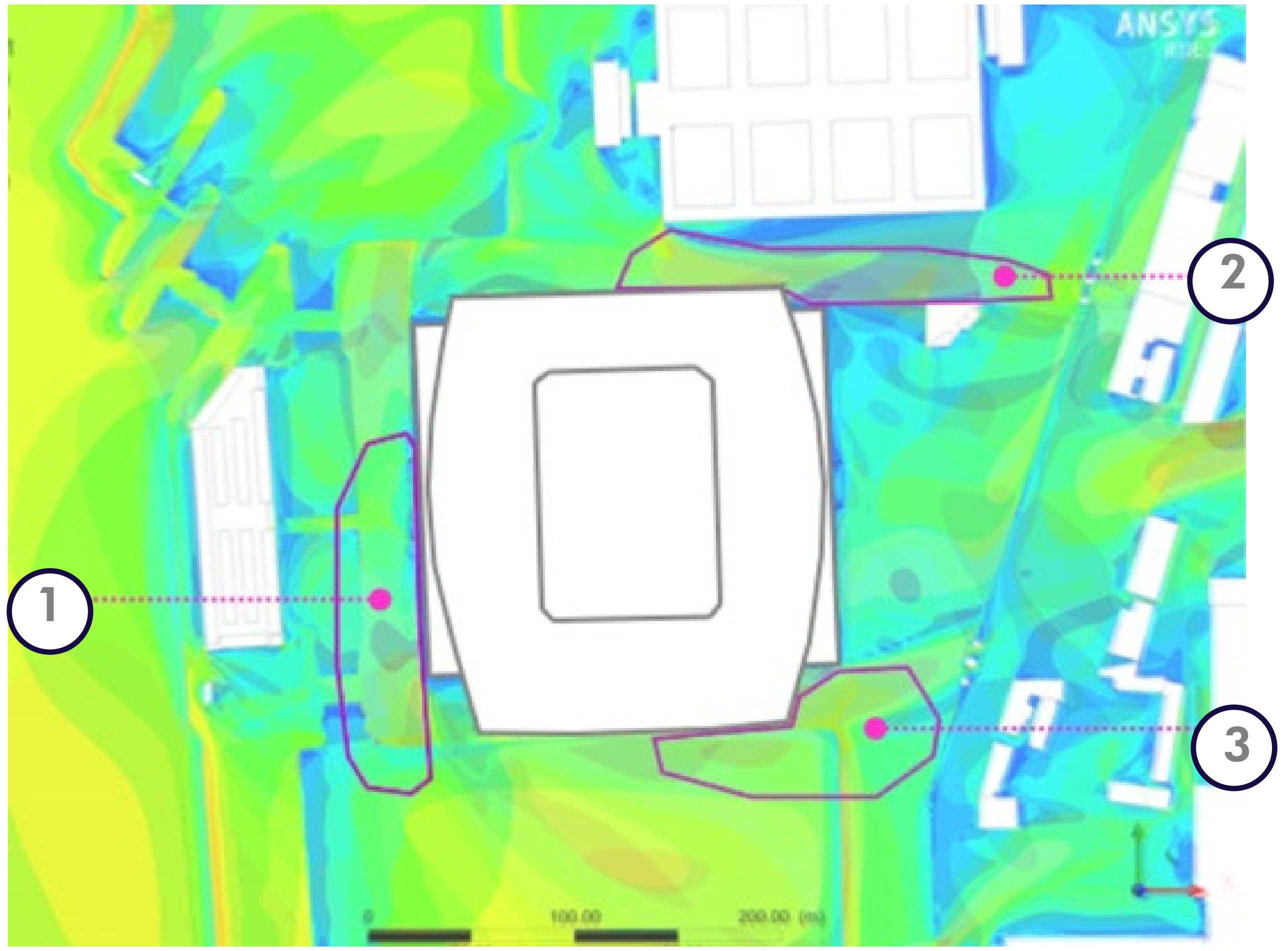


Figure 3—4 Base Design CFD Exceedances

- Western wind issue occurs at 247.5° and 157.5° wind directions 1
- Northern wind issues occurs at 315° and 292.5° wind directions 2
- Southern wind issue occurs at 270°, 247.5° and 157.5° wind directions 3

Wind exceedances on the west of the stadium were generated by down draught resulting from the interaction of winds with the massing of the building.

