FINAL REPORT

SYDNEY FOOTBALL STADIUM

SYDNEY, AUSTRALIA

AEROACOUSTIC ASSESSMENT OF WIND GENERATED NOISE
RWDI # 2000267
October 9, 2020

SUBMITTED TO

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1 INTRODUCTION

RWDI was retained to consult on the potential risk of wind-induced noise of the project elements and features on the Sydney Football Stadium (SFS) Redevelopment. The SFS will be located along Moore Park Road in Moore Park, NSW, Australia and is illustrated in Figure 1.

Figure 1: Location of the proposed SFS Redevelopment in Moore Park, NSW

The objective of this study is to address the project Planning Requirements B8a, B8b and the Project Brief Requirements F8.5.3 via a design review as to the potential susceptibility of building elements to generate wind-induced noise, and to provide guidance to reduce the risk of wind-induced noise events where and if applicable. Conditions B8a and B8b state:

"B8. Prior to the commencement of construction of the stadium structure above the concourse level, the Applicant must provide evidence to the satisfaction of the Planning Secretary to demonstrate that:

(a) A desktop aero-acoustic noise (wind generated noise) assessment has been conducted to inform the final detailed design of the stadium and / or the public domain areas (if applicable). This assessment must have a focus on the wind-noise induced mechanisms listed in Section 4.3.5 of the Stage 2 SSDA – Noise and Vibration Assessment prepared by ARUP dated 30 August 2019 and must identify and demonstrate that potential impacts at nearby sensitive receptors are acceptable.

(b) The recommendations in the Stage 2 SSDA – Noise and Vibration Assessment prepared by ARUP dated 30 August 2019, in relation to aero-acoustic noise (wind-generated noise), as updated by B8(a) (if any) have been incorporated into the design and / or alternative design measures have been proposed to reduce wind generated noise from the stadium structure and / or public domain areas within the site."

While the sound level of tonal wind-induced noise events cannot be predicted with an aeroacoustic desktop study, we propose that the project requirements with respect to mitigation of wind-induced noise would be met if all elements identified in this review are assessed as having a Low Risk for wind-induced noise (refer to Section 3 for a description of low, medium and high risk for wind-induced noise).

An early stage aeroacoustic study was previously carried out by Wacker Ingenieure. This current assessment is a more in-depth review that considers the local wind speeds expected at the site, frequencies of vibration of various façade features where relevant and RWDI's extensive experience of mitigating aeroacoustic issues on past projects.

This assessment and recommendations are based on a desktop review of the following electronic design documents received by RWDI up to August 19, 2020:

- AS-01 (Acoustic Screens).pdf
- ASK-844_rev03.pdf
- CW01 (Curtainwall).pdf
- FG01 - Atrium & Awning.pdf
- WackerIngenieure_SydneyFootballStadium_AeroacousticNoise.pdf
- SFS-JHG-00-CM-AL00XX01.nwd - (3D Navisworks model)
- SFS-COX-01-DR-AR60XX08[01] - (Sunshade Details – Sheet 03)
- SFS-COX-01-DR-AR100006[2] - (Architectural Site Plan)
- SFS-ASP-00-DR-LS20ZZ00[6] - (Landscape Masterplan)
- ASK1289_L1 Security Gates to the SCG Plaza – Palisade Security Gates to the SCG Plaza

Furthermore, this review has been conducted with reference to the relevant sections of the conditioned Stage 2 SSDA – Noise and Vibration Assessment prepared by ARUP and dated August 30, 2019 (namely section 4.3.5 of the acoustic report).

2 WIND CONDITIONS

To predict the potential susceptibility to flow-induced noise, local wind conditions have been estimated based on historical data from Sydney International Airport, recorded at an elevation of 10 m above grade for approximately a 20-year period between 1994 and 2014. The standard ESDU method (1982, 1983) for evaluating changes in the mean velocity profile for varying ground roughness was used to account for local terrain effects around the stadium. This is consistent with the Australian Standards approach (AS1170.2).

The histogram shown in part a) of Figure 2 illustrates the expected wind speeds at the maximum height of the stadium approximately 40 m above average local grade, with part b) of Figure 2 showing the annual directional distribution of common winds at the Sydney International Airport Weather Station (approximately 6.5 km south-west of the site). As part of this review, aeroacoustic phenomena were assessed for all wind speeds up to the highest expected hourly wind speed in an average year, at the highest elevation of the building. Wind speeds greater than this design wind speed, i.e. those that occur for less than 1 hour a year, would not be expected to occur frequently enough to cause annoyance due to wind-induced noise. The wind climate study summarized herein is generally consistent with Wacker Ingenieure's wind climate assumptions (1,000-year return period wind speed of 35m/s), but as noted above, such extreme wind speeds occur too infrequently to generate aeroacoustic concerns.

The stadium is expected to generate increased wind speeds in some areas (e.g. the facades aligned nearly parallel to the oncoming wind flows) and reduced wind speed in other areas (e.g. the facades aligned nearly perpendicular to the oncoming wind flows). Based on RWDI experience of previous projects this speed-up effect would increase the oncoming wind speeds by 40-60% relative to the free-stream wind speed, and up to 2 times the oncoming wind speed in very localized areas at the upwind roof edges. RWDI assessed the possible impacts of such accelerations by focusing on the position of façade elements that are particularly risky for aeroacoustic problems. Some of these elements were in areas of increased wind speeds due to the stadium aerodynamics, such as perforated elements at the upper edge of the parapet. Many of the façade features assessed are in locations where acceleration is not expected to affect the generation of noise, as the accelerated flows would be parallel to the porous features.

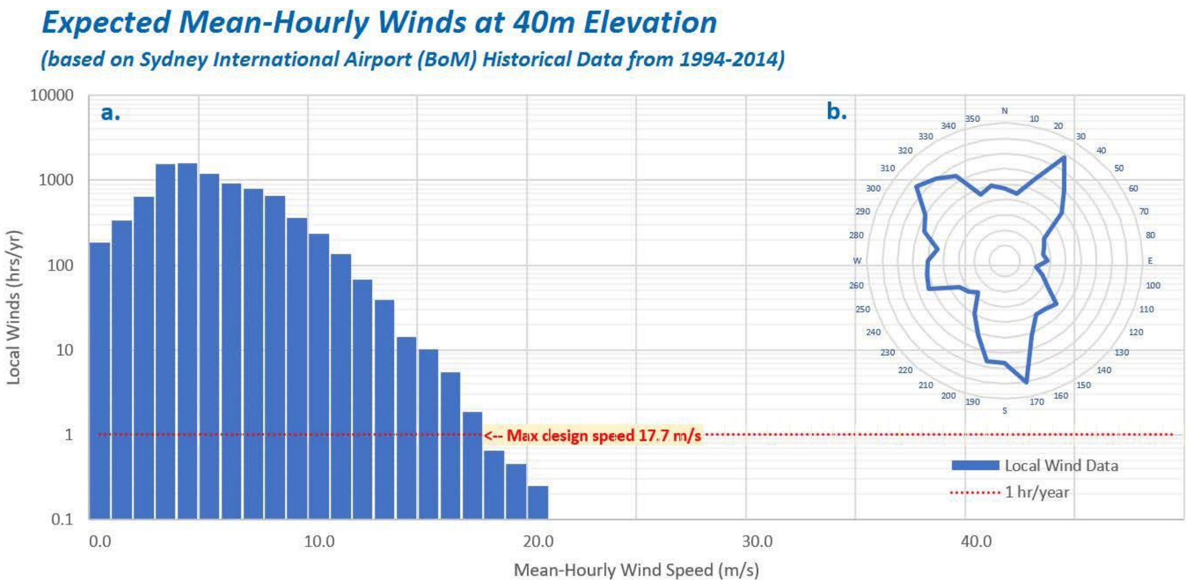


Figure 2: **a) Expected mean-hourly wind speed in m/s at the maximum structure elevation of 40 m at the site, b) Annual wind directional distribution (%) at Sydney International Airport for 1994-2014**[1]

Based on the common wind conditions, and the building height, the aeroacoustic analysis parameters adopted for this assessment are summarised in Table 1**.**

Table 1: **Aeroacoustic analysis parameter summary**

Analysis Parameters	
Project Location	**Sydney, Australia**
Maximum Elevation Above Local Grade	**40 m**
Maximum Design Wind Speed (≥1-hour/year, sustained, mean-hourly) – at roof height, undisturbed *	**18 m/s**

** - local accelerations are considered in our assessment of risk for key areas*

3 EXPLANATION OF CRITERIA

For the purposes of this review, observations, discussion and recommendations have been classified by describing the risk for aeroacoustic noise as low, medium or high risk. The degrees of risk are described below.

LOW	**A** low **risk of wind-induced noise or vibration is a situation in which only under specific and unusual circumstances would a wind-induced noise or vibration event occur. Typically, a low risk architectural feature means that there are obstructions that limit wind exposure, or wind speeds required to produce a noise event are beyond a reasonable return period.**

[1] **This wind analysis is based on a general statistical model of the local wind climate and does not include any local flow effects or accelerations caused by flow around the building, or due to local buildings in the vicinity.**

	For a low risk feature, it is normally not necessary to do any further testing or design modification.
MEDIUM	**A** medium **risk is a scenario in which the geometry of an architectural feature shows potential for wind-induced noise or vibration. Medium risk is used when wind-induced noise will have limited impacts (e.g., it is a single source, remote from occupants and nearby receptors), or airflows around the feature are rarely expected to excite the feature (create noise or vibration). A medium risk also occurs when there is no apparent means for amplifying the sound (e.g., no large panels for radiating sound).**
	Minor modifications can usually reduce the risk, although further testing or mitigation may be necessary.
HIGH	**A** high **risk occurs when the geometry of an architectural feature is expected to 1) encounter flows that could produce significant vibration or strong tonal sounds, and 2) a mechanism exists for the sound or vibration to be re-enforced. Common features repeated over a large area of a building surface can create a situation in which a large number of low noise sources combine to create high levels of noise.**
	Design modifications and/or full-scale testing of either a small section or a mock-up of a large section are typically recommended for such cases.

4 WIND-INDUCED NOISE MECHANISMS

Section 4.3.5 of the ARUP Stage 2 SSDA – Noise and Vibration Assessment (dated August 30, 2019) identifies two types of wind-induced noise, namely broadband noise (where a wide range of frequencies of a similar level are generated simultaneously) and narrow band or tonal noise (where a single dominant frequency is excited).

