Reintroduction of Natural Ventilation to a Historic Opera House

The issue of providing fresh air to people in crowded situations is challenging; large theatres are an extreme example. This article explores the natural ventilation system designed into a 100+-year-old theatre through CFD analysis; calibration of the CFD predictions against measured data; and observation of the efficacy of design changes. It is based on a paper presented at the 38th AIVC - 6th TightVent & 4th venticool Conference, 2017 "Ventilating healthy low-energy buildings" held on 13-14 September 2017 in Nottingham, UK.

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An Overview of the Royal Wanganui Opera House Project

The Royal Wanganui Opera House (RWOH) built in 1899, is an 830-seat theatre in Whanganui, New Zealand. Due to its recent comfort complaints, seismic renovations, and a history of natural ventilation design, the owners of the RWOH, the Whanganui District Council, wanted to find a cost-effective solution to ensure the building's use as a performance space could continue.

The original design of the RWOH was explored, and changes through its life span that have affected the ventilation were identified. The basic geometry of the building was 3D computer modelled in Revit. Temperature and humidity sensors were placed throughout the auditorium itself to collect measured data regarding the building's existing operation. The measurements were taken at 5-minute intervals over a two-week period during winter. The goal was to obtain sufficient data to build quickly a trustable analytical model, which would enable the modification of the building prior to an early summer performance that has had a full house in past seasons and has engendered significant overheating complaints.

The geometry was imported into Autodesk Simulation CFD (Autodesk Inc., 2015), and selected situations (weather conditions, occupancy numbers, known openings, use of equipment) of the building were simulated. The CFD model was calibrated against a series of observations of the performance of the existing building. CFD modelling to test the likely success of new or restored interventions to the ventilation scheme was then undertaken. The input data was taken from weather data measured in the area at the same time as the measurements. The results of the CFD models were compared with the measured temperature and humidity data from inside the auditoria, entrance area, roof space, and back of stage. Once the model's geometry, materiality, solar exposure, and internal heat loads produced results aligned with the measured temperature data, these modelling conditions were confirmed and the design option modelling process could begin.

Once calibrated, the model was used in a fully occupied state to analyse performance in summer weather conditions. The goal was to assess key problem areas for overheating in the occupied space. This knowledge acquired from the analysis of the existing building helped identify the proposed ventilation alterations. The designs were then discussed with the building owners for construction feasibility, and the underlying geometry model was altered to reflect the proposed designs. The CFD analysis helped form design and operation recommendations focused on potential comfort hours in summer. From these recommendations, the project to mitigate the RWOH's overheating issues in summer months was split into two stages. Stage one necessitated immediate operational changes for an imminent heavily occupied performance. Stage two involves constructional changes to the building.

Figure 1. The Royal Wanganui Opera House (Wanganui Opera Week, 2016).

Use of Computational Fluid Dynamics (CFD) in Natural Ventilation Design

As a design tool, CFD is unique as it can predict the air motion at all points in the flow. CFD modelling can be used to predict temperature and velocity fields inside buildings for steady-state problems (Allard, 1998). Due to the intensive nature of the computations, CFD is normally only used to generate 'snapshots' of how the design would work at a given point in time (CIBSE, 2005). Accordingly, this software can be used to test extreme or representative conditions at a single point in time. This is different from thermal analysis programs, which today generally calculate an energy balance for each hour of a typical year. This is a key limitation of CFD, as the modelling does not take into account what is happening in the space before and after the analysis, making the specification of boundary conditions to define the existing space extremely important.

With the addition of thermal equations, CFD can predict the effects of buoyancy and the temperature field, addressing questions of stratification and local air movement (CIBSE, 2007). This is particularly important in auditoria such as RWOH, as inlet and outlet levels as well as the height of an auditorium, affect the stratification levels of air. Warm stale air collects below the ceiling; CFD can be used to test whether this air will remain above the occupied zone (Short & Cook, 2005). Since indoor conditions of naturally ventilated spaces are difficult to predict using alternative building simulation tools, the use of CFD simulation becomes necessary (Hajdukiewicz, Geron & Keane, 2013).