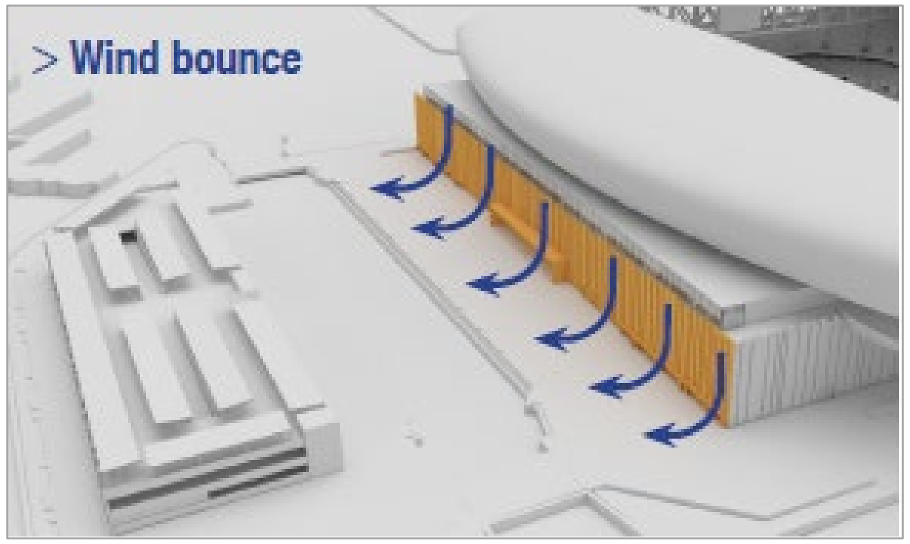


Figure 3—5 Down draught off the massing of the building on the pre-mitigated design

4 Design Interventions

4.1 Surface Materiality of the Curved Roof

A first part of the design journey explored a variety of permeabilities to the curved façade. The goal was to seek, if possible, a surface that would absorb energy from westerly wind to reduce down draught effects. It would need to achieve this whilst restricting too much wind from passing into the seating tiers and creating uncomfortable conditions for spectators. Such a solution is difficult to achieve as realistic values of surface porosity still make the surface appear solid enough to the wind to still generate important downdraughts into the western zone. The porosity is part of the final roof curved surface, however its effect is considered to be minimal in regard to wind mitigation.

4.2 Massing Changes

Design Interventions that were explored covered a variety of scales from the smaller grain of local landscaping to the larger scales of overall block massing. Options for alternative large scale massings were explored before landscaping measures were considered.

Lowering the stadium and reducing the exposed volume of building to the wind would likely be a massing measure that could reduce wind effects. However, on this site, the pitch level and hence overall building height is constrained by the finished floor level specifications agreed with the Environment Agency, as well as other constraints, such as they limited size of the site. Thus, the building cannot be lowered and, as such, this design intervention was not explored further.

The massing design options that were explored focused on the west stand and led to a major design change to join the car park to the stadium, see figure below, the location of the original carpark right side picture and two alternative options to the centre and left. The design goal was to shelter the ground level spectators in the west by building above them and prevent strong down draughts from the west side of the building from reaching directly to ground.

A number of creative geometric design solutions were conceived by the team and subjected to testing and compared to the original pre-mitigated design. A representative selection of these solutions are shown in the figure below.