Broadband noise due to airflow over exposed architectural elements is to be expected and will increase with an increase in wind speeds. This is normal and cannot be avoided. Broadband noise can be likened to the sound of wind blowing through the leaves of a tree and is typically unobtrusive in nature and blends in with the ambient noise environment. Considering this, broadband noise caused by airflow over façade elements is unlikely to result in any adverse noise impacts at sensitive receptors and is considered low risk.

Tonal noise on the other hand can be highly annoying as it typically stands out from the ambient noise environment when generated at sufficiently high sound levels. Section 4.3.5 of the ARUP acoustic report identifies a number of wind-induced mechanisms that can result in tonal noise and these can be grouped into three major types of aeroacoustic phenomena: vortex shedding; cavity resonance; and perforation noise. These mechanisms are expounded upon below:

> *Cavity resonance* is caused by wind flowing over the opening of a slot, enclosed air volume or cavity (similar to a flute or blowing across the opening of a bottle). Cavity resonance tends to produce tonal sound at discrete frequencies related to the cavity volume and the size of the opening and can produce sources of intense sound over a large range of wind speeds.
>
> *Perforation noise* is caused by wind blowing through or along a repeating pattern of holes or openings in a flat plate. The interaction between the wind and the perforations can generate tonal sounds. In addition, wind flow passing over thin, sharp panel edges can produce audible noise at high frequency due to a shearing of the wind flow.
>
> *Vortex shedding* occurs when a fluid (i.e. wind) flows past a blunt object, causing vortices to be formed. These vortices oscillate in a very regular pattern from one side of the object to the other at a rate directly proportional to the flow speed, and the width of the blunt object (i.e. the dimension perpendicular to flow). When the frequency of vortex shedding is similar to the frequency of resonant structural mode(s) of nearby components such as the bluff bodies themselves or attached structural components, resonance occurs.

The building features that have been reviewed as part of this study were assessed for their potential to be excited by these three aeroacoustic mechanisms. General guidance with respect to the typical mechanisms for aeroacoustic noise and vibration are provided in Appendix A.

5 RESULTS AND RECOMMENDATIONS

A review of the design documents received has been conducted. The review has assessed potential risk related to the three major classes of phenomena driving risk of aeroacoustic noise: vortex shedding, cavity resonance and perforation noise.

A summary of our findings is presented in Table 2 and this should be read in conjunction with the marked-up drawings provided in Appendix B to provide clarity of the building façade elements being discussed. Also, Table 3 provides the mitigation measures that the design team is currently considering for reducing the risk of aeroacoustic mechanisms, and the anticipated levels of risk once the mitigation measures are implemented.

Table 2: **Summary of potential risk for flow-induced noise and vibration of various building features.**

Item #	Feature Description	Concern	Potential Risk	Comments / Potential Solutions
1	**Perforated Sunshade Fins**	**Perforation Noise**	High	• **Perforations were noted in the vertical segments of several sunshade fins that are highly exposed to the prevailing winds.** • **These perforations cover considerable portions of the stadium façade on levels 3 and 5, with some areas of the upper parapet likely to experience accelerated flows for certain wind directions.** • **While drawing SFS-PSA-01-SD-FC62XX06 (*dated 2020-04-02*) in the CW01 package indicated 10mm diameter circular holes, the more recent drawing SFS-COX-01-DR-AR60XX08[1] (*dated 2020-05-20*) shows rounded slots with dimensions 5mm wide by 25mm long. Given the size and uniformity of both of these perforation patterns, the interaction frequencies of the perforated fins are calculated to be in the audible range. Thus, it is of RWDI's opinion that perforation noise from either of the perforated fin patterns is of** high risk**.** • **Possible mitigation measures can include:** - **Increasing the size of the perforations; and/or** - **Introducing more variation in the size and shape of adjacent perforations – refer to the concept figure in** Appendix A – Figure 4 **for examples of introducing perforation variation for the panels** • **For this site, if a 3-4mm thick aluminium sheet with a uniform perforation pattern is to be used, we recommend a minimum perforation dimension of 50 mm to maintain a** low risk **of wind-induced noise. The design team is currently planning to incorporate a perforation patterns with multiple hole sizes and larger dimensions (see** Table 3 **and** Figure 3**).**

Item #	Feature Description	Concern	Potential Risk	Comments / Potential Solutions
2	L-Shaped Sunshade Fins	Vortex-Induced Vibration Noise	Low	• Wind-induced noise due to vortex shedding across the sunshade fins has been reviewed. The first vibration eigenfrequencies of the fins were determined to be > 45 Hz, which are predicted to be above the expected range of vortex shedding frequencies across the fins given their dimensions and the expected wind speeds. Considering this, the local wind conditions (including 60% acceleration) are unlikely to excite the resonant frequencies of the fins. • Based on the dimensions of the fins and the expected wind conditions, it is RWDI's opinion that noise due to vortex-shedding has a low risk. • Should the predicted vibration eigenfrequencies differ from those predicted by façade designers, the risk for this element is recommended to be revisited.
3	Slots in Curtain Wall Aluminium Extrusion Panels	Cavity Resonance	Low	• The critical wind speed to generate cavity resonance at the slots in the curtain wall aluminium extrusion panels is calculated to exceed the design 1yr wind speed expected on-site. • It is RWDI's opinion that the slots in the aluminium extrusions have a low risk of generating cavity resonance noise given the slot dimensions and the expected wind conditions at the site.

Item #	Feature Description	Concern	Potential Risk	Comments / Potential Solutions
4	Cables Supporting Glass Canopy	Vortex-Induced Vibration Noise	Medium	• The drawings provide limited information about the properties and dimensions of the cables supporting the glass canopy. It is noted that the cables are connected to the building façade and the glass canopy, both of which could act as sound radiating surfaces should the cables be excited by wind flow. • There are two properties of the cables that will influence their susceptibility to vortex-induced vibration noise: - The diameter of the cable; and - The tension of the cable (which will dictate the cable's resonant frequency). • Given these two properties of the cables are not known at the time of this review, it is of RWDI's opinion that the cables have a medium risk of vortex-induced vibration noise. • To achieve a low risk of wind-induced noise generation for the cables, we recommend: - That the cables have a diameter of at least 10 mm; and - That they are a multi-strand helical rope configuration (less susceptible to strong vortex-shedding).
5	Steel Roof Truss Members	Vortex-Induced Vibration and Noise	Low	• Analysis indicates that the frequency of wind-induced excitation of the steel truss members located on the stadium rooftop is expected to be below the audible range (<20 Hz). • Based on this finding, it is RWDI's opinion that steel roof trusses are a low risk item for generating noise due to vortex shedding. • Should the predicted vibration eigenfrequencies differ from those predicted by structural designers, the risk for this element is recommended to be revisited.

Item #	Feature Description	Concern	Potential Risk	Comments / Potential Solutions
6	**Permanent Fencing (ground level)**	**NA**	Low	• **Drawing SFS-ASP-00-DR-LS20ZZ00[6] indicates that much of the permanent fencing around the stadium will be solid (i.e. brick wall, landscape walls, planter boxes, or solid balustrades).** • **Drawing SFS-COX-01-DR-AR100006[2] indicates some small sections of fencing and security gates at the southern end of the stadium which, per document ASK1289, is shown to be palisade-style fencing.** • **It is our understanding that any other permeable fencing will be chain-link with high porosity and large openings.** • **These styles of fencing have a** low **risk of generating wind-induced noise.** • **In addition, wind conditions near the ground (close to the bottom of the wind boundary layer) means lower wind speeds and increased turbulence, which further reduces the risk of noise.**

6 MITIGATIONS

The following table summarises the mitigation measures implemented by the Sydney Football Stadium Redevelopment design team to reduce the risk of aeroacoustic noise, and the anticipated residual levels of risk.

Table 3: Mitigation measures currently considered by the design team, and the residual risk when these are implemented in the project.

Feature Description	Concern	Original Design - Potential Risk	Mitigation Measures Considered	Residual Risk
Perforated Sunshade Fins	Perforation Noise	High	An updated perforation pattern will be implemented using three different hole sizes with larger hole dimensions.	Low
Cables Supporting Glass Canopy	Vortex-Induced Vibration Noise	Medium	All canopy supports will no longer use cables. We understand that these members will be 88.9mm diameter CHS members. Final selected members will be in excess of 10mm diameter due to their role as struts, not cables.	Low

7 APPLICABILITY OF RESULTS

The results presented in this aeroacoustic assessment report pertain to the information received by RWDI. Other sources of wind-induced noise may exist but are beyond the scope of the current study. For example:

- Shaking or rattling of components is common on many structures and is best addressed through good workmanship to ensure seals and fasteners are properly installed.
- Creaking, groaning, and other noise due to friction at joints (e.g. stick-slip motion), including whole building motion are not assessed in an aeroacoustic review. Frictionless restraints are preferred where flexing and expansion are part of the building design.
- Broadband noise due to airflow over exposed architectural elements is to be expected and will increase with an increase in wind speeds. This is normal and cannot be avoided.

- Some as-built conditions (e.g., slots, holes or cavities) may occur that were not represented in the drawings reviewed. These conditions are beyond the current scope of work and are best addressed by good workmanship and field inspection during construction.

This design review, and the study of wind-induced noise and vibration (i.e., aeroacoustics), is intended to help reduce the incidents of potentially problematic wind noise under common wind conditions. However, regardless of the results of the study and implementation of any recommendations, we cannot guarantee that all potential wind-induced noise will be identified or eliminated. The reason for this uncertainty is that the nature of aeroacoustic issues can be very complex and may arise due to many factors or a combination thereof (including, but not limited to, design, quality of construction and meteorological events). Nevertheless, an aeroacoustic study such as this carried out by experienced acousticians is the most appropriate method of identifying the highest risk mechanisms and developing mitigation solutions prior to construction. Any high or medium risk mechanisms can be evaluated in more detail through the use of aeroacoustic wind tunnel studies, however this can be avoided by making appropriate design interventions where possible.

8 CONCLUSION

The proposed Sydney Football Stadium façade and structure have been reviewed for susceptibility to wind-induced noise. The perforated plates on upper open areas of the façade have been identified as a High Risk for wind induced noise and various cables have been identified as having a Medium Risk for wind induced noise. The design team is currently assessing the feasibility of several mitigation strategies – as summarised in Table 3 of this report - to achieve a Low Risk of aeroacoustic noise for these facade components.

All other building elements that were reviewed have been identified as Low Risk for wind-induced noise.