About the Case Study: The Royal Wanganui Opera House

The building has a large dome above the main seating area with a grille vent into the ceiling space. From the ceiling space, original plans show two penthouse louvres located above the stage space and seating area, seen in **Figure 2**. The large penthouse louvre over the seating area has been replaced with a curved ridge vent with a smaller aperture. The penthouse louvre over the stage has also been replaced with a ridge vent, however the opening was boarded up. Within the auditorium, multiple external openings are situated at the perimeter of the high-level seating space. These openings appear to be the main exhaust air location for the higher-level seating. Due to light and noise pollution, these openings are no longer opened, but are shut tight during performances. Despite comfort complaints, no mechanical system has been added. An upgrade to the system is urgently required.

3D Computer Geometry Modelling

A combination of original plans, updated drawings from the recent seismic renovations, photographs, and measurements taken on site contributed to the 3D modelling of the RWOH in Autodesk Revit Software. In order to import a 3D model into Autodesk CFD (the air flow assessment software) the 3D model needs

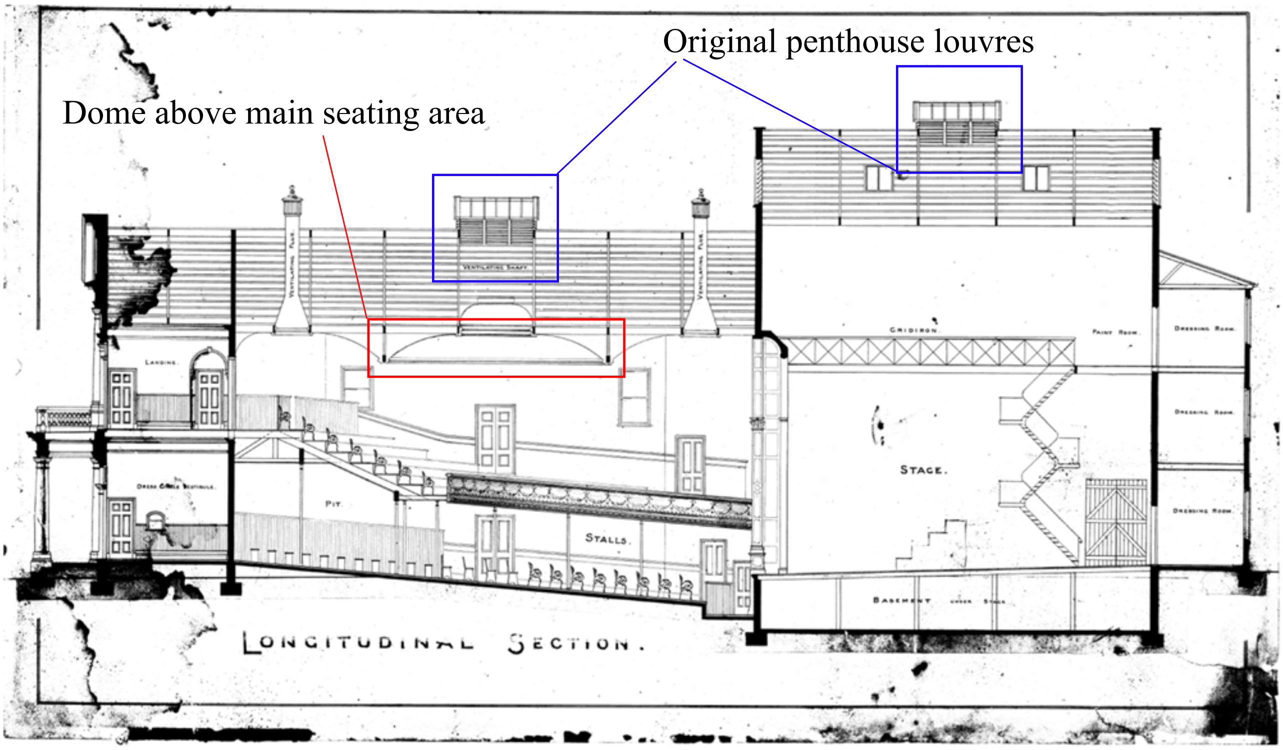

Figure 2. Longitudinal Section of the Wanganui Opera House, completed by architect George Stevenson, 1899.

to be as simple as possible. A basic Revit model has been completed of the space, maintaining volume, wall area and the shell geometry. Due to the hierarchy of importance of elements and low complexity level required for a CFD model, ensuring the external shell and volume within the occupied space is as closely aligned with reality as possible was the main priority. Elements such as columns within the seating area, individual seating and balustrades were not modelled due to their likely minimal effect on air flow. The operable area of openings has been modelled, and each external window and door has been modelled as a slot, even when closed, to account for air seepage.