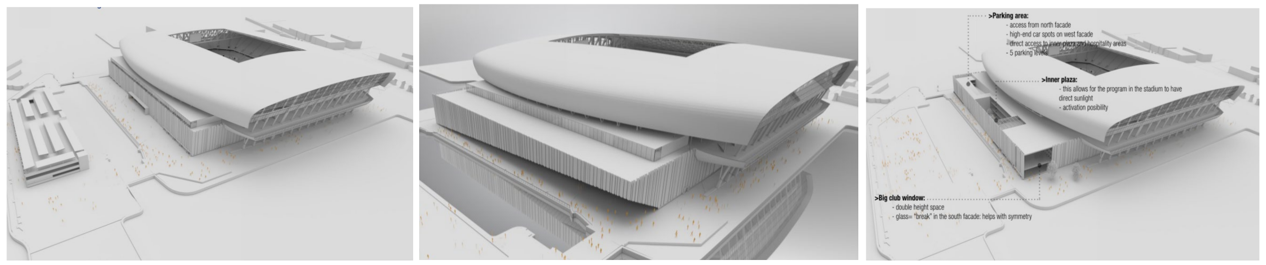


Figure 4—1 CFD Modelling as an iterative design tool

With the inclusion of this design intervention, downdraughts off the curved upper façade were restricted to upper terrace level before the majority of these winds would be dispersed laterally north and south without reaching ground level, improving wind conditions at ground level to the west of the stadium. Wind hitting the lower regions of the westerly building would generally be controlled to create the windiest conditions over the water channel, again away from key pedestrian spectator circulation.

4.3 Fixed Landscaping

Passive wind design interventions were tested through the process and extensive detailed optioneering carried out. The CFD testing helped produce design information to guide the selection of the optimum arrangement.

On the south of the site, the governing wind is predominantly from the south west and the CFD image below is of wind from 157.5 degrees. The image shows how south westerly wind impacts on the southern facades of the stadium and is channelled towards the west of the site. This indicates that, in the absence of design interventions, exceedances are expected to occurs within a zone, which is subject to important pedestrian activity.