We conclude that this assessment satisfies the project Planning Requirements B8a, B8b. Once all the above identified elements are mitigated to have a low risk of wind-induced noise, we also expect the Project Brief Requirements F8.5.3 to be met without requiring any further aeroacoustic studies or aeroacoustic wind tunnel testing.

9 REFERENCES

1. ESDU (1982) *Strong Winds in the Atmospheric Boundary Layer. Part 1: Mean Hourly Speeds*, Item 82026, Issued September 1982 with Amendments A and B April 1993. Engineering Sciences Data Unit, ESDU International, 27 Corsham Street, London N16UA.
2. ESDU (1983) *Strong Winds in the Atmospheric Boundary Layer. Part 2: Discrete Gust Speeds*, Item 83045, Issued November 1983 with Amendments to 1993. Engineering Sciences Data Unit, ESDU International, 27 Corsham Street, London N16UA.

APPENDIX A

APPENDIX A: AEROACOUSTIC MECHANISMS

AEROACOUSTIC MECHANISM FORMATION, BEHAVIOUR, & BEST PRACTICES TO AVOID THEM

Audible sounds can have many frequencies at once, such as the noise from a fan (broadband sound), or can be concentrated in a small range of frequency, such as a person whistling (tonal sound). Broadband sound is typically less annoying because it often blends into the background noise, versus a tonal sound that is more noticeable relative to ambient noise. Aeroacoustic noise studies focus primarily on tonal noise.

Wind-induced (aeroacoustic) noise is typically generated when pressure waves are created by oscillations in air flow conditions and/or vibration of an architectural element. These pressure waves occur at a frequency defined by the combination of flow speed and direction, and the shape and construction of the architectural feature. While the waves can occur at any frequency, only those in the range of 20 to 20,000 Hz are audible to most people. Moreover, people are less sensitive to the noise as the frequency approaches these upper and lower frequency limits.

Aeroacoustic noise may result from flow over cavities, flow over/through perforations and edges, and/or vortex shedding around cylinders and other bluff (non-streamlined) bodies, as shown in Figure 1**. Each of these phenomena occur strongest at certain wind speeds and wind flow directions with respect to the architectural feature. Therefore, knowledge of the local wind climate helps to determine the associated risk.**

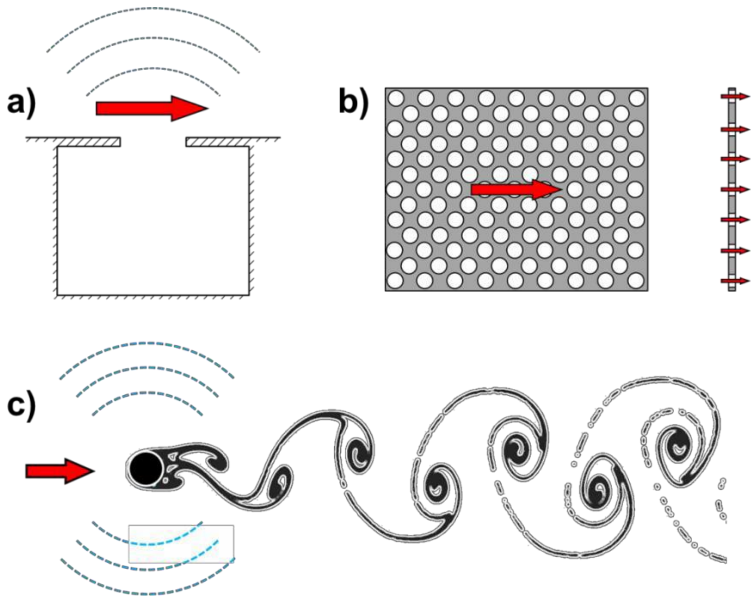


Figure 1: *simplified schematic of sound produced by: a) flow over a confined cavity or Helmholtz resonator, b) flow over or through a perforated plate, and c) vortex shedding of flow over a cylinder.*

A.1 Cavity Resonance

Cavity resonance is caused by wind flowing over the opening of a slot, enclosed air volume or cavity (similar to a flute or blowing across a bottle). Cavity resonance tends to produce tonal sound at discrete frequencies related to the cavity volume and the size of the opening, and can produce sources of intense sound over a large range of wind speeds.

A.1.1 Mechanism

As the air passes the cavity opening and hits the trailing edge, the air stream alternately deflects into/out of the cavity, causing pressure pulsations inside the cavity. This mainly becomes a problem when the edge tone frequency is close to the natural frequency (or harmonics) of the chamber or cavity. When this occurs, the resonance causes an amplification of the edge tone which makes it capable of creating very loud, tonal sounds.

A.1.2 What to look for…

Helmholtz resonators and basic cavities vary in shape, but generally will be a small opening or slot with a cavity behind. In general, flanged cavities (Helmholtz resonators), as shown part a) of Figure 2, or cavities which have substantial depth (D) compared to the opening size (L), as shown in part b) of Figure 2, are the most problematic in terms of flow-induced noise. Shallow cavity systems, where the depth of the cavity is smaller than the opening size as shown in part c) are typically not problematic.

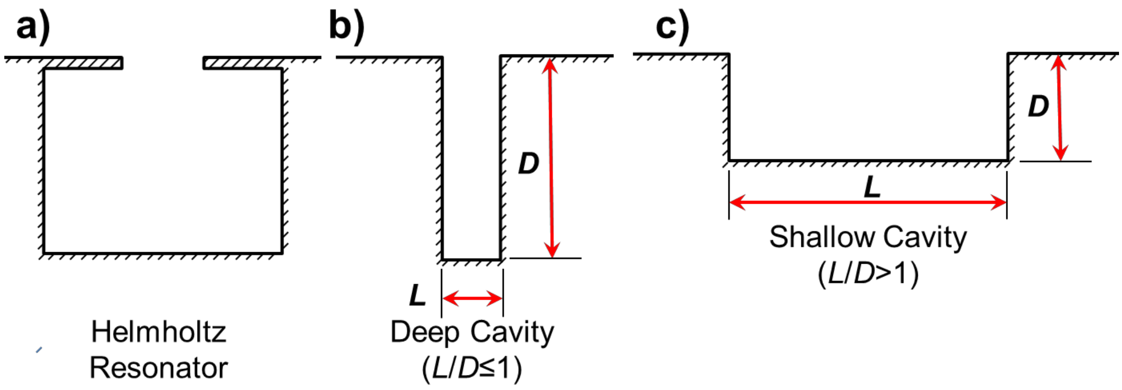


Figure 2: *Simplified schematic of different cavity types, consisting of a) a traditional Helmholtz resonator, b) a deep cavity (L/D<1), and c) a shallow cavity system (L/D>1).*

The most common architectural features of concern for cavity resonance are slots and gaps between cladding panels, open-ended hollow tubing, building maintenance unit tracks, and façade corner details. Mullion connections are also occasionally susceptible to cavity resonance due to the as-built construction conditions. Occasionally, gaskets or seals shown in architectural drawings can be damaged, installed incorrectly, or missing altogether, and the finished structure can generate annoying aeroacoustic noise levels. We recommend careful installation and inspection of the gaskets to avoid costly repairs.

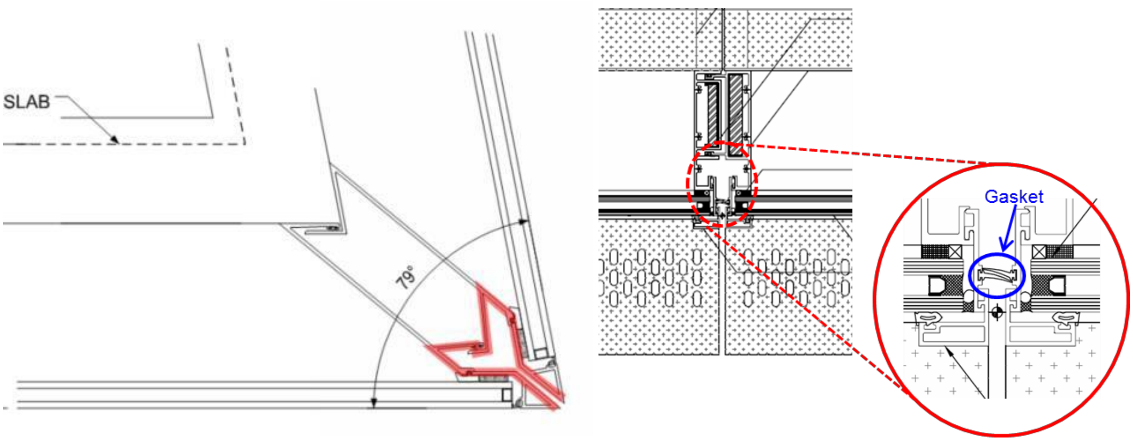


Figure 3: Example of a) a corner mullion cavity with no gasket shown, and b) a mullion cavity sealed with a gasket.

Confined geometry having dimensions less than 3 m, that are exposed to wind flows across the opening should be reviewed for the potential for noise generation. Risk of noise depends strongly on the ratio of cavity volume to opening size.

A.1.3 Best Practices for Mitigation

It is possible to predict the potential for a tonal sound to be created by these systems, and prevention and remediation can be incorporated into building design. Risk of flow-induced cavity noise can generally be mitigated by capping, sealing or obstructing the cavity openings, and/or by filling the cavities. Often changing the width of the opening relative to the cavity volume can shift the resonant frequency away from common wind speeds.

Where cavity geometry cannot be altered, a possible secondary approach is to disrupt the oscillating airflow at the cavity opening using mesh or brush strips across the hole or slot.

It should be noted that small holes and openings less than ½" or less in diameter on the structure exterior to facilitate drainage are generally not problematic, but should be reviewed to assess risk. If possible, locate drainage holes for hollow architectural elements in areas that are least exposed to wind.

A.2 Perforation Noise

Perforation noise is caused by wind blowing through or along a repeating pattern of holes or openings in a flat plate. The interaction between the wind and the perforations can generate tonal sounds. In addition, wind flow passing over thin, sharp panel edges can produce audible noise at high frequency due to a shearing of the wind flow.

A.2.1 Mechanism

Perforation noise is quite complex, and is the least defined mechanism of the common sources of architectural wind-induced noise. Noise generation is influenced significantly by the percentage of the panel that is open, pressure differential from one side to the other, perforation sizes, spacing, and plate thickness, as well as the wind speed, angle of attack, and turbulence. The mechanism is an interaction between the jetlets of air through the perforations, and if the perforations are repeated over a substantial area, the mechanism is reinforced. Cumulative noise generated by the perforations can reach audible and annoying levels.