Detail has been incrementally added to the model to more closely to align the simulated result with the measured data. The dome ceiling shape needed to be made more complex in order to reflect the pattern of air within the space, see **Figure 3**.

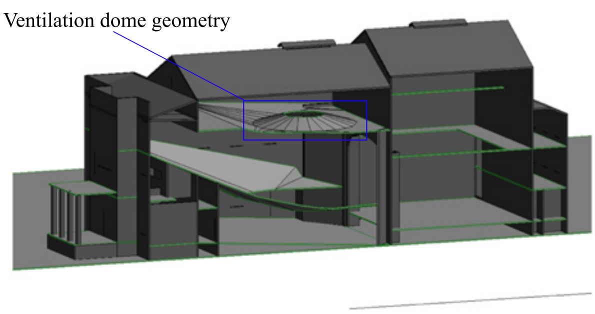

Figure 3. Longitudinal Section through the 3D Model, showing detail required for calibrated CFD analysis.

Collection of Temperature Data

To calibrate the CFD simulation of the existing situation, thirteen calibrated Testo-175-H2 temperature and humidity recording devices were placed throughout the RWOH for a period of two weeks, set to record at 5-minute intervals. The Testo devices were themselves calibrated against an aspirated hygrometer temperature standard prior. During the two-week period, several performances occurred including a local school production, where operational alterations to the ventilation of the space were made.

Recordings from these performances, as well as when the building was empty, and real time external data from the Whanganui Weather Station provide the calibration data (NIWA, 2016). The recorded data of the temperature measurements taken during the two performances, in different weather conditions, show stratification in air temperature. The major test for the CFD simulations was to ensure it could re-create this stratification of air temperatures.

CFD Calibration

Calibration of the CFD modelling for the RWOH consisted of two stages. First, the model of the existing building was calibrated for the building's simplest situation: an unoccupied space during temperate weather conditions. Following a series of simulated iterations, incrementally altering the boundary conditions, turbulence equations, solar radiation inputs, wind speed ratios, existing surface temperatures, assumed dimensions, and modelled materiality, the CFD outputs aligned with the measured data and fitted within the specified calibration tolerances and the limitations of the measuring devices.

The second stage of the CFD modelling involved calibrating two models of the RWOH during an occupied time, when the number of occupants and state of the openings were known. One of the models depicted the space occupied as it is in usual operation with the majority of the openings closed; the second occupied model simulated the space when several high-level openings had been opened. These models used the materiality, turbulence equations, solar radiation process, and assumed dimensions, that were confirmed in the stage one calibration. Following a series of simulated iterations, to determine the most effective way of modelling human heat gains within the space to decipher their influence on air temperature, the outputs from both models became aligned with the measured data and fitted within the specified calibration tolerances and the limitations of the measuring devices. The CFD output of a calibrated model of the occupied space was overlaid with the architectural drawings to identify the temperature measuring device location for numerical analysis.

Modelling Proposed Design Changes

The CFD analysis of the summer performance identified several key areas of overheating concern. Potential changes to the RWOH were considered including: operational changes to air inlets, and air outlets; constructional changes to inlets, and outlets; and major alterations to the building. The first alterations tested were operational. These included reopening the ridge vent above the stage space, opening the butterfly dampers above the dome, and operating the perimeter windows that had been prohibited. Allowing perimeter doors to be open during performances greatly improved the inlet air supply, but the operational issues of such a change restricted its uptake. Given the success of this last operational option, a construction change that was considered was operable louvres in these doors.

The major occupied area of concern noted in the CFD modelling, and confirmed by anecdotal evidence, was the high-level seating at the back of the auditorium, shown in **Figure 4**. The shape of the ceiling rising above the high-level seating creates a warm air trap. In the original design of the building, high level windows on the three perimeter walls surrounding this area were operable. Since the design of the building in 1899, the adjacent road has become significantly busier with motor vehicles. These windows are no longer opened during performances due to noise, as well as the light leak issues that will have existed from the outset. The constructional change agreed with the building owners was the addition of an airflow route from this high-level seating space into the ceiling, by the way of a pelmet slot.