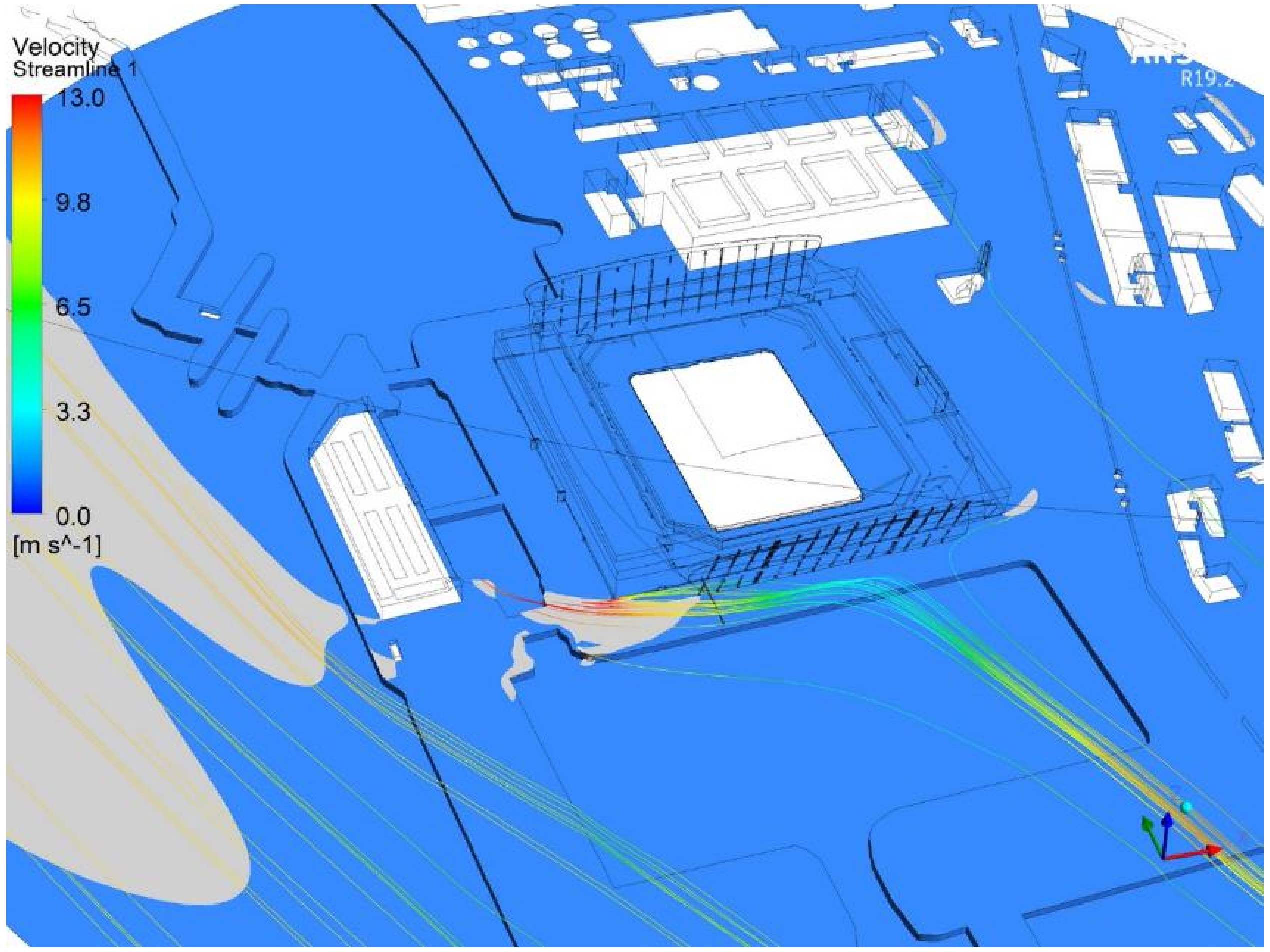


Figure 4—2 CFD Modelling as an iterative design tool

A variety of landscaping designs were explored of different types, sizes, spacings and support conditions. Testing indicated that the inclusion of barriers (in the form of banners) in the area to the south of the stadium was the optimum solution. In general, barriers are best located at ninety degrees to the direction of the wind energy and wind tunnel testing revealed that banners of about 50% permeability produce the best solution for absorbing wind energy. Optioneering included the spacing and numbers of banners in order to try and reduce the scale of intervention in visual and cost terms. However, due to the potential for strong winds in this area, the design solution required frequent banners offering sufficient wind energy absorption. A representative image of one of the early optioneering studies from one of the wind tunnel test images is shown below, of an early design with a series of flags at the southern edge. These early designs provided design information that helped as part of the journey to develop the final solution.