A.2.2 What to look for…

Large flat surfaces with a highly repetitive pattern of holes or slots are the most problematic. Perforation patterns of relatively small, round holes that are exposed to high wind flow have the highest risk of noise. These geometries are quite often found as balcony railings, sunshades, mechanical screens, trellis elements, crown elements, etc.

Generally, perforations openings larger than 100mm (4-inches) are not expected to have a high risk of generating noise.

A.2.3 Best Practices for Mitigation

Wind tunnel testing is presently the only viable technique for accurately determining real-world behavior of these phenomena in advance of construction, due to the complexities of the physical mechanism. If highly exposed perforated materials are to be used in the design, potential risk of tonal wind-induced noise from these materials may be reduced though the implementation of one or more of the following techniques.

Based on our aeroacoustic testing experience, we recommend that the design of any perforated panels:

- **Avoid uniformly sized openings of a given shape, in favour of openings with a variety of sizes. In order to disrupt the noise generating mechanism, openings should have a 25-35% variation in size as compared to their nearest neighbors, and patterns should use 3-4 different opening sizes. It should be noted that other hole size variation rates, such as doubling or halving of adjacent opening sizes, are typically less effective in reducing potential risk than the 25-35% variation cited above. A more gradual variation in hole size, i.e. changing opening size from 25mm to 12mm gradually over several feet, offers some benefit as compared to uniformly sized openings, but these designs often still carry elevated levels of risk. Refer to** Figure 4 **for conceptual examples of perforation patterns and associated risk for wind-induced noise.**

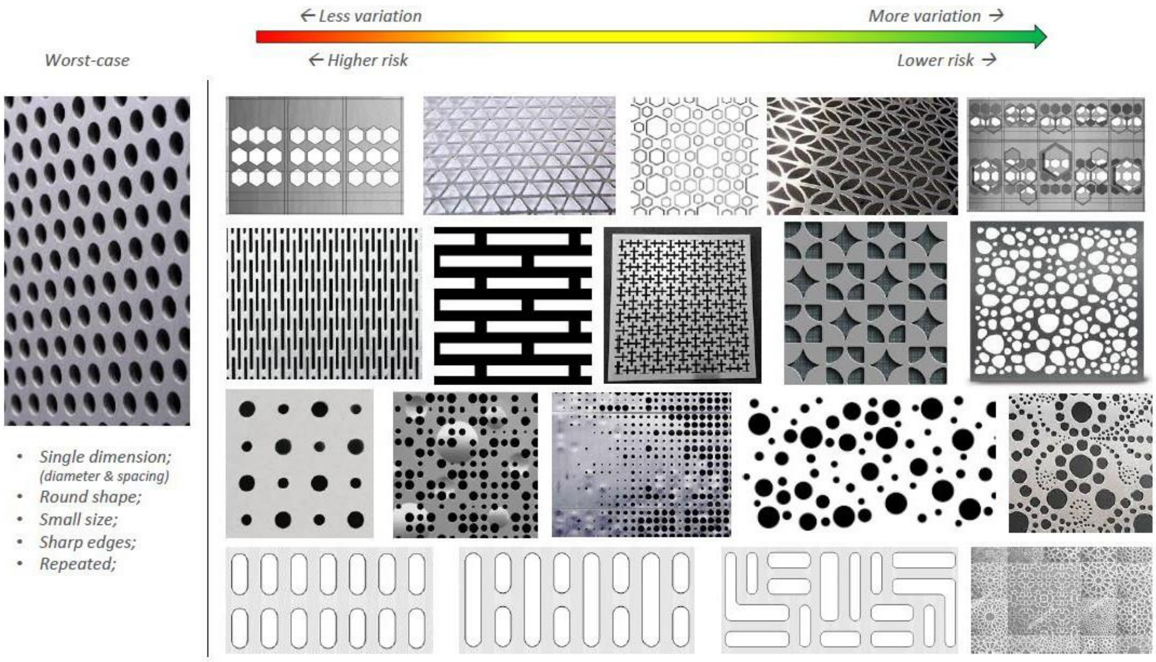


Figure 4: *Conceptual Example of Perforation Patterns and Degree of Risk for Wind-Induced Noise*

- **Avoid round openings, in favour of other opening shapes (i.e. triangles, rectangles, hexagons, etc.), as circular perforations tend to be more susceptible to generating wind-induced whistles and tones.**
- **Increase the size of perforations. The use of larger openings generally has a lower degree of risk as compared to smaller openings. Panels with very large openings (e.g. 100mm or greater) have significantly lower levels of risk, while smaller openings (on the order of 10mm) have the highest risk.**
- **If only one side of the panel will be exposed to wind, panels with punched or formed openings are preferred (as opposed to waterjet or laser cut openings), orienting the panels with the rounded edge towards the wind.** Figure 5 **below shows examples of two round perforated openings that were previously tested by RWDI with a) sharp edges produced by water-jet cutting, and b) rounded edges produced by punching. These two panels tested under identical conditions produced significantly different results, with the water-jet cut panels resulting in much more pronounced whistling noise.**

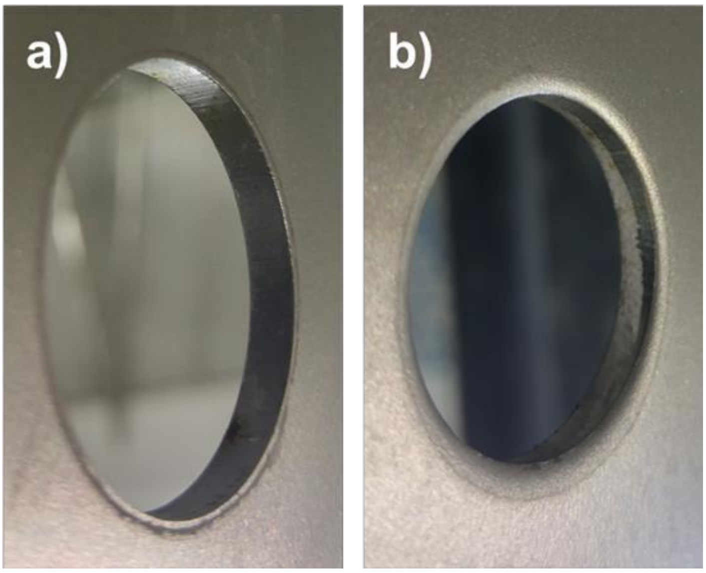


Figure 5: *Examples of two round perforation openings manufactured using a) water-jet cutting, and b) punching.*

- **Use alternate materials, such as woven metal mesh, which generally carry a lower level of risk for wind-induced noise as compared to perforated metal. RWDI have tested samples of some of these types of meshes, and those tested have had a low level of risk for wind-induced noise.**
- **If the above recommendations cannot be implemented, airflow through the perforations can be reduced or blocked using a solid backer panel. If desired, the backing panel can be made of Perspex or other transparent/ translucent materials to maintain daylighting. Note that this approach can lead to significant issues related to cleaning and dirt/dust retention.**

Implementing the above recommendations in the design will increase the likelihood of a positive result in subsequent wind tunnel testing.

A.3 Vortex Shedding

Vortex shedding can produce an acoustic source due to the alternating flow occurring in the wake of cylinders and other bluff bodies. Aeroacoustic noise generated by vortex shedding tends to be less intense than for cavity resonance. However, vortex shedding is a common source of flow-induced vibration.

A.3.1 Mechanism

As a fluid flows past a blunt object, vortices are formed. These vortices oscillate in a very regular pattern from one side of the object to the other at a rate directly proportional to the flow speed, and the width of the blunt object (i.e. the dimension perpendicular to flow). When the frequency of vortex shedding is similar to the frequency of resonant structural mode(s) of nearby components such as the bluff bodies themselves or attached structural components, resonance occurs.

A.3.2 What to look for…

Any long, flexible, blunt objects are a source for vortex shedding. The most common architectural features are normally found as elements of a trellis or sunshade, exposed structural truss members, tensioned cables, or antennae, to name a few examples. The object does not necessarily have to have a circular cross section, but must allow wind to pass on all sides.

As a general rule of thumb, any flexible spans, approximately 650 mm in diameter or less, have the potential to generate noise caused by vortex shedding.

Figure 6: *Example of exposed canopy sun-shade tubes with potential for vortex shedding*

A.3.3 Best Practices for Mitigation

In order to mitigate vortex shedding, RWDI typically look at the following options:

- Reduce the unsupported length of the elements. Shortening the span can shift the resonant structural mode frequencies well above the vortex shedding frequencies expected on-site;
- Increase the diameter/cross-section of the elements. Increasing the cross-section has the effect of both increasing the natural frequency of the structure, and decreasing the vortex shedding frequency;
- Divert or block significant wind flow over and around the elements, or disrupt the flow around the object using a variety of techniques such as; spoiler plates, helical strakes, etc.

A.4 Applicability of Aeroacoustic Review Results

Aeroacoustic design reviews, and the study of wind-induced noise (i.e., aeroacoustics), are intended to help reduce the incidents of potentially problematic wind noise under common wind conditions. However, regardless of the results of the study and implementation of any recommendations, we cannot guarantee that all potential wind-induced noise will be identified or eliminated. The reason for this uncertainty is that the nature of aeroacoustic issues can be very complex.

