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Design Optimisation of Arch-Supported Membrane Canopies Utilising CFD Technology

A Master's Thesis submitted for the degree of
"Master of Engineering"

supervised by
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Buderim Australia 4.10.2015

Affidavit

I, **TREVOR LINDSAY SCOTT**, hereby declare

1. that I am the sole author of the present Master's Thesis, "DESIGN OPTIMISATION OF ARCH-SUPPORTED MEMBRANE CANOPIES UTILISING CFD TECHNOLOGY", 73 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

Vienna, 4.10.2015

Signature

ACKNOWLEDGEMENTS

I would like to express my deep appreciation for the support of my lovely wife Lucille, my children Jessica, Alexander, and Lachlan and for their continued support and motivation. Without the support of my beautiful wife, the following research would not have been able to be completed.

I would like to express my gratitude to the academic supervisors for the time taken to offer guidance and support in the writing of the thesis

ABSTRACT

Optimization of the profile shape of a free roof canopy determines the relationship between height to span (H/S) ratio and cost relating to tonnage of structural steel. A free roof canopy is a compromise between form, function and cost. The form of a free roof canopy is determined by utilizing four basic shapes Barrel Vault, High Point (Conic), Hypar, Saddle and variations/combinations of these forms/shapes. This research thesis investigates the relationship between the H/S ratios of the Barrel Vault free roof profile.

Within building design, tensile membrane canopies are becoming widely accepted as an alternative to conventional building roof materials. In European situations, wind and snow are the two main load cases applied to a canopy during analysis. In Australia wind is the main load case as very few projects are constructed within the alpine regions. Water ponding on an impervious canopy is also a major consideration, therefore the profile of the fabric roof canopy must be able to shed water during heavy rainfall which is often accompanied by wind.

The free form nature of a tensile membrane canopy and the niche position they have in the construction industry, leads to the issue of lack of relevant data relating to the wind action on the canopy. For large free form canopies wind tunnel tests are conducted to determine relative C_p values. On small scale projects wind tunnel tests are not feasible due to time constraints and the related expense.

Due to advances in software technology Computational Fluid Dynamics (CFD) is a viable aid in the design process of tensile membrane structures. CFD is able to quickly visualize the wind effect and wind turbulence created by the roof profile. Pressure mapping from the CFD to the FEA software begins the optimization process of a free roof canopy thus determining the relationship between Height to Span (H/S) ratio and cost (structural support-tonnage of steel) that influences the design of the final project.

An increase in the H/S ratio may positively influence the form and aesthetic appeal of the structure while not significantly increasing the cost - tonnage of steel. The aim of the research is to provide designers with data which will be of assistance during the design phase of a barrel vault tensile membrane project

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1 INTRODUCTION

Tensile membrane structures are a unique building form which has been utilized for thousands of years. From the tents of the ancient nomadic tribes of the Americas, the Middle East and various other regions where weather protection was paramount, as well as ease of relocation, and the ability to withstand all possible weather events, to the retractable canopies of the ancient coliseum where spectator comfort was the design intent.

During the evolution of the tensile membrane structure, four main free roof profile configurations have been realized and are now considered the basis for all tensile membrane structure design, the Hypar, the Conic (High Point), the Saddle, and the Barrel Vault. Numerous research papers and thesis have been written on the first three of the free roof profile configurations.

1.1 Introduction & Motivation

Pun P. completed his master thesis ‘Analysis of a tension membrane hypar subjected to fluctuating wind loads’ 1993, and the result of the research was the AS/NZS 1170.2:2002 p68 Table D7 Figure D5 and the latest code release AS/NZS 1170.2:2011 p74 Table D7 and Figure D5 (Figure 1.1) of the wind code a free roof canopy profile for a hypar shape has been included.

The AS/NZS 1170.2:2002 was the first country code to recognize the tension membrane form due to the prominence of the shade sail product constructed within Australia.

TABLE D7

NET PRESSURE COEFFICIENTS ($C_{p,n}$) FOR HYPAR FREE ROOFS—EMPTY UNDER (see Figure D5)

Conditions	θ, degrees	$C_{p,w}$	$C_{p,\ell}$
Empty under, $0.25 < h/d < 0.5$, $0.1 < c/d < 0.3$, and $0.75 < b/d < 1.25$	0	+0.45	+0.25
		−0.45	−0.25
	90	+0.45	+0.25
		−0.45	−0.25

NOTE: $C_{p,n}$ is defined as positive downwards, and only combinations of values of the same sign need to be considered.

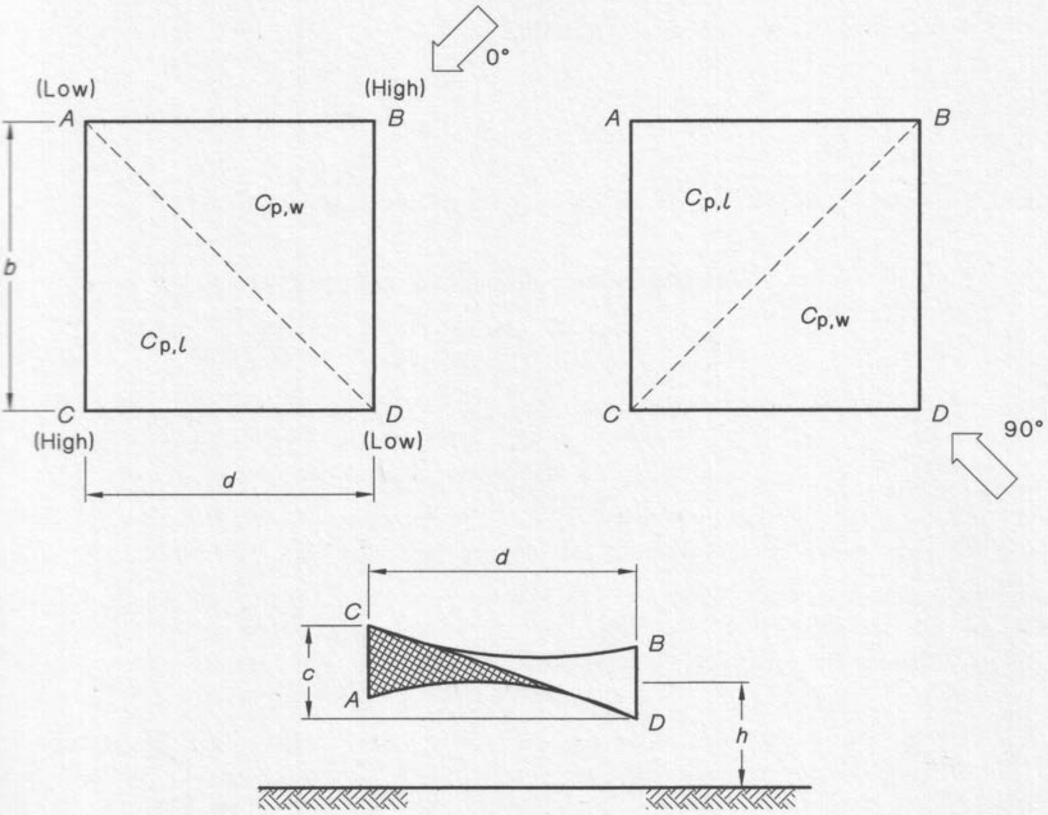

FIGURE D5 HYPERBOLIC PARABOLOID (HYPAR) ROOFS

Figure 1.1 AS1170.2:2011 C_P values for hypar free roof canopies

The ‘European Design Guide for Tensile Surface Structures’ Foster & Mollaert 2004 documents pressure coefficient for closed sided hypar structures. (Figure 1.2)

C_p VALUES FOR SIMPLE TENSILE STRUCTURE SHAPES

A1.4 HYPAR / SADDLE STRUCTURE

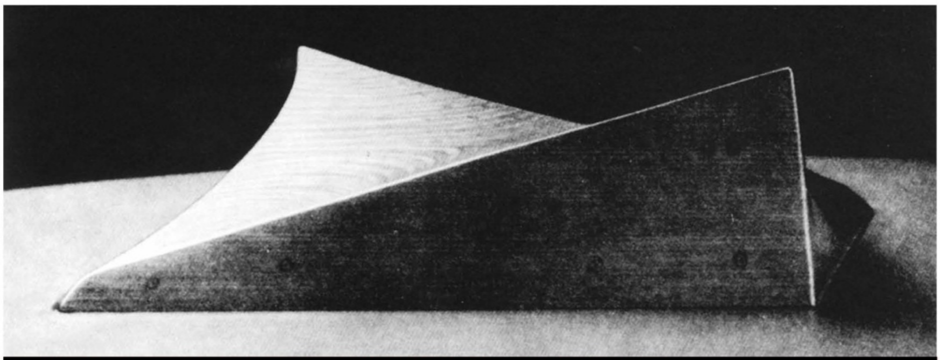

Fig. A1.5 Wind Tunnel Model of the Hypar Form – published in ‘Das Hangende Dach’ Frei Otto 1954.