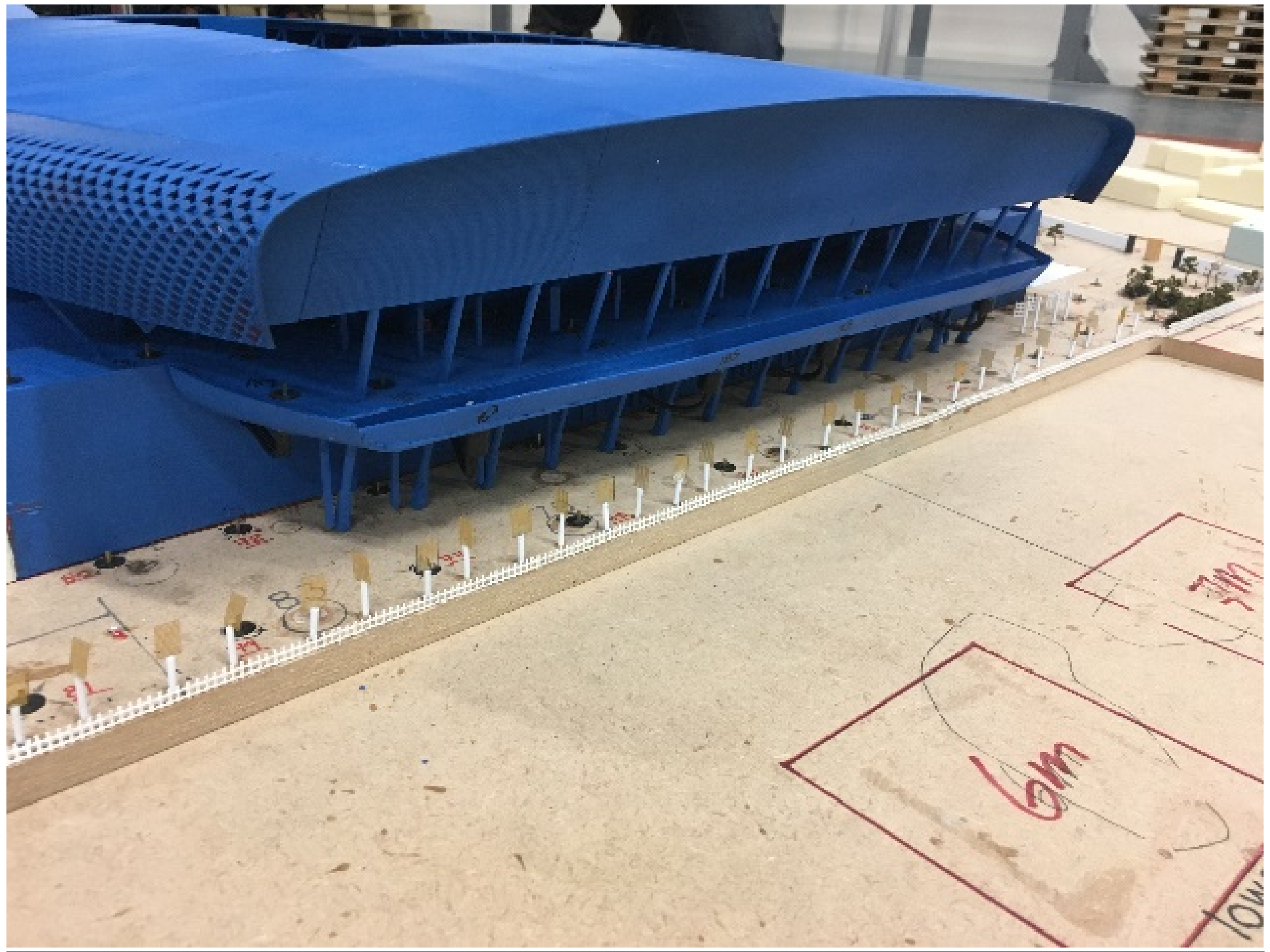


Figure 4—3 Wind Tunnel Test model with Design Intervention elements

A model image is shown below of one of the last CFD analysis models. It shows the high level of detail embodied in the computer model including the designs of banners along the south of the site,