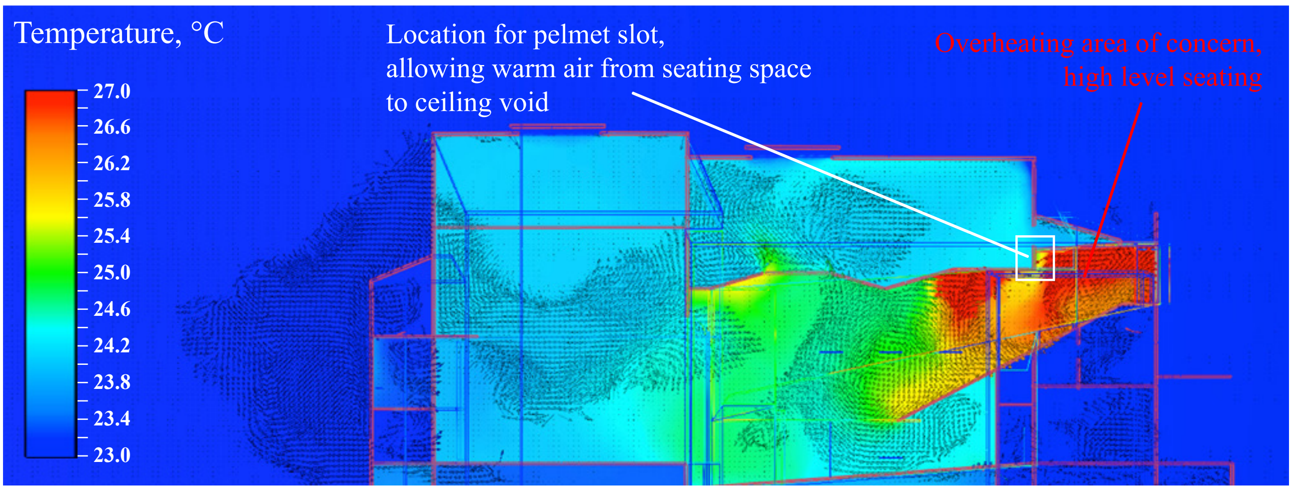

Figure 4. CFD Results from the Fully Occupied Summer Scenario, exposing the key problem area.

Major constructional changes tested with CFD included removing the ridge vents, and reintroducing the original penthouse louvres above the stage and dome ceilings, as seen in the original section of **Figure 2**. The free area of these vents was far greater than their ridge vent replacements, and the height of the penthouse structures likely created a chimney effect. Restoration of the penthouse outlets would be a historical, as well as functional, feature.

Conclusions

Natural ventilation systems often have a reduced cost in initial installation, as well as running and maintenance, over a fully mechanical heating, cooling and ventilation equivalent. Every town and city throughout New Zealand contains one, if not multiple, 100+ occupancy performance venues. Many are of similar historical value as the Royal Wanganui Opera House. Like the RWOH, as a result of recent severe earthquakes in New Zealand, many of these buildings are in the process of significant structural strengthening work. The RWOH experience has shown that the systems with which these buildings were originally designed have the potential to meet modern day standards of cooling and fresh air. The potential to restore not only the appearance but also the ventilation technology as a feature of historic preservation and earthquake strengthening is clear.

This project is applying the same analysis to a large, 1380 seat, brick Opera House building constructed in 1913 in Wellington. Designed by Australian architect, William Pitt, the auditorium originally had a dome like the RWOH, but in place of the ridgeline vent it possessed a sliding roof opening of some 4m x 4m free area. Like the RWOH, the Opera House in Wellington has no contemporary description of how effective its original system was. Initial analysis suggests that its original design lacked the air inlets to bring cooling air into the auditorium to match the hot air exiting through the roof. Calibration studies have established a quality assured model. Design studies are exploring ways to restore the operation of the sliding roof and sliding ceiling during earthquake strengthening in a manner that restores this historical curiosity so visitors can see the building as designed, but ensures effective cooling and fresh air delivery for 1380 people on three levels in the auditorium.

The applicability of a similar process to assess the passive ventilation potential of similar buildings is vast in New Zealand. Ultimately, with these practical case study demonstrations of the potential of CFD analysis, the aim of this research is to produce a user guide for the investigation, analysis, and subsequent recommendations for the ventilation improvement of similar large audience buildings. ■

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