Shape parameters:

a) Ratio : $\dfrac{\text{Diagonal Dimension}}{\text{Vertical distance between high and low corners}}$

b) Closed sides only

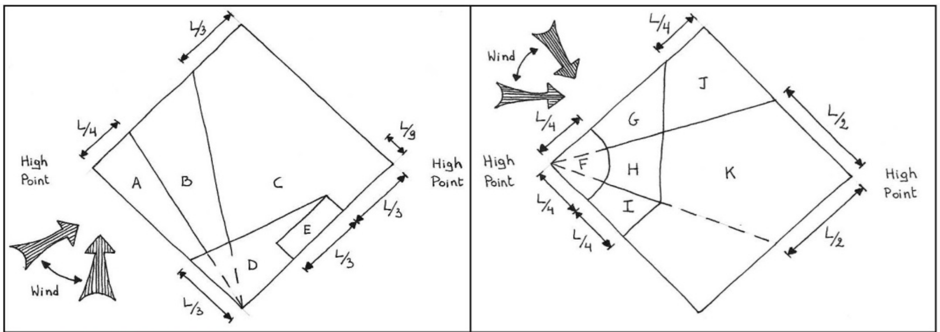

Fig. A1.6 Hypar C_p Zone Definition

External C_p Values	Zones										
	A	B	C	D	E	F	G	H	I	J	K
positive	+0	+0	+0.3	+0.3	+0.3	+0	+0	+0.2	+0	+0	+0.2
negative	-1.45	-0.9	-0.65	-0.70	-1.20	-1.80	-1.20	-0.90	-1.20	-0.65	-0.65

Table 3 External C_p Values for hypar / saddle structures

Data based on a closed sided structure with a shape ratio of 4.7

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Figure 1.2 Extract from European Design Guide – Hypar structures

Conic roof profiles have been covered by the very detailed research completed by Burton J. in her PhD thesis ‘Wind loading on conic roofs’ 2006 (Figure 1.3). The research completed by Burton documents the conic free roof profile in single and multiple configurations with the pressure coefficients for the various zones of the profile. Prior to Burton’s research the pressure coefficients for a conic were very conservatively taken from the wind code documentation of a monoslope, & duopitch free roof.

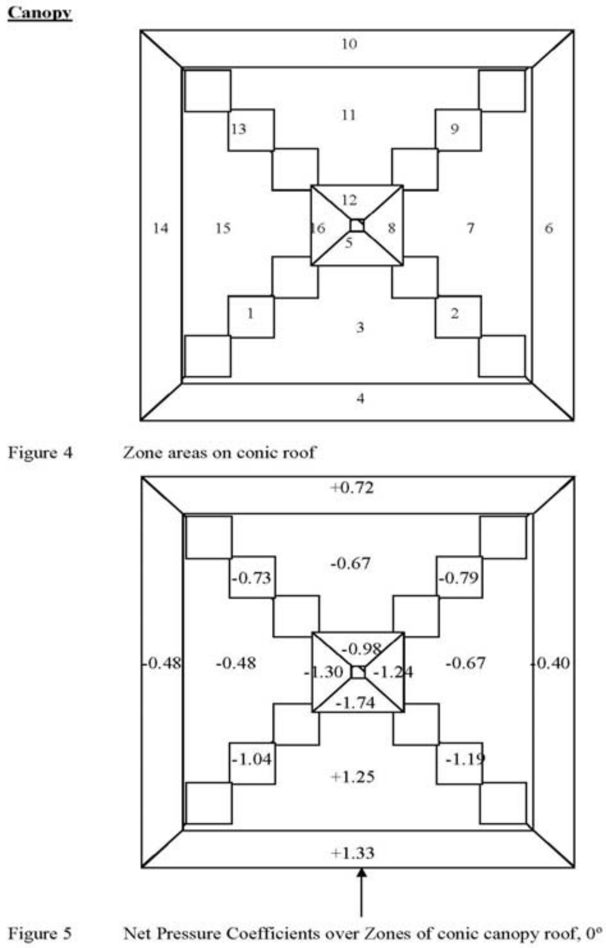

Figure 1.3 Extract from ‘Wind loading on conic roofs’ 2006 by Burton J. in her PhD thesis

Monoslope, duopitch, and troughed free roof profiles are documented in the wind codes utilized throughout the world. AS/NZS 1170.2:2011, (Figures 1.4 and 1.5) BS 6399: Part 2 : 1997, ASCE 7-05, & Eurocode 1, ENV 1991-1-4 :1996 being just four examples.

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TABLE D4(A)

NET PRESSURE COEFFICIENTS ($C_{p,n}$) FOR MONOSLOPE FREE ROOFS—0.25 ≤ h/d ≤ 1 (see Figure D2)

Roof pitch (α) degrees	θ = 0 degrees				θ = 180 degrees			
	$C_{p,w}$		$C_{p,\ell}$		$C_{p,w}$		$C_{p,\ell}$	
	Empty under	Blocked under	Empty under	Blocked under	Empty under	Blocked under	Empty under	Blocked under
0	−0.3, 0.4	−1.0, 0.4	−0.4, 0.0	−0.8, 0.4	−0.3, 0.4	−1.0, 0.4	−0.4, 0.0	−0.8, 0.4
15	−1.0	−1.5	−0.6, 0.0	−1.0, 0.2	0.8	0.8	0.4	−0.2
30	−2.2	−2.7	−1.1, −0.2	−1.3, 0.0	1.6	1.6	0.8	0.0

TABLE D4(B)

NET PRESSURE COEFFICIENTS ($C_{p,n}$) FOR MONOSLOPE FREE ROOFS—0.05 ≤ h/d < 0.25 (see Figure D2)

Conditions	h/d	Horizontal distance (x) from windward edge	Net pressure coefficients ($C_{p,n}$)
For $\alpha \leq 5°$, or For all α with $\theta = 90°$	$0.05 \leq h/d < 0.25$	$x \leq 1h$	Values given for $C_{p,w}$ in Table D4(A), for $\alpha = 0°$
		$1h < x \leq 2h$	Values given for $C_{p,\ell}$ in Table D4(A), for $\alpha = 0°$
		$x > 2h$	−0.2, 0.2 for empty under −0.4, 0.2 for blocked under

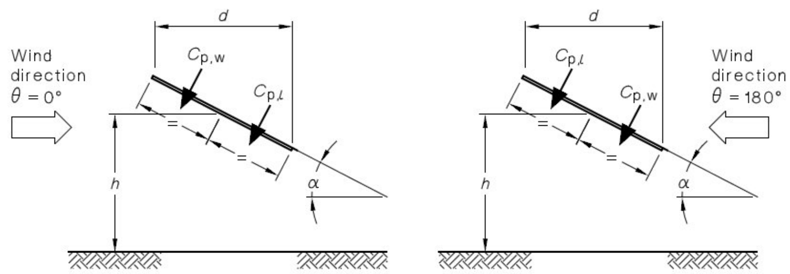

FIGURE D2 MONOSLOPE FREE ROOFS

Figure 1.4 Extract from AS/NZS 1170.2:2011, Monoslope Free Roofs

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TABLE D5

NET PRESSURE COEFFICIENTS ($C_{p,n}$) FOR PITCHED FREE ROOFS—0.25 ≤ h/d ≤ 1 (see Figure D3)

Roof pitch (α) degrees	$\theta = 0°$			
	$C_{p,w}$		$C_{p,\ell}$	
	Empty under	Blocked under	Empty under	Blocked under
≤15	−0.3, 0.4	−1.2	−0.4, 0.0	−0.9
22.5	−0.3, 0.6	−0.9	−0.6, 0.0	−1.1
30	−0.3, 0.8	−0.5	−0.7, 0.0	−1.3

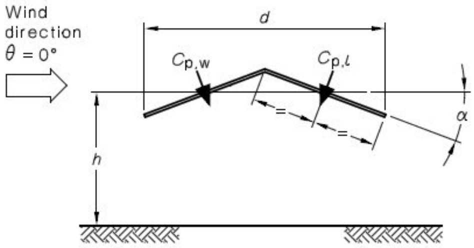


FIGURE D3 PITCHED FREE ROOFS

TABLE D6

NET PRESSURE COEFFICIENTS ($C_{p,n}$) FOR TROUGHED FREE ROOFS—0.25 ≤ h/d ≤ 1 (see Figure D4)

Roof pitch (α) degrees	$\theta = 0°$			
	$C_{p,w}$		$C_{p,\ell}$	
	Empty under	Blocked under	Empty under	Blocked under
7.5	−0.6, 0.4	−0.7	0.3	−0.3
15	−0.6, 0.4	−0.8	0.5	−0.2
22.5	−0.7, 0.3	−1.0	0.7	−0.2