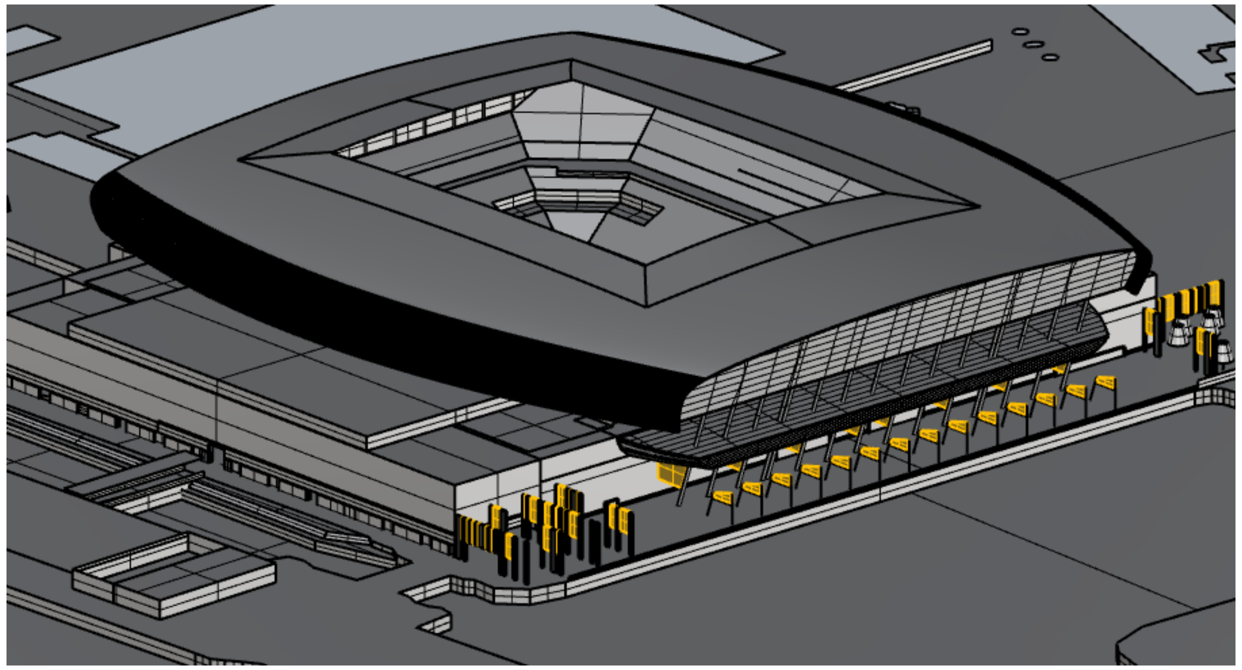


Figure 4—4 Image of CFD model

On the north of the site, the building is in close proximity to the site boundary. Landscaping design intervention optioneering included assessing both the effects of banners located in the cross-section of the north stand of the stadium and also the effects of the application site north boundary fence.

4.4 Finalised Design Interventions

The full list of final design intervention measures is provided in the Wind Microclimate ES chapter.. The chapter and other supporting appendices describe in detail how each measure is appropriate and relevant to a particular exceedance and concern; however, all measures work together in a cumulative manner.

A representative CFD wind speed contour plot for prevailing wind of 270 degrees for the corresponding option tested is shown below and illustrates much improvement in site conditions from the baseline conditions.