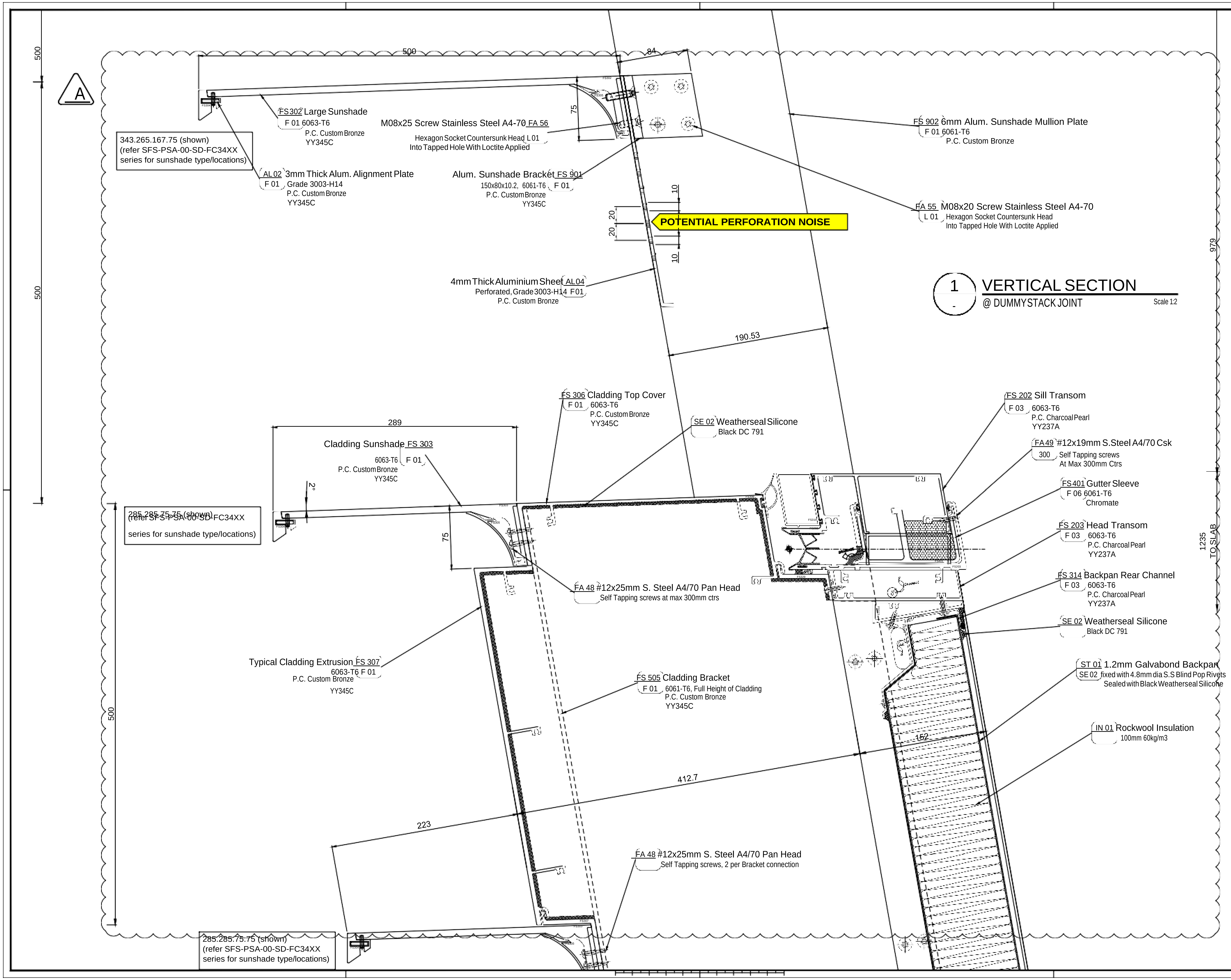
The results of an aeroacoustic assessment pertain to the drawings received by RWDI. Other sources of wind-induced noise may exist, but are beyond the scope of the current study. For example:

- Shaking or rattling of components is common on many structures and is best addressed through good workmanship to ensure seals and fasteners are properly installed.
- Broadband noise due to airflow over architectural elements is to be expected, and will increase with an increase in wind speeds. This is normal, and cannot be avoided.
- Some as-built conditions (e.g., slots, holes or cavities) may occur that were not represented in the drawings reviewed. These conditions are beyond the current scope of work and are best addressed by good workmanship and field inspection during construction.

APPENDIX B

Feature (1)

- Perforations in L-Shaped Sunshade Fins



LOCATION PLAN

Rev	Amendments	Date
0	FIRST ISSUE FOR APPROVAL	02.04.20
A	ISSUED FOR CONSTRUCTION	15.07.20

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Discipline FACADE

Project No. 91186

Project Sydney Football Stadium Redevelopment
Driver Ave, Moore Park
NSW, 2021

Phase: DETAILED DESIGN

Document Control Status: FOR CONSTRUCTION

Drawing Title
DETAILS
-SECTION CW-01
-STACK JOINT AT OPEN AIR/CLADDING

A1 DRAWING SHEET

Drawn: R.V
Checked by: J.L
Designed by: Pisa PTY
Approved by: J.S
Scale: 1:2@ A1,
Date: 2020-04-02
Revision: A

Drawing Number: SFS-PSA-01-SD-FC62XX13

North:

SUN SHADE PERFORATED...	
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19. 422.343.258.167.P	40
24. 422.500.258.350.P	40
29. 500.422.350.258.P	40
34. 500.500.167.258.P	24
35. 500.500.258.167.P	24
36. 500.500.258.350.P	24
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38. 500.500.350.350.P	344
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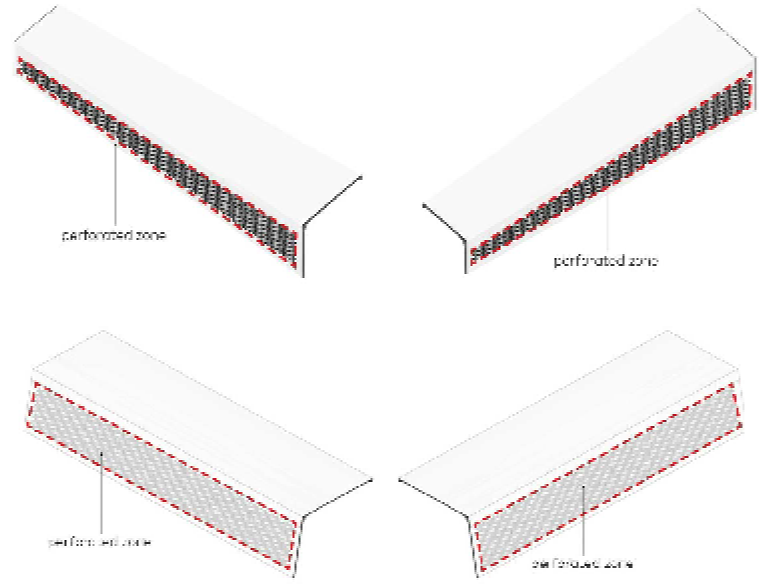
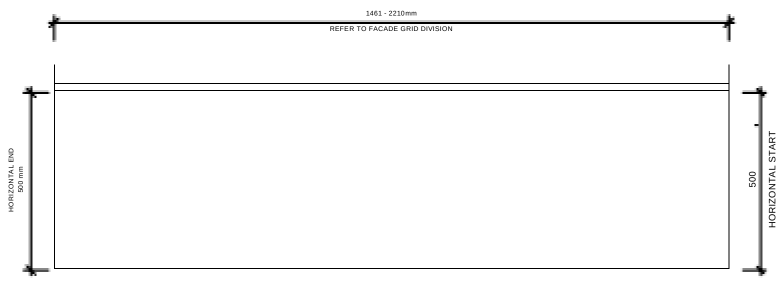
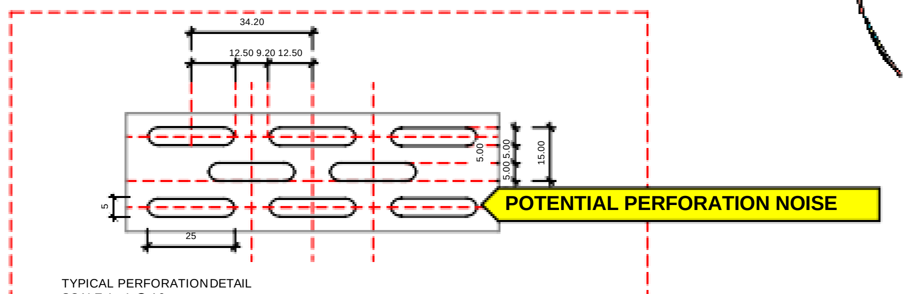
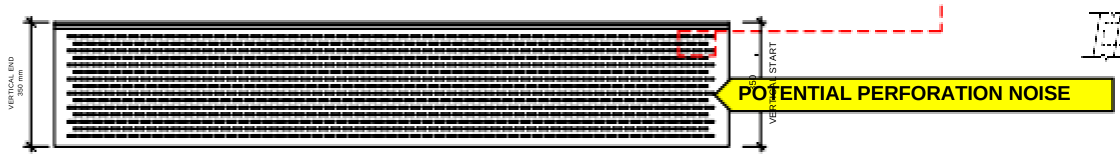
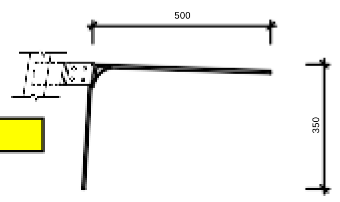