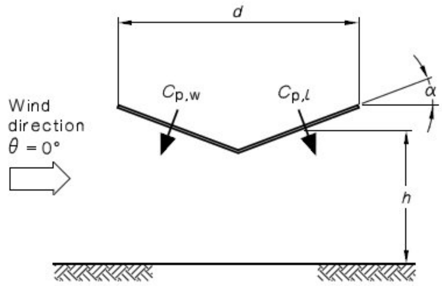
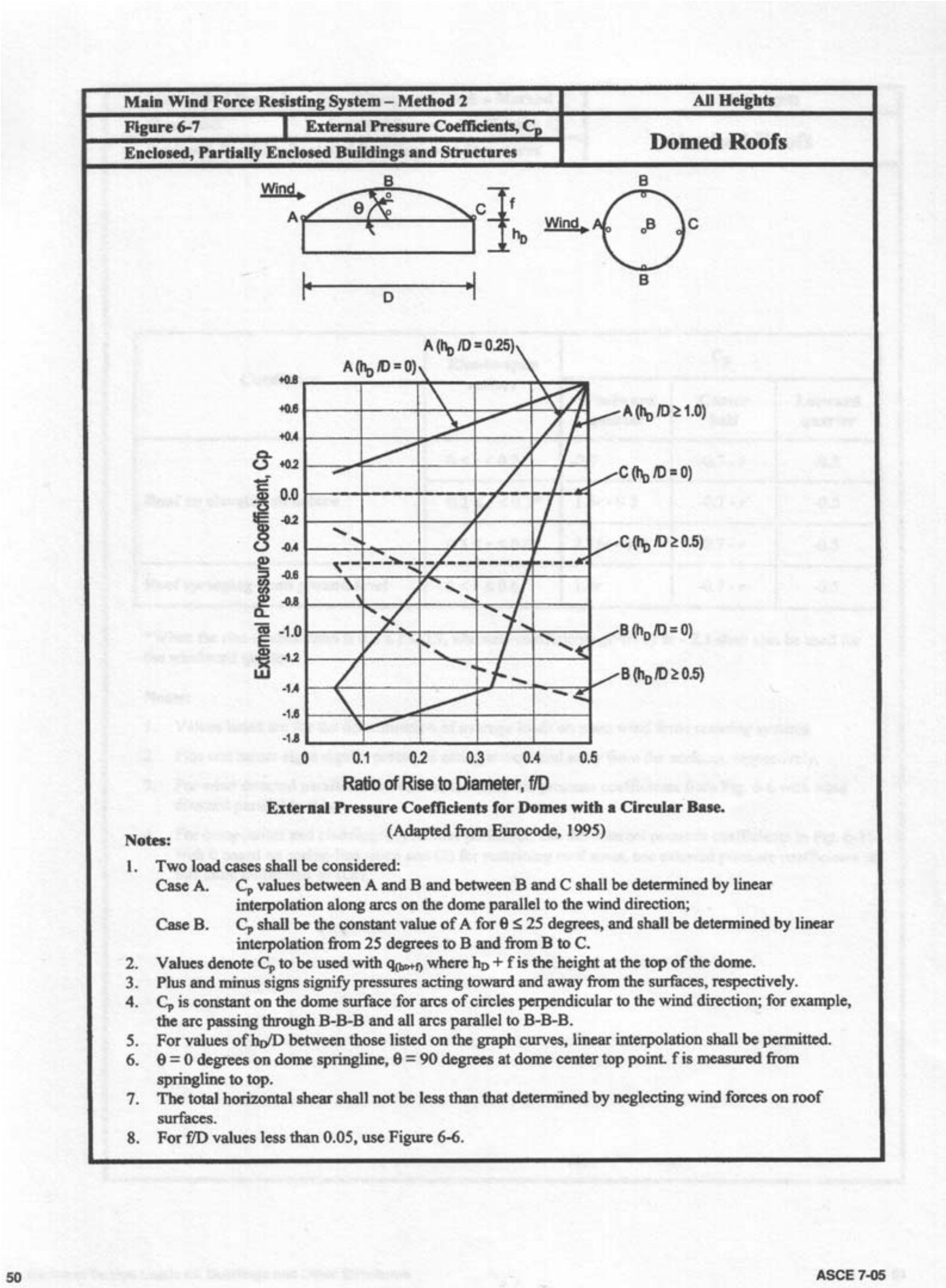


FIGURE D4 TROUGHED FREE ROOFS

Figure 1.5 Extract from AS/NZS 1170.2:2011, Pitched and Troughed Free Roofs

When designing a saddle tensile membrane canopy the pressure coefficients for monoslope, and duopitch are utalised. The three free roof profiles are well documented as they are connected with conventional type structures constructed throughout the world.

ASCE 7-05 p50-51 (Figures 1.4 & 1.5) documents Domed roofs and Arched roofs for Enclosed, partially enclosed building and structures



Main Wind Force Resisting System – Method 2		All Heights
Figure 6-7	External Pressure Coefficients, C_p	Domed Roofs
Enclosed, Partially Enclosed Buildings and Structures		

External Pressure Coefficients for Domes with a Circular Base.

(Adapted from Eurocode, 1995)

Notes:

1. Two load cases shall be considered:
   Case A. C_p values between A and B and between B and C shall be determined by linear interpolation along arcs on the dome parallel to the wind direction;
   Case B. C_p shall be the constant value of A for θ ≤ 25 degrees, and shall be determined by linear interpolation from 25 degrees to B and from B to C.
2. Values denote C_p to be used with $q_{(h_D+f)}$ where h_D + f is the height at the top of the dome.
3. Plus and minus signs signify pressures acting toward and away from the surfaces, respectively.
4. C_p is constant on the dome surface for arcs of circles perpendicular to the wind direction; for example, the arc passing through B-B-B and all arcs parallel to B-B-B.
5. For values of h_D/D between those listed on the graph curves, linear interpolation shall be permitted.
6. θ = 0 degrees on dome springline, θ = 90 degrees at dome center top point. f is measured from springline to top.
7. The total horizontal shear shall not be less than that determined by neglecting wind forces on roof surfaces.
8. For f/D values less than 0.05, use Figure 6-6.

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Figure 1.6 Extract from ASCE 7-05 Domed Roofs

Main Wind Force Res. Sys. / Comp and Clad. – Method 2		All Heights
Figure 6-8	External Pressure Coefficients, C_p	Arched Roofs
Enclosed, Partially Enclosed Buildings and Structures		

Conditions	Rise-to-span ratio, *r*	C_p		
		Windward quarter	Center half	Leeward quarter
Roof on elevated structure	$0 < r < 0.2$	-0.9	$-0.7 - r$	-0.5
	$0.2 \le r < 0.3$*	$1.5r - 0.3$	$-0.7 - r$	-0.5
	$0.3 \le r \le 0.6$	$2.75r - 0.7$	$-0.7 - r$	-0.5
Roof springing from ground level	$0 < r \le 0.6$	$1.4r$	$-0.7 - r$	-0.5

*When the rise-to-span ratio is $0.2 \le r \le 0.3$, alternate coefficients given by $6r - 2.1$ shall also be used for the windward quarter.

Notes:

1. Values listed are for the determination of average loads on main wind force resisting systems.
2. Plus and minus signs signify pressures acting toward and away from the surfaces, respectively.
3. For wind directed parallel to the axis of the arch, use pressure coefficients from Fig. 6-6 with wind directed parallel to ridge.
4. For components and cladding: (1) At roof perimeter, use the external pressure coefficients in Fig. 6-11 with θ based on spring-line slope and (2) for remaining roof areas, use external pressure coefficients of this table multiplied by 0.87.

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Figure 1.7 Extract from ASCE 7-05 Arched Roofs

AS/NZS 1170.2:2011 p64 Table 3 (Figure 1.8) documents the external pressure coefficients for curved roofs-Buildings.

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TABLE C3

EXTERNAL PRESSURE COEFFICIENTS ($C_{p,e}$)—CURVED ROOFS

Rise-to-span ratio (r/d)	Windward quarter (U)	Centre half (T)	Leeward quarter (D)
0.18	($0.3 - 0.4\ h/r$) or 0.0	$-(0.55 + 0.2\ h/r)$	$-(0.25 + 0.2\ h/r)$ or 0.0
0.5	($0.5 - 0.4\ h/r$) or 0.0		$-(0.1 + 0.2\ h/r)$ or 0.0

NOTES:

1 h is the average roof height and r is the rise of the arch (see Figure C3).

2 For intermediate values of rise to span ratio, linear interpolation shall be used.

3 For $h/r > 2$, Table C3 shall be applied with $h/r = 2$.

4 For $r/d < 0.18$, Table 5.3(A) shall be applied.

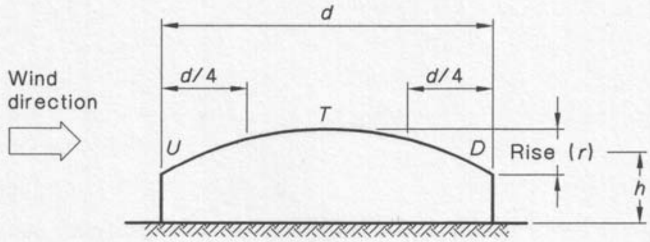

FIGURE C3 EXTERNAL PRESSURE COEFFICIENTS ($C_{p,e}$)—CURVED ROOFS

Figure 1.8 AS1170.2:2011 C_P values for Curved Roof buildings

The ‘European Design Guide for Tensile Surface Structures’ Foster & Mollaert 2004 has the most comprehensive data for tensile membrane structures, Appendix A1 C_PValues for Simple Tensile Structure Shapes & Appendix A2 C_PValues for Open Stadium Roofs

The barrel vault free roof canopy does not have a reference in any of the design wind codes.