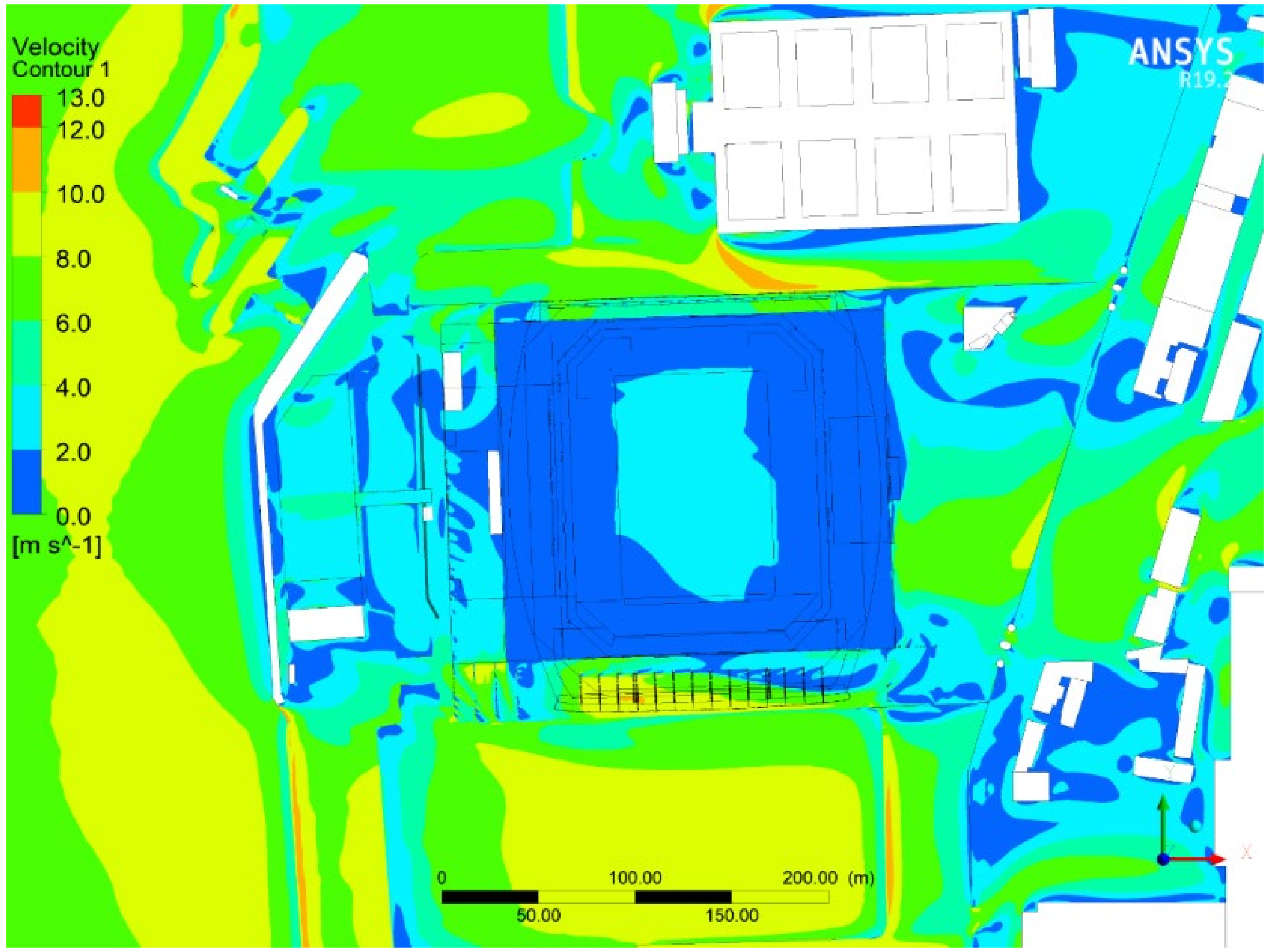


Figure 4—5 Typical CFD analysis: wind speed contour plot for mitigated design

4.5 Mitigation: Active Management

As reported in the ES chapter, some residual areas of exceedance of the Lawson criteria remain in the finalised development scenarios, including design interventions. It is proposed that these localised areas on site, can be addressed by controlling access to these areas during windy conditions. These measures are described in more detail in the ES chapter..

At a wider level, given the scale and extent of the landscaping proposed, the team considered whether there were other management means that could be considered that might allow the scope of the physical fixed interventions to be reduced. The main area of examination concerned the southern part of the site because of the amount of banners in this zone. However, this area will be subject to a substantial number of people passing on a match-day as part of the overall circulation strategy and consistent with the site constraints. Removing permanent landscaped design intervention from this zone would require a management approach to be deployed on windy match days. However, such a managed design would potentially need evacuation across the pitch and is deemed unfeasible from a practical sense.

5 Conclusion

This technical appendix provides:

- information on the wind tunnel and CFD tests undertaken prior to the wind tunnel tests reported in the Wind Microclimate ES chapter
- information on the design interventions integrated into the proposals in response to these tests

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