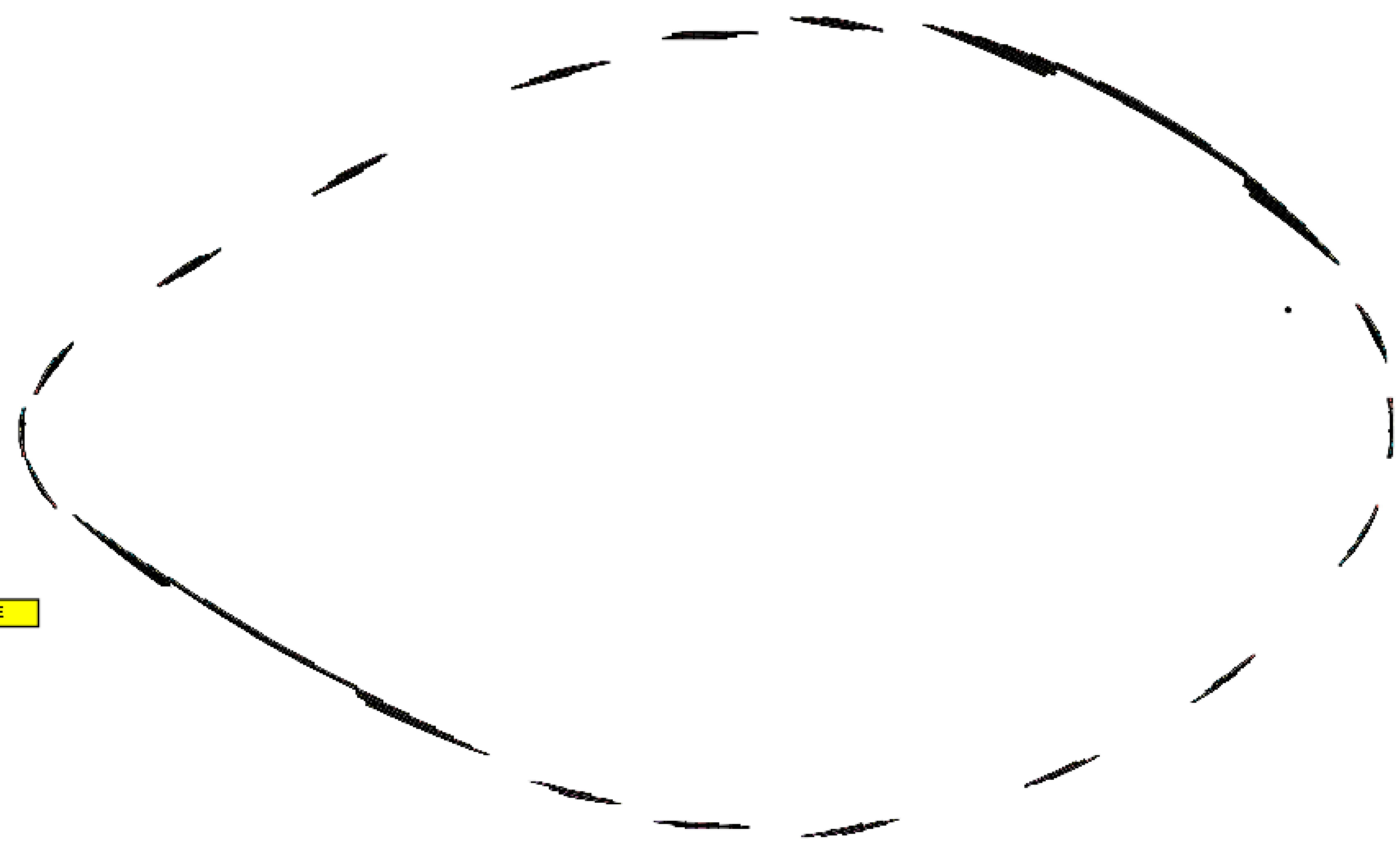
STANDARD SUNSHADE - PERFORATED











3D - SUNSHADES - PERFORATED
SCALE

SUN SHADE EXTENDED TYPES	
PANEL TYPE	Count
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21. 422.500.75.75.E	20
22. 422.500.75.75.E.X	2
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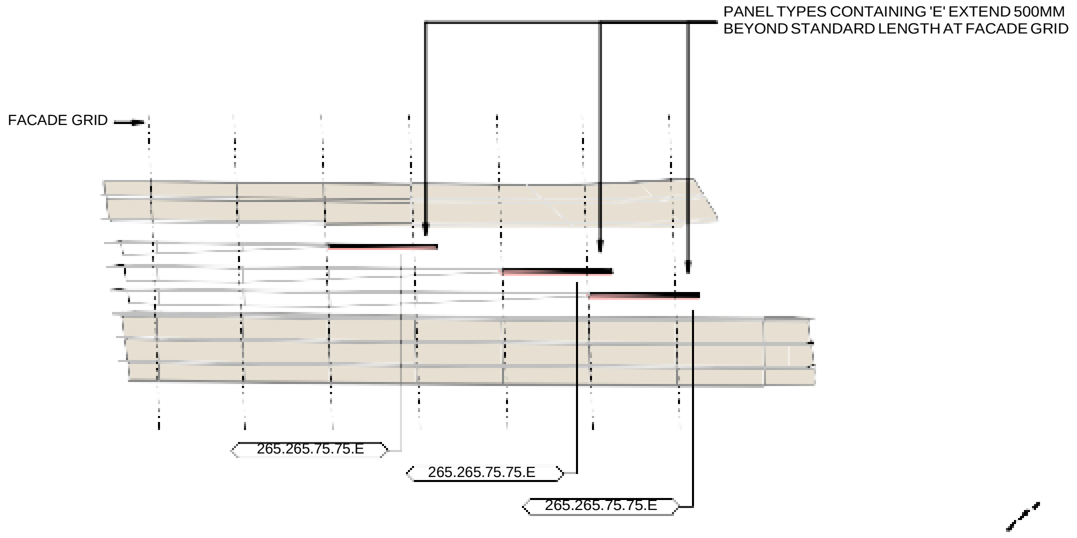
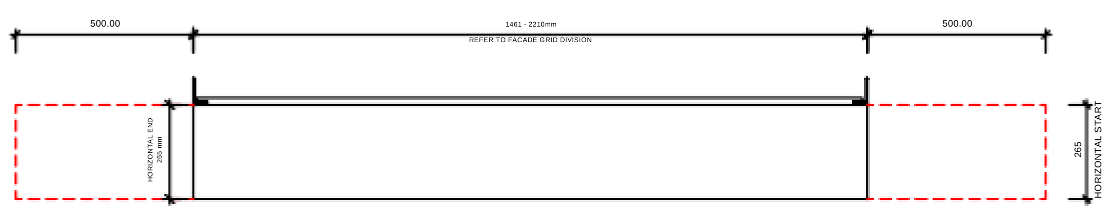
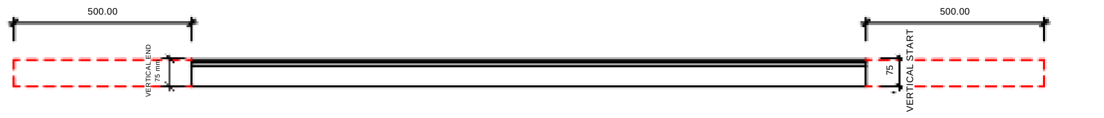
Grand total: 120	



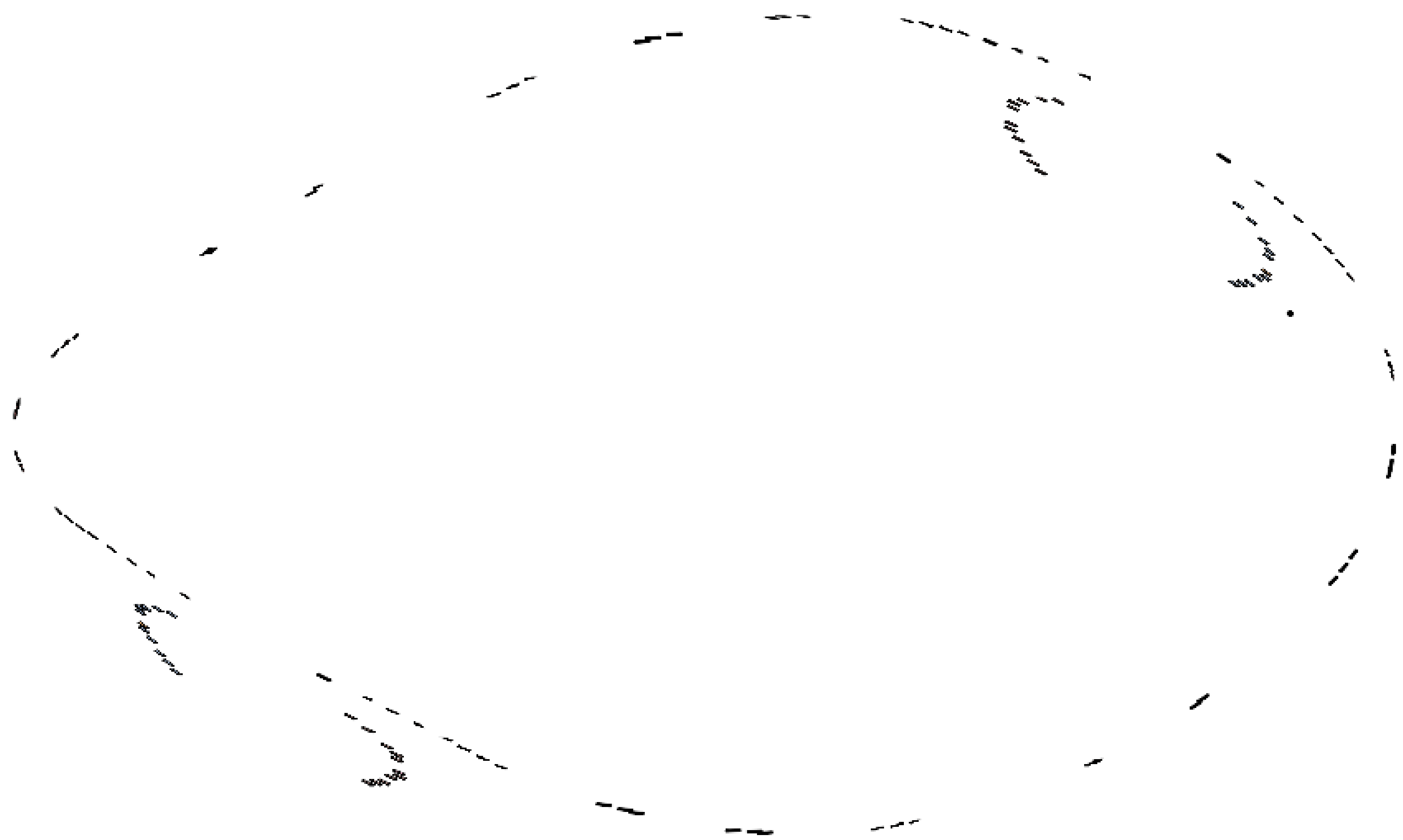
500mm FIXED EXTENSION CAN OCCUR AT START OR END CONDITION. REFER TO AR33 SERIES FOR EXTENSION DIRECTION