Barrel vault free roof profiles are utilized in the design of shopping centre car park structures, walkway structures, porte cochere structures, restaurant and café structures, building entry structures etc. The barrel vault profile is cost effective to manufacture due to the minimal wastage of tensile membrane fabric, and is a functional design profile due to the low perimeter line of the fabric offering maximum sun and weather protection. These design considerations are the main reason this roof profile is chosen over the hypar or wave hypar style where the high points allow sun and rain penetration under the structure. (Figure 1.9)

Figure 1.9 Hypar profile

The conic (Figure 1.10) has a high percentage of wastage of tensile membrane fabric during manufacture, high degree of expertise required in the form finding process, the patterning process, the manufacturing process, and the installation process.

Figure 1.10 Conic profile

The saddle free roof profile (Figure 1.11) has similar issues to the hypar regarding sun and weather penetration underneath the canopy. To minimize the effects of the high points, the site orientation of the structure is paramount as with the hypar profile.

Figure 1.11 Saddle profile

Due to the high usage within the market place of the barrel free roof canopy profile, (Figure 1.12) research is required into the exact dynamics of the profile shape.

Figure 1.12 Barrel vault profile

1.2 Definition and outline of the research problem

The free form nature of a tensile membrane canopy and the niche position they have in the construction industry, leads to the issue of lack of relevant data relating to wind action on the canopy surface and support structure. For large free form tensile membrane canopies and structures, wind tunnel tests are conducted to determine relative C_p values. On small scale projects, wind tunnel tests are not feasible due to time constraints and the related expense.

The barrel vault free roof profile will have an optimum height to span ratio (Figure 1.13 to Figure 1.17) which is the ideal configuration for the barrel vault canopy as far as cost - tonnage of steel to support the tensile membrane fabric roof. An increase in height to span ratio may positively influence the form and aesthetic appeal of the structure while not significantly increasing the cost - tonnage of steel. The aim of the research is to provide designers and engineers with data which will be of assistance during the design phase of a tensile membrane project.

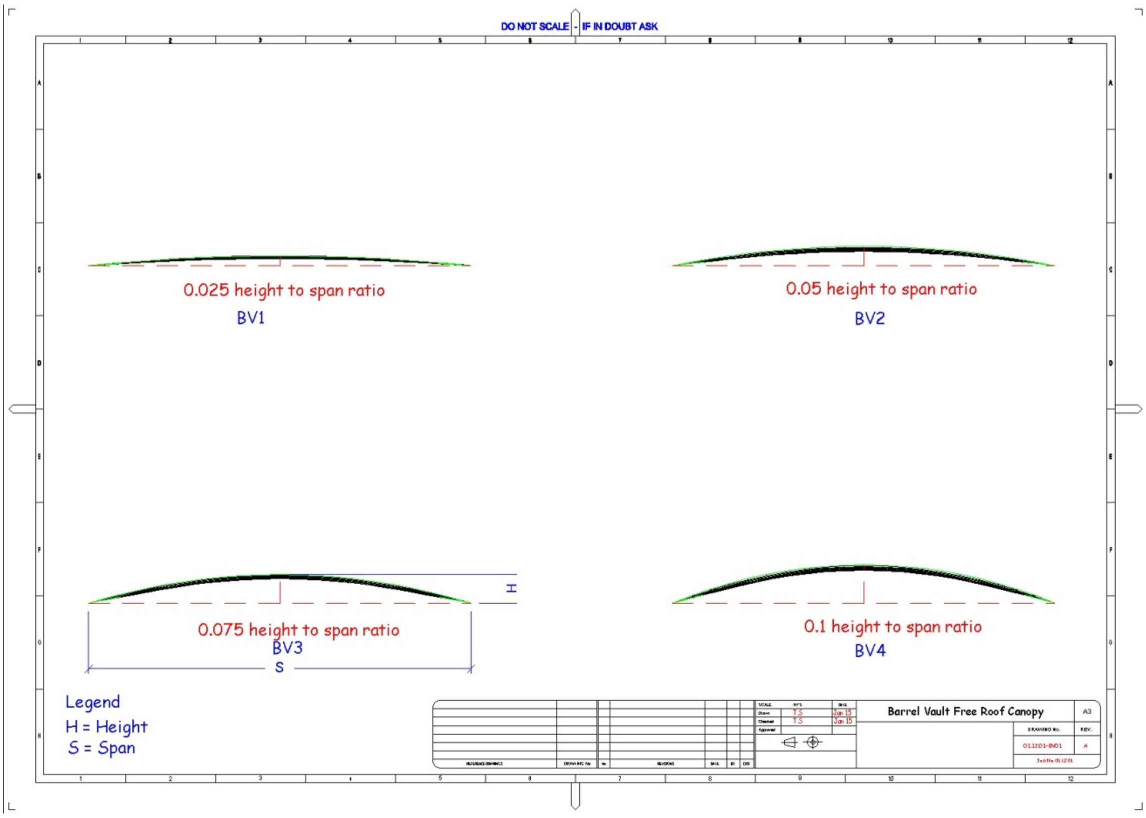

Figure 1.13 Barrel vault profiles height to span ratio 0.025 (BV1) to 0.1 (BV4)

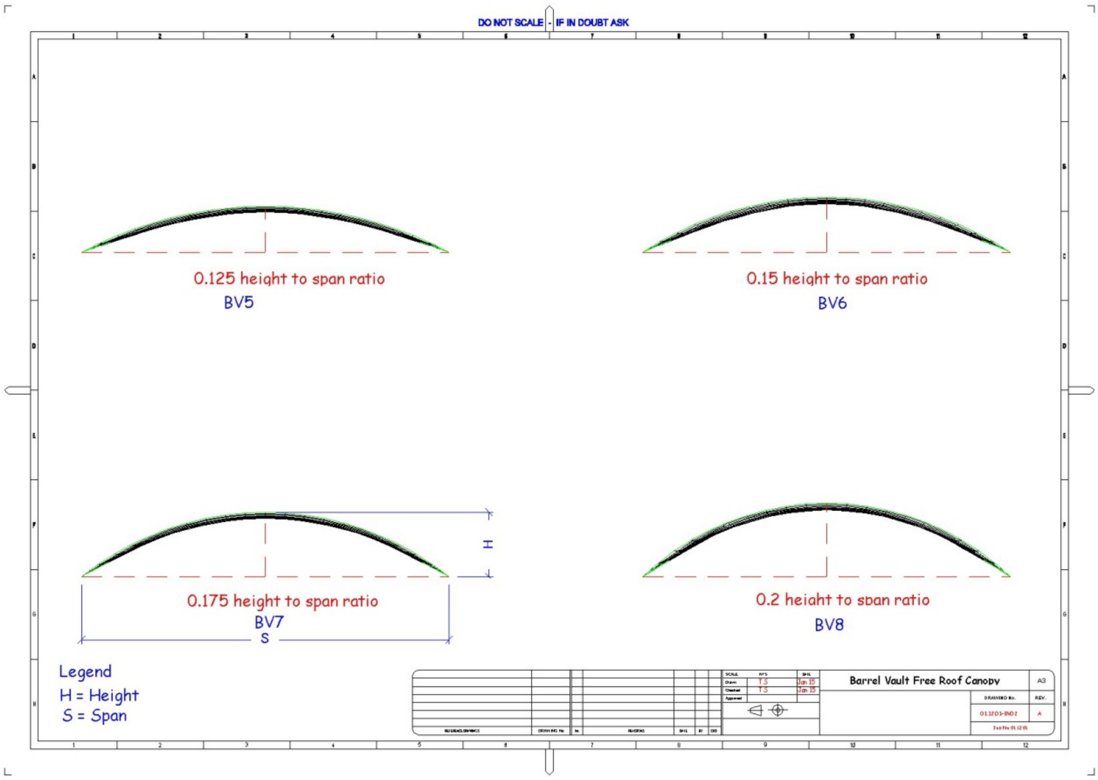

Figure 1.14 Barrel vault profiles height to span ratio 0.125 (BV5) to 0.2 (BV8)

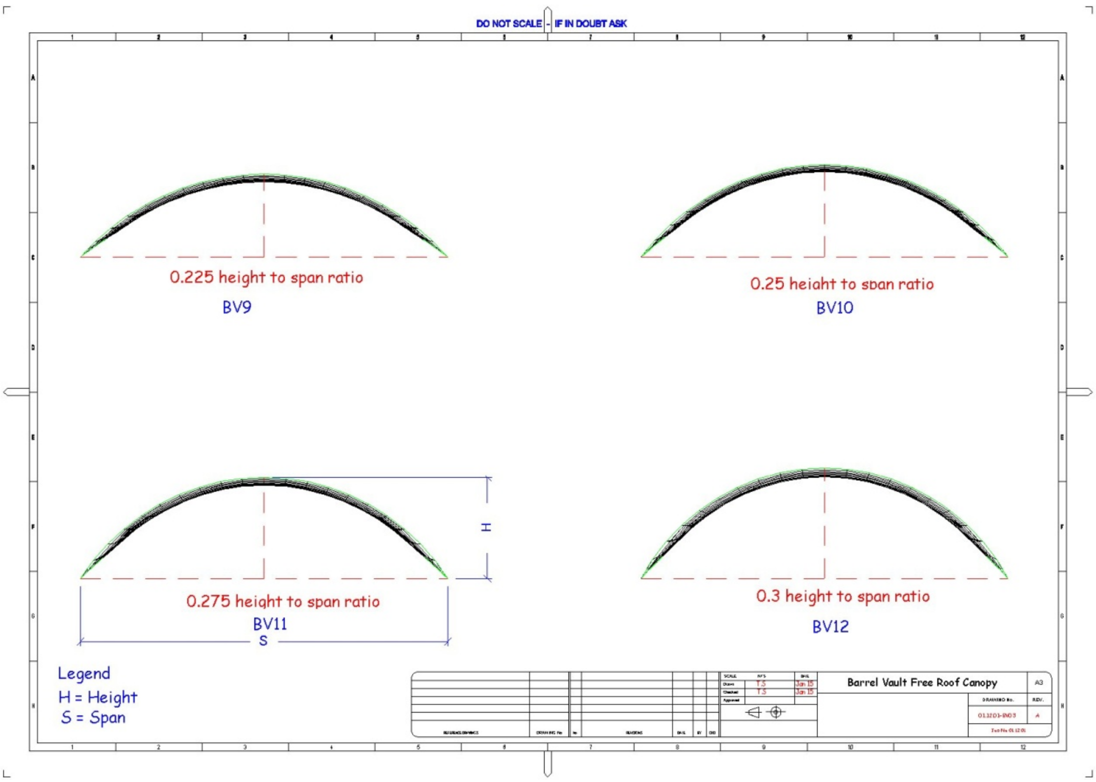

Figure 1.15 Barrel vault profiles height to span ratio 0.225 (BV9) to 0.3 (BV12)

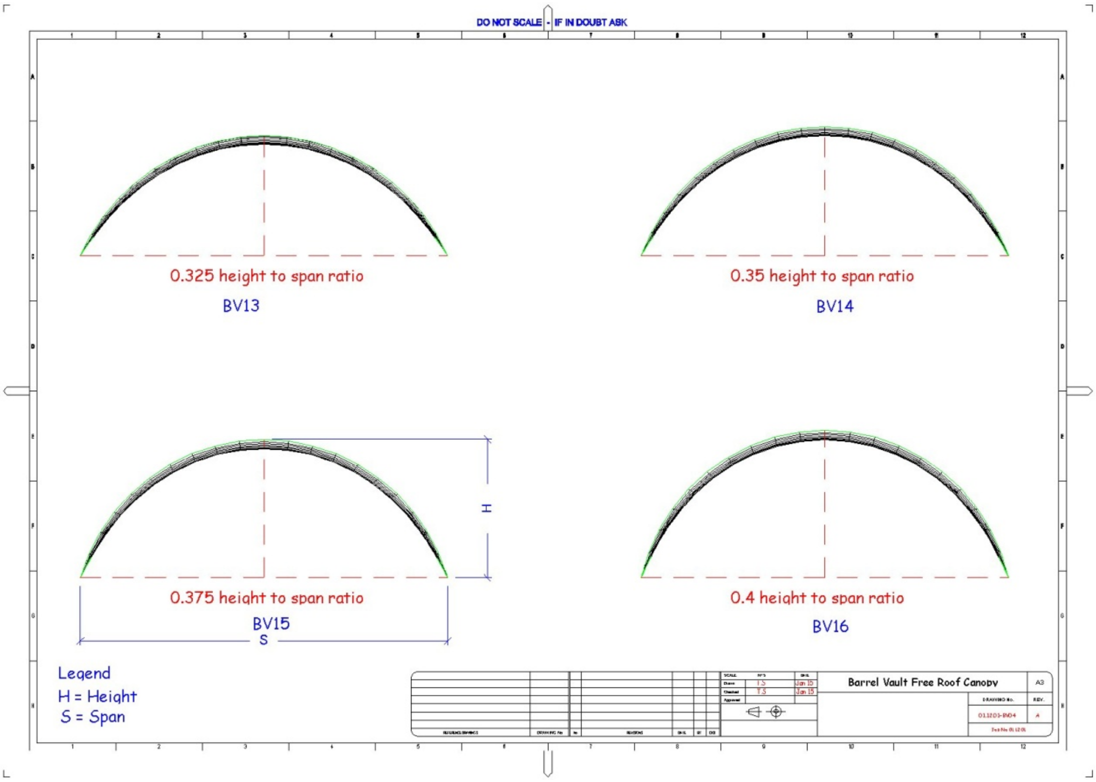

Figure 1.16 Barrel vault profiles height to span ratio 0.325 (BV13) to 0.4 (BV16)

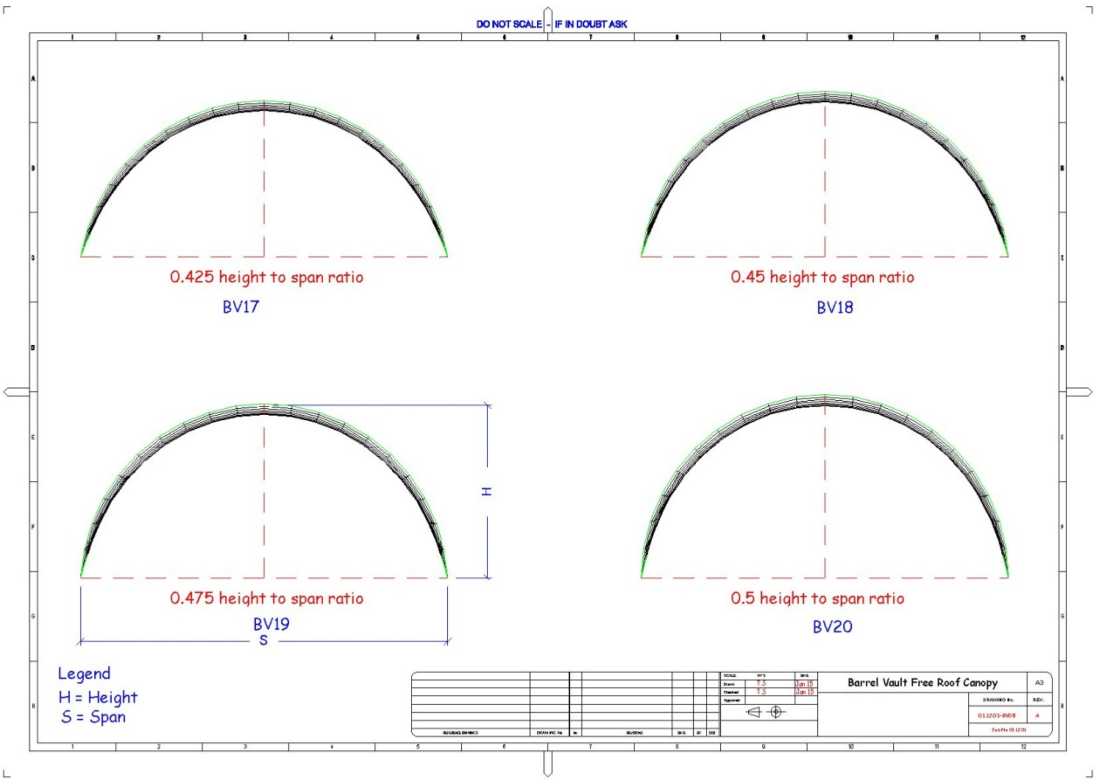

Figure 1.17 Barrel vault profiles height to span ratio 0.425 (BV17) to 0.5 (BV20)

The research aims to.

- Investigate the height to span (H/S) ratio of barrel vault canopies and compare the analysis results to find the optimum shape profile
- Investigate the percentage difference of the profiles either side of the optimum shape
- Assist designers with a guide to optimize tensile membrane design and not be afraid to use a higher H/S ratio barrel vault profile for fear that the cost of the structure will increase dramatically.
- Pressure coefficients for the 4 main zones on each profile shape, for each profile shape
- Document that the increase to the height to span ratio of the barrel vault canopy will diminish the deflection of the canopy under wind load.
- Optimise the dip ratio between support rafters to increase structure aesthetics

1.3 Research Questions

Due to the lack of appropriate data for free roof barrel vault canopies the designer and the engineer must take a very conservative approach when analyzing this roof profile

Question 1

Q1: Is there is an optimum height to span ratio for a barrel vault free roof profile.

Question 2

Q2: What are the cost implications or significant percentage increase/decrease in construction costs when designing a barrel vault free roof structure which varies above or below the optimum profile shape.

Question 3

Q3: What is the pressure distribution on each of the profile shapes.

Question 4

Q4: Will an increase of the dip ratio between the support rafters, compromise the optimum height to span ratio for the sake of aesthetics

1.4 Significance and limitations of the study

The aim of the study is to be able to find the optimum height to span ratio for a barrel vault free roof profile. Then document the cost implications when the height to span ratio of the barrel vault free roof canopy profile is varied above or below the optimum profile shape.

The designer of a project will be able to make an educated consideration when selecting a specific height to span ratio for future projects where the results of the research will influence higher aesthetic appeal into the design of the barrel vault free roof structure by utilizing invreased height into the design.