PLAN
SCALE 1 : 10



ELEVATION
SCALE 1 : 10



3D - SUNSHADES - EXTENDED
SCALE

Rev	Amendments	Date
1	Issued For Information	22.05.2020

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Discipline
ARCHITECTURAL

Project No.
218018.00

Project
Sydney Football Stadium Redevelopment
Driver Ave, Moore Park
NSW, 2021

Phase:
DESIGN DEVELOPMENT

Document Control Status:
FOR INFORMATION

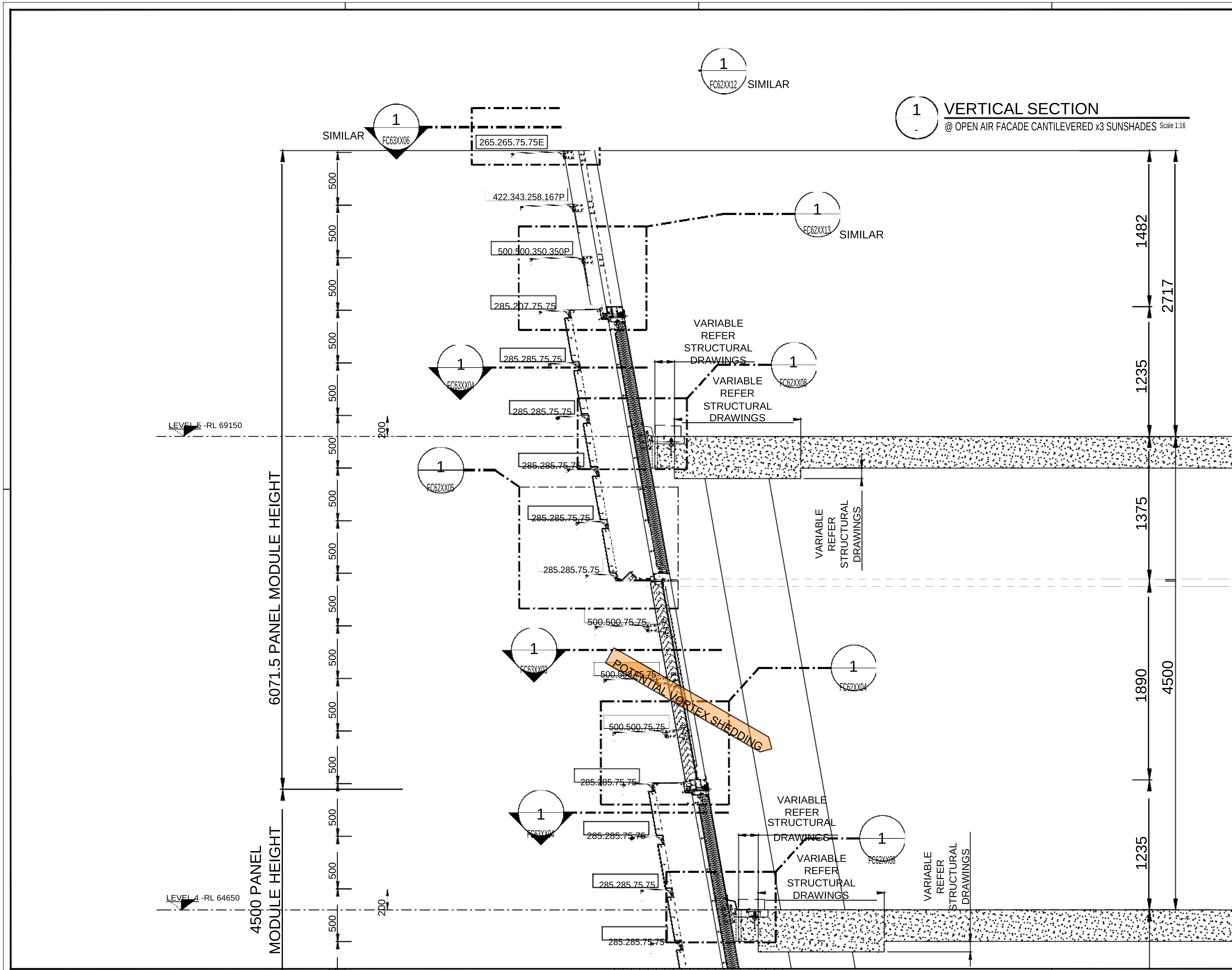
Drawing Title
ARCHITECTURAL SERVICES - FACADE DETAIL - SUNSHADE DETAILS SHEET 03

A0 DRAWING SHEET

Checked by:	SK	**Drawn:**	Author
Designed by:	SH	**Scale:**	1 : 10 @ A0
Approved by:	AR	**Date:**	22.05.2020
Drawing Number:	SFS-COX-01-DR-AR60XX08	**Revision:**	1
		North:	

Feature (2)

- Vortex Shedding Across L-Shaped Sunshade Fins



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Rev	Amendments	Date
0	FIRST ISSUE FOR APPROVAL	22.07.20

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Discipline: FACADE

Project No.: 91186

Project: Sydney Football Stadium Redevelopment
Driver Ave, Moore Park
NSW, 2021

Phase: DETAILED DESIGN

Document Control Status: FOR APPROVAL

Drawing Title: DETAILS
-SECTION CW-01
-OPEN AIR FACADE CANTILEVERED x3 SUNSHADES

A1 DRAWING SHEET

Drawn: R.V

Checked by: J.L

Scale: 1:16@ A1,

Designed by: Pisa PTY

Date: 2020-07-22

Approved by: J.S

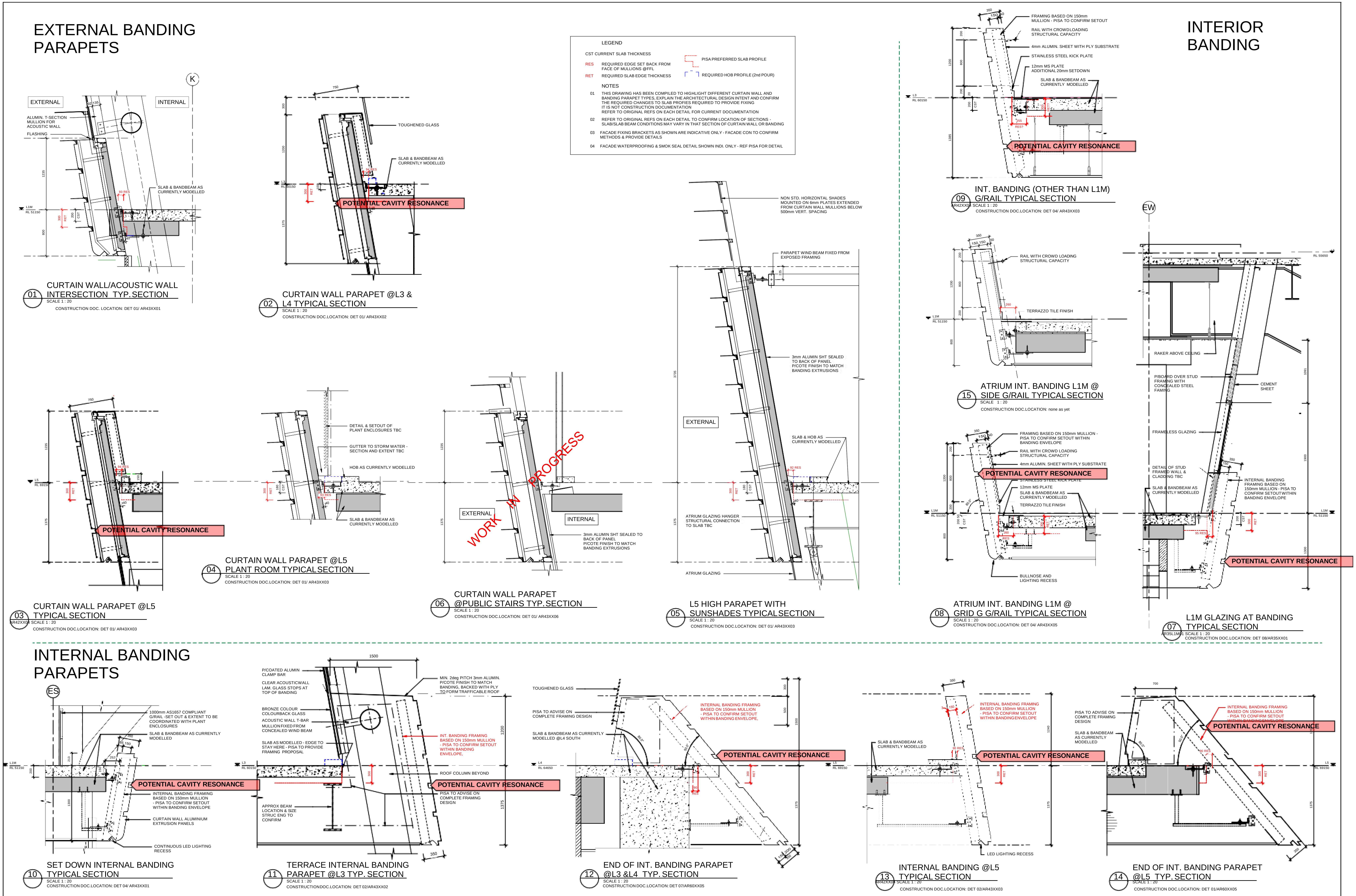
Revision: 0

North:

Drawing Number: SFS-PSA-01-SD-FC52XX12

Feature (3)

- Slot Cavities in Curtain Wall Aluminium Extrusion Panels



Project: **SFS - FACADE**

Drawing Title: **CURTAIN WALL & BANDING SLAB INTERFACE**

Drawing Number: **ASK844**

Revision: **3**

Date: **20/07/20**

Scale: **1 : 20 @ A0**

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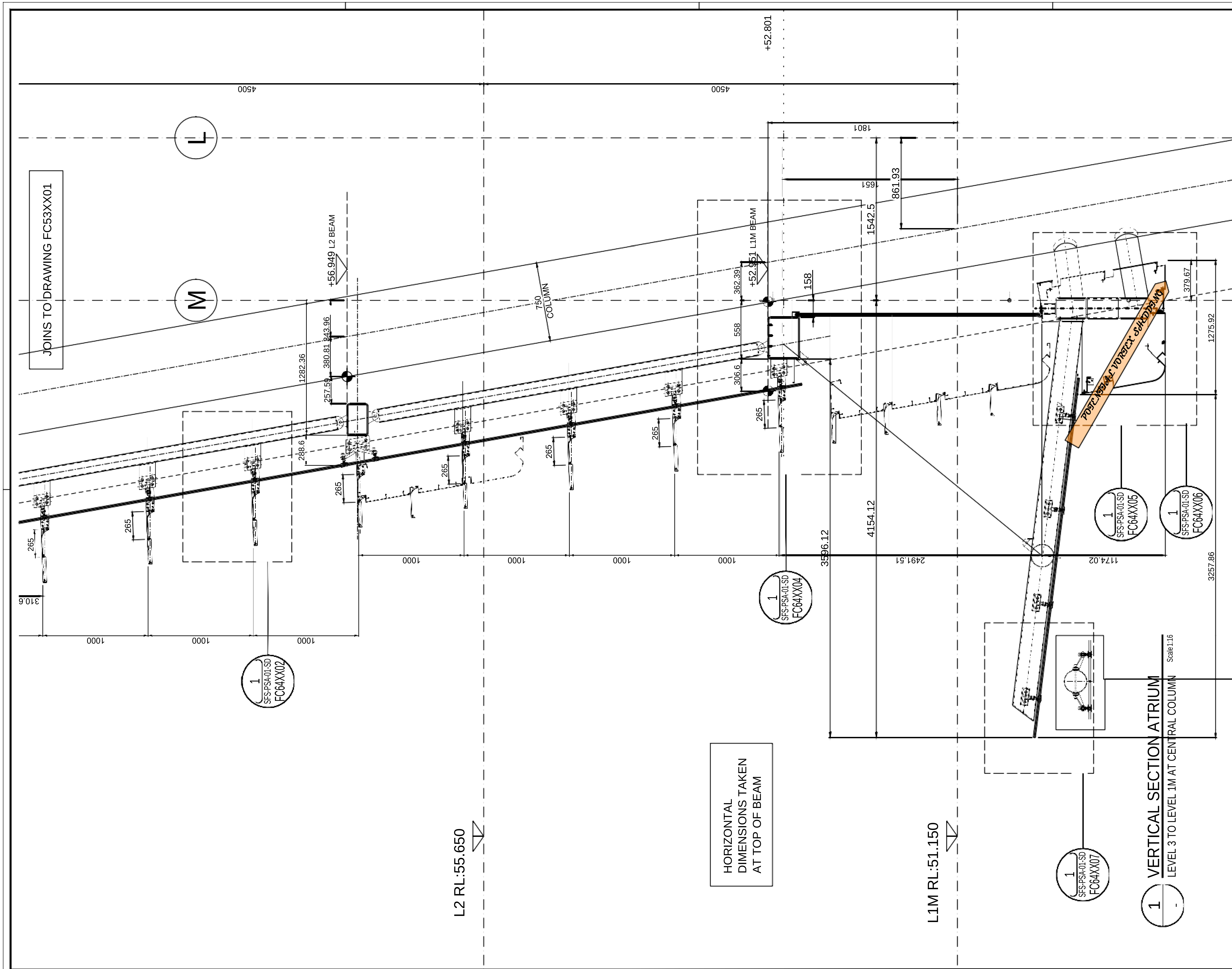
COX