With any tensile membrane design the secret to creating an awesome project is to have the maximum amount of surface area of the fabric of the structure visible to the viewer. In other words the more height of the structure the more aesthetic appeal the structure has to the viewer.

Designers of tensile membrane structures resist adding height to a project design as the general opinion is that height increases the overall construction cost by a significant percentage.

Limitations

This research project is only looking at a barrel vault free roof canopy profile which is symmetrical across the width of the profile. Often barrel vault profiles with one raised side are utilized in project designs. This research project does not look at this profile variation of the barrel vault free roof canopy.

2 LITERATURE REVIEW

For reasons both practical and cultural, the vast majority of contemporary construction is rectilinear, its form described by straight lines and right angles. (Huntington 2004 p3)

D.Tain explores the history of tensile membrane structures in modern architecture in the Master Thesis document “Membrane Materials and Membrane Structures in Architecture”. (2011) Numerous projects where the tensile membrane is a major component of the building are outlined. From the multiple hypar sails at Yulara Australia constructed in 1984 through to the used of conic style canopies used for the stadium roof at Don Valley Stadium Sheffield. The grandstand canopy of the San Nicola Stadium Italy 1990, The Millennium Dome of Greenwich UK 1999, and the Good Shepherd Lutheran Church Fresno USA 1982 all show the diversity of design achievable with the tensile membrane product.

Horst Berger’s paper, “Form and function of tensile structures for permanent buildings. “ (1999) also looks at the use of tensile membrane product utilized as the roof component of a building. Chapter 5 page 676 Berger discusses Arch-supported structures and their ability to span large distances. This feature of the arch structure allows their use for the coverings of wide span sports arenas.

S. Arnout in the paper “The optimal design of a barrel vault in the conceptual design stage” investigates the barrel vault design and its structural behavior when used in the construction of shell structures notes that “*the goal of structural optimization is to fine the best compromise between cost and performance.”*

P Blackmore’s paper “Wind loads on curved roofs” states that “*Curved roofed buildings are increasingly used in modern built environments because they offer aerodynamically efficient shapes and provide architects and designers with alternative to regular building forms. However, there is little information available on wind loads on these roof forms”.*

The paper specifically discusses buildings with curved roofs. Again there is no documented information on barrel vault free roof canopies.

The diversity and location where tensile membrane structures are constructed creates a new set of problems. Each country has its own wind code with building profiles and C_p values the designer can refer.

Page 2--- Book Review by Leighton Cochran of "Wind Loading of Structure-Second Edition" by John D. Holmes states, ""I was hoping to see some discussion of wind loads on small tensile fabric roofs, as this industry is truly ignored in most codes around the world (AS/NZ1170 has some data on free hypar fabric roofs) and they are grasping for viable design pressures. Perhaps this will appear in the third edition? Anyway, "Wind Loading of Structures" by John Holmes is a must have for any wind engineer's library."" The Australasian Wind Engineer Newsletter Vol 21 Issue 1, January 2008

The Eurocode 1, ENV 1991-1-4:1996, the AS/NZS 1170.2:2011, the ASCE 7-05 and the BS 6399: Part 1 : 1966 are the main building codes utilized in countries where Tensile Membrane Structures are constructed. The codes only document monoslope, duo-pitch and troughed free roof canopy details.

Peter Pun's master thesis "Analysis of a tension membrane hypar subjected to fluctuating wind loads" (1993) has thoroughly researched the hypar free roof canopy profile due to the numerous projects which are now being constructed utilizing the new building form created by Frei Otto. Pun's thesis work has been included in AS/NZS 1170.2:2002 where the hypar free roof canopy was first included in the Australian and New Zealand wind code.

Uematsu Yasushi and associates in various papers "Wind Loads on free-standing canopy roofs" "Wind Loads on free-standing canopy roofs: Part 1 local wind pressures" "Wind Loads on free-standing canopy roofs: Part 2 overall wind forces" Conduct wind tunnel tests and investigate the wind loads and pressure coefficients on various free roof canopy styles, gable, troughed, and mono-slope with pitches from 0 to 15 degrees. Their experiments were compared to AS/NZ code and generally compared favorably with the code.

R Barnard's paper "Predicting dynamic wind loading on cantilevered canopy roof structures" looks at the wind loading on large cantilever stadium roofs

Bletzinger Kai-Uwe, Looks at different forms of tensile membrane structures in the paper "Structural optimization and form finding of light weight structures." Again there is very little reference to barrel vault free roof canopies in the document.

Tension fabric roofs are lightweight structures susceptible to large deflections outside the range considered acceptable for conventional structural materials. These deflections are caused predominantly by wind load, so it is important to have adequate wind loading design data and to understand the behavior of the lightweight surface under this loading. For lightweight structures wind loading is a critical load case but the wide variation in shape and sizes of tension fabric roofs has limited the undertaking of adequate parametric wind loading studies and the development of wind loading design guidance. (Burton 2006 p1) Burton has thoroughly investigated the conic profiles, conducting numerous wind tunnel tests, on single and multi canopies and has documented concise results which are useful to the designer and engineer.

The Tensinet publication, " European Design Guide for Tensile Surface Structures" documents C_p values for Simple Tensile Structure Shapes in Appendix A1, Open Stadium Roofs in Appendix A2. This covers various configurations, inclusive of hypars and conics.

Dr Garry Palmer in the paper "The practical Application of CFD to Wind Engineering Problems" states

"The advantages of computational solutions over traditional wind tunnel testing are,

- *Flexibility in altering the model. The major cost and delay in wind tunnel testing is in the preparing the physical model. CFD offers the option of altering and refining the model to examine more design alternatives*
- *Speed of analysis. A CFD model can be built from an architectural drawing and analysed in a matter of days, whereas preparing a physical model and arranging for a wind tunnel test may take weeks."*

From the completed research, there is only a small amount of information on barrel vault canopies utilized as the roof of a building and virtually no information on barrel vault free roof canopies.

Figure 2.1 Barrel vault canopy as the roof of the building and a barrel vault free roof canopy as the Porte Cochere to the building entry.

Figure 2.2 Barrel vault canopy as the roof covering of a shopping mall car park to shade customers vehicles

3 METHODOLOGY

Computational Fluid Dynamics (CFD) is a software tool which has been evolving over recent years. In the past a mainframe computer was required to run this level of simulation. In recent times the CFD software is now able to be run on a desktop computer, which places it in the hands of designers and engineers who can utilize the power of the technology in design development. Due to the free form nature of Tensile Membrane Structures, CFD is the perfect tool to assist with design development.

3.1 Research Methods

To complete a research project consisting of 24 individual profile variations of the barrel vault free roof canopy (BV1 to BV20), and (BV6A BV6B BV13A and BV13B) by modeling and wind tunnel testing would be a time and cost prohibitive process.

During this research project each of the barrel vault roof profiles (BV1 to BV20, BV6A & B, and BV13A & B) will be created in industry specific form finding software specially designed to find the optimal form within the designated tensile membrane parameters.

The barrel vault profile shape BV6, has a h/s ratio of 0.15 which is commonly utilized in the design of barrel vault car park projects. BV6 will be referenced during the research due to the continued used of the profile shape.

Due to advances in software technology Computational Fluid Dynamics (CFD) is a viable aid in the design process of tensile membrane structures. CFD is able to quickly produce visualizations of the wind effect (Figure 3.1) and wind turbulence (Figure 3.2) created by each of the barrel vault roof profiles. CFD is also able to determine the exact wind pressure acting on each of the individual plates of the roof profile.

The wind pressure will then be pressure mapped onto the analysis model which has been imported into the FEA software to complete the structural analysis.

The complete process will entail:

1 Create 20 individual barrel vault profile shapes, with each successive profile shape increasing the rise to span ratio (h/s ratio) by a factor of 0.025. Commencing at 0.025 (minimum rise) through to 0.50 (maximum rise). 20 individual barrel vault profile shape increments is considered a satisfactory range to be able to determining the required outcome of the research with accuracy

2 Number each specific shape for accurate future reference BV1 (h/s ratio 0.025) to BV20 (h/s ratio 0.50)

3 Import each of the 20 barrel vault profile shapes into the FEA analysis software (Strand 7)

4 Modify and export each of the 20 barrel vault files from the FEA software in a format which is compatible with the CFD software (ESI -- CADAlyser)

5 Separately import each of the 20 barrel vault profile shapes into the CFD software and run a complete simulation to "Normal Termination" for each of the profile shapes.

6 Save the simulation data from each of the 20 barrel vault profile shapes and pressure map the data back into the FEA software (answer to Q3). Compile a series of tables which will allow the data to be imported and utilized in future projects

7 For each of the 20 individual barrel vault profile shapes, build the structural members for the canopy profile and structure within the FEA software.

8 Run the FEA simulation

9 Extract the data from the FEA software and analyze each of the structural members to determine final component size.

10 Create a table to compile the structural member sizes for the model BV1 to BV20

11 Compare and contrast each of the BV1 to BV20 models and determine the optimum profile shape (answer to Q1)

12 Compare each of the BV1 to BV20 models to determine cost considerations for construction (answer to Q2)

13 Once the optimum profile shape is determined BV?? Consider the implications of Q4: "Will an increase of the dip ratio between the support rafters, compromise the optimum height to span ratio for the sake of aesthetics"

14 Create 2 variations of the optimum barrel vault profile shape BV?? With differing ratios of dip between the rafter members.

15 Number each specific shape for accurate future reference BV??A BV??B

16 Complete steps 1 to 12 in consideration to the BV?? Shape

17 Create 2 variations of the barrel vault profile shape BV6 With differing ratios of dip between the rafter members.

18 Number each specific shape for accurate future reference BV6A BV6B

19 Complete steps 1 to 12 in consideration to the BV6A and BV6B Shape

20 Compile the data for (answer to Q4)

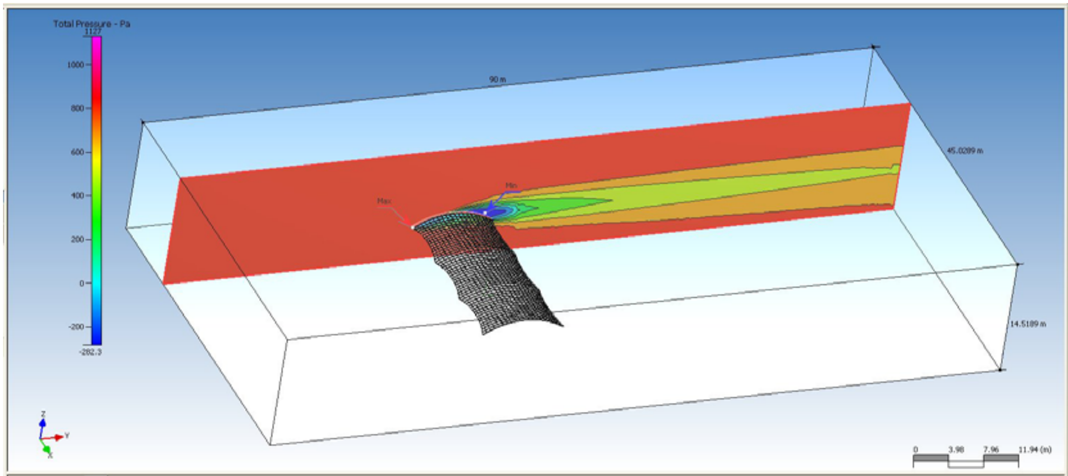

Figure 3.1 Visualation slice on end of end bay BV6

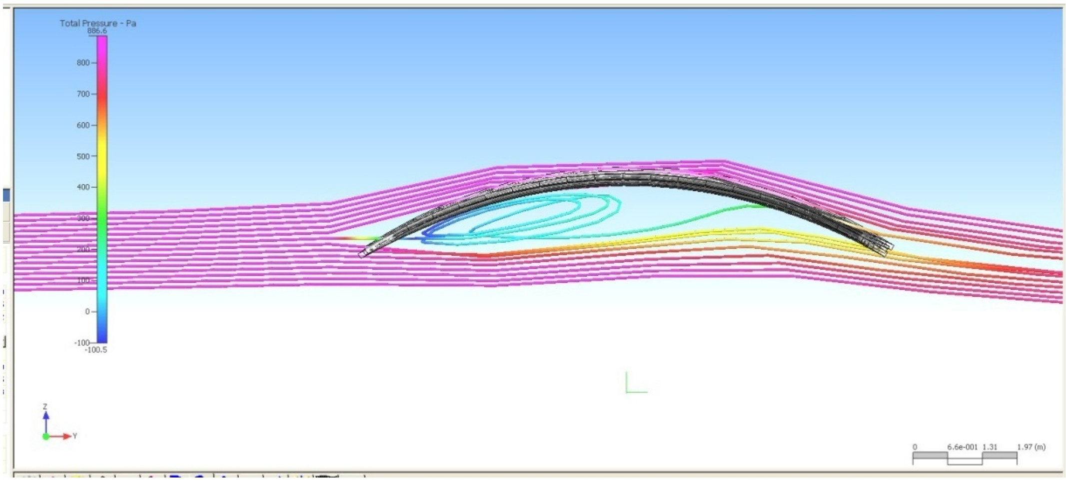

Figure 3.2 Particle trace showing turbulence side view of BV6.

3.2 Limitations of the methodology

Only CFD software technology has been used to determine the wind pressure onto each of the 24 barrel vault free roof canopy profiles. Time and budget limitations prevented other methods being tested and a comparison documented between the methods.

4 CONDUCT AND OUTCOME OF THE RESEARCH

The aim of the research is to identify if there is an optimium profile shape for a barrel vault canopy.The research will consist of the creation, utalising industry specific formfinding software, the geometry of 24 barrel vault canopies. Each canopy will vary in specification and dimensions, to create a range, with an end view profile of, slight curvature to semicircle.

The main body of the research will focus on 20 barrel vault profiles, with height to span ratios of 0.025 to 0.5, with each increment increase of 0.025. The 20 Profiles will be numbered for ease of identification from BV1 to BV20.

The analysis of the resarch data will reveal the optimium profile form. The geometry of this form will then be manipulated, by altering the dip between the structural support rafters, to determine if the barrel vault form must conform to a strict set of geometric specifications, or it can still be relatively free form in nature and the research data still be relevant.

4.1 Modeling

Each of the initial mesh geometries (BV1 to BV20) have been created by a formfinding software program specifically designed to find optimal form within the nominated tensile membrane geometry.

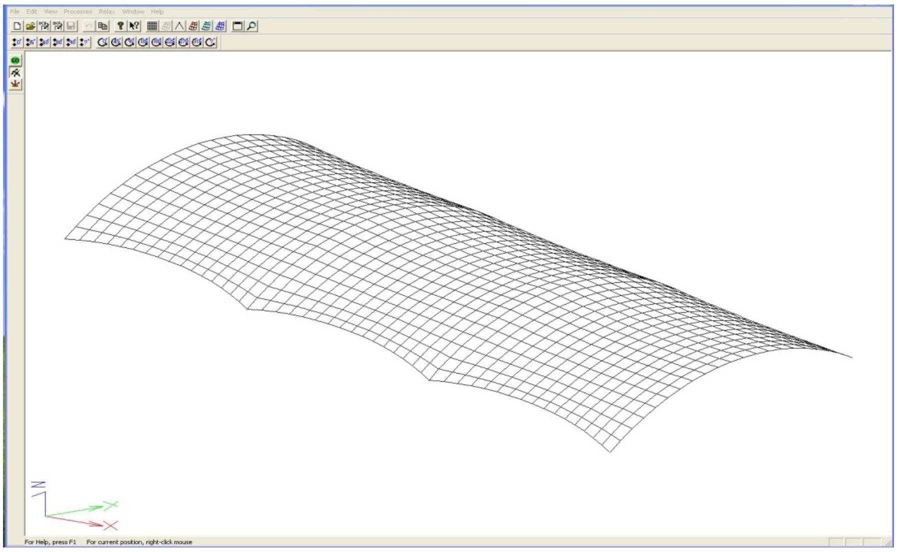

Figure 4.1 Barrel vault profile BV6 created in formfinding software. Dimensions 22.5 mts long x 10 mts wide with a rise 1.5 mts being a H/S ration of 0.15

The BV1 profile has a mesh geometry dimension of 22.5 mts long x 10 mts wide with a rise of 0.250 mts being a height to span ratio 0.025. The mesh geometry is set with the low edge of the canopy 2.7 mts and highest point at the centre of the curved rafter 2.950 mts from the ground level. The 22.5 mt length is divided into 3 increments each of 7.5 mts. The mesh geometry consists of 48 plate elements long x 20 plate elements wide.

The BV6 profile (Figure 4.1) has a mesh geometry dimension of 22.5 mts long x 10 mts wide with a rise of 1.50 mts being a height to span ratio 0.15. The mesh geometry is set with the low edge of the canopy 2.7 mts and highest point at the centre of the curved rafter 4.2 mts from the ground level. The 22.5 mt length is divided into 3 increments each of 7.5 mts. The mesh geometry consists of 48 plate elements long x 20 plate elements wide.

The BV20 profile has a mesh geometry dimension of 22.5 mts long x 10 mts wide with a rise of 5.0 mts being a height to span ratio 0.5. The mesh geometry is set with the low edge of the canopy 2.7 mts and highest point at the centre of the curved rafter 7.7 mts from the ground level. The 22.5 mt length is divided into 3 increments each of 7.5 mts. The mesh geometry consists of 48 plate elements long x 20 plate elements wide.

The BV2 to BV19 profiles have identical geometry with the low edge of the canopy 2.7 mts and highest point at the centre of the curved rafter increasing by 0.25 mts on each successive model.

Individually, each of the 20 (BV1 to BV20) mesh geometries (.dxf file format) are imported into Strand 7 Finite Element Analysis (FEA) software which is used for the final analysis of each of the design configurations. During the initial stage Strand 7 prepares the mesh geometry, applies a consistent 1000Pa pressure normal to each of the individual plate surfaces of the geometry. The individual plate surfaces consist of 48 plates long x 20 plates wide. A .dat file is exported for future pressure mapping and an .iges file for import into Solidworks.