Feature (4)

- Cables Supporting the Glass Canopy



LOCATION PLAN

Rev	Amendments	Date
00	1ST ISSUE	28.07.20

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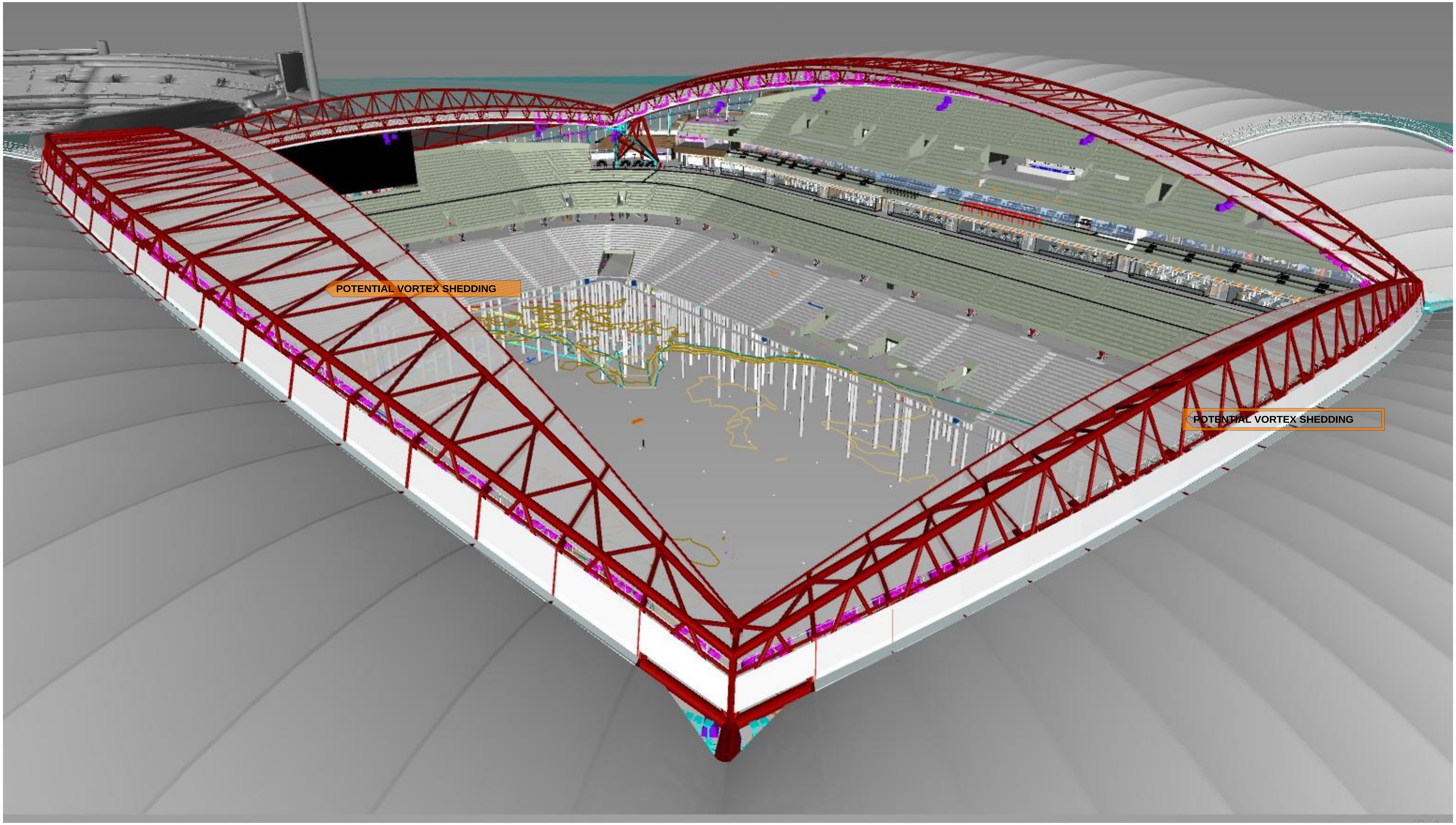
Discipline	FACADE
Project No.	91186
Project	Sydney Football Stadium Redevelopment Driver Ave, Moore Park NSW, 2021
Phase:	DETAILED DESIGN
Document Control Status:	FOR APPROVAL
Drawing Title	EAST ENTRY ATRIUM SECTION LEVEL 3 TO LEVEL 1M
A1 DRAWING SHEET	Drawn: T.M
Checked by: J.L	Scale: (A1 size) 1:16 @ A1
Designed by: Pisa PTY	Date: 24.07.2020
Approved by: L.W	Revision: 00
Drawing Number: SFS-PSA-01-SD-FC53XX02	North:

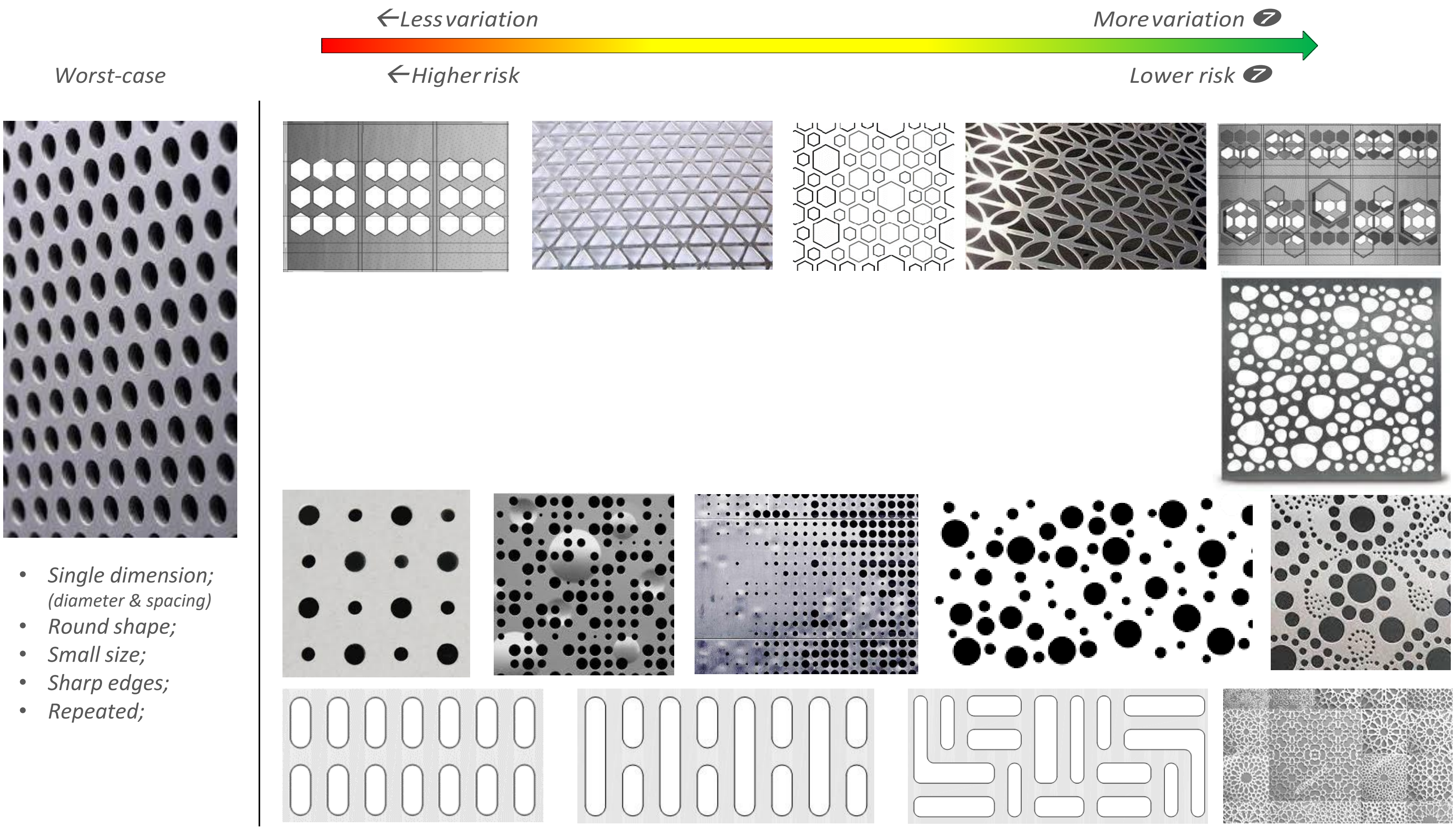
Cox Architecture Pty Ltd ACN 002 535 891

Feature (5)

- Steel Roof Truss Members


POTENTIAL VORTEX SHEDDING
POTENTIAL VORTEX SHEDDING

APPENDIX C



Adding Variation to Perforated Panels

To reduce the risk of wind-induced perforation noise

Conceptual Examples

Drawn by:	AKB	**Figure:**	1
Project #:	2000267		
Date:	2020-08-21		