Within Solidworks the mesh geometry is cleaned of most geometric imperfections then thickened by 0.1mt to create a solid element. CFD software, CADAlyzer by ESI France, is actuated from within Solidworks, thereby transmitting the solid element into the work environment of the CFD program.

A bounding box is built around the solid element to contain the applied wind force/pressure. Properties applied to the simulation bounding box area are, Inlet, Outlet, Model, and Symmetry. (Figure 4.2)

Applied wind pressure, AS/NZS1170.2:2011 Region A, Terrain category 3 (M_{zcat}), Wind direction M_d, Shielding M_s, = 46m/s * 0.83 * 1.0 * 1.0 = 38.18m/s

Wind pressure is applied from the inlet of the simulation area. Once all program parameters are set, the simulation area mesh is generated. This is the environment in which the simulation will be modeled.

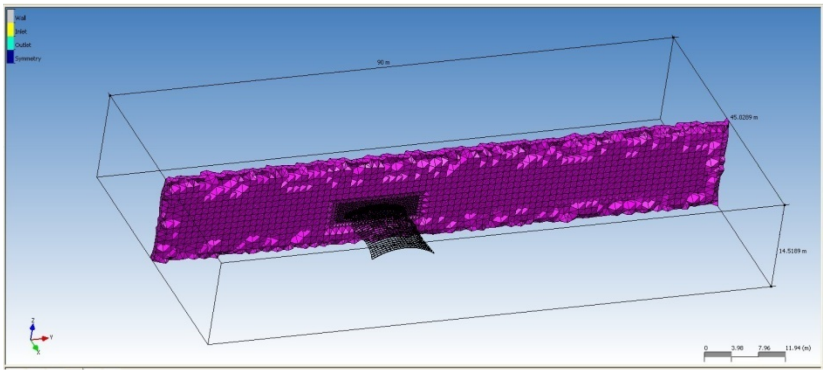

Figure 4.2 Bounding box with x dir slice showing the simulation area mesh. Inlet left side, outlet right side, symmetry top bottom front and rear.

CADAlyzer completes numerous iterations of the problem equation until convergence “Normal Termination” is reached.

Model BV 1 converged in 248 iterations. Time taken… Pre processing set up of model 2hrs, processing time in CADAlyzer approximately 5 hrs, Post processing of the model 1.5 hrs.

Model BV 20 converged in 1557 iterations. Time taken… Pre processing set up of model 2hrs, processing time in CADAlyzer approximately 29 hrs, Post processing of the model 1.5 hrs.

For models BV2 to BV19 the processing time can be interpolated between the processing time of BV1 & BV20

There is a significant time saving by using CFD software over the procedure of modeling, wind tunnel tests, and compiling the results.

Scripting expressions have been written to allow the results from CADAlyzer to be automatically generated ready for import into Strand 7.

The converter script specifically created, over writes the .dat file which in the initial phase of the process was exported from Strand 7. The consistent 1000Pa applied normal to each plate surface is overwritten with the final data extracted from CADAlyzer. The individual plate pressures from CADAlyzer are automatically pressure mapped to the exact plate positions in Strand 7. (Figure 4.3) The scripts which have been written to automate the process save numerous hours completing the process manually.

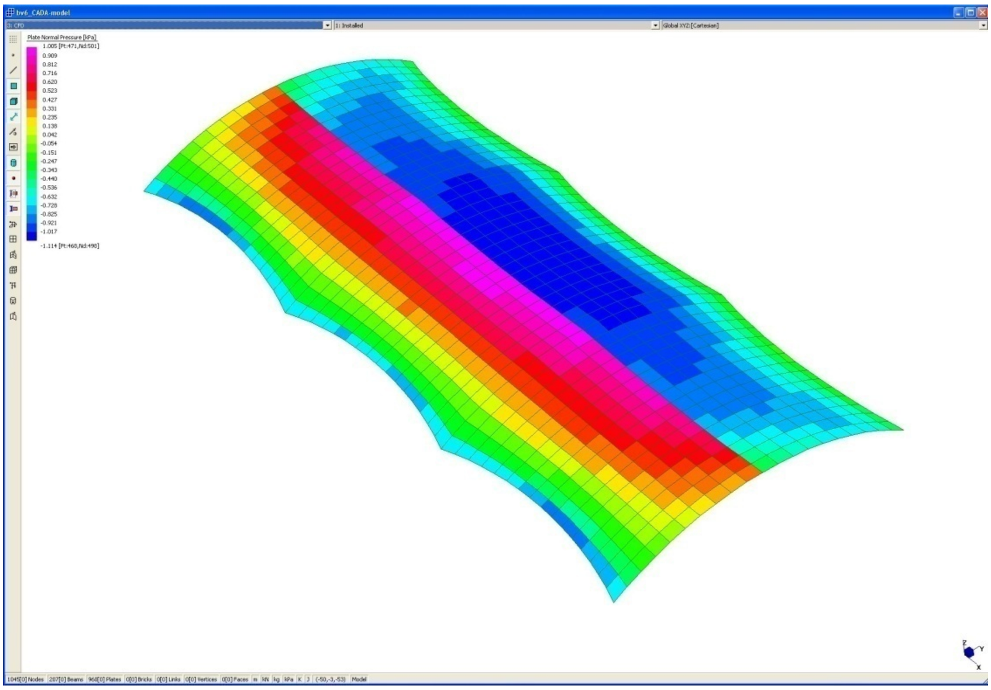

Figure 4.3 Pressure mapping BV6.

4.2 Research process

The Strand 7 barrel vault canopy profile is ready for the construction of the final FEA model. Beam elements are created to represent the columns, rafters, braces and struts of the model. Material properties are assigned to each of the individual beam elements. Model fixities are assigned to the 4 column supports. (Figure 4.4)

4 load cases are set up in the FEA software:

- Prestress
- Gravity
- Prestress and Gravity
- Applied CFD pressure mapped to FEA canopy

The canopy pressure is applied in even increments of 0.1 value from 0.1 to 1.0 as well as 1.2 and 1.4 being safety factors of 20% and 40% respectively..

The FEA model with all program settings to required parameters will run to convergence on each of the load case intervals.

The above process is repeated for each of the 20 profile configurations.

And the later research for the extra 4 profile configurations.

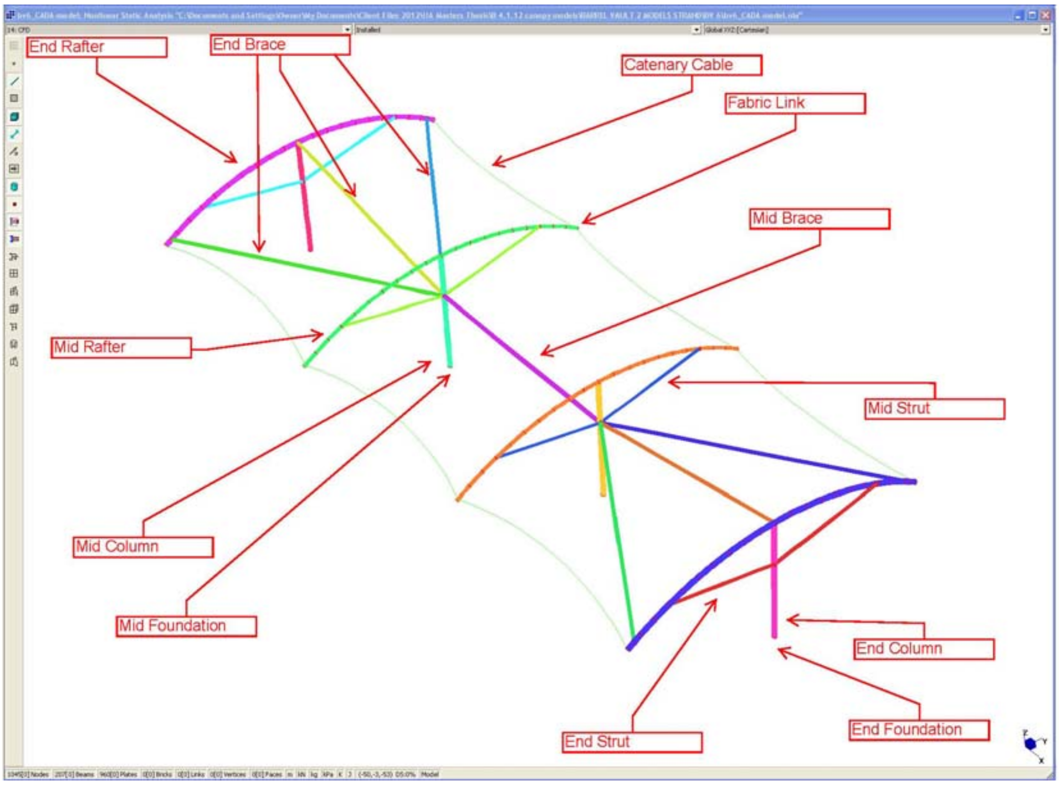

Figure 4.4 Structural supports BV6

4.3 Data Analysis

Within each of the Strand 7 profile configurations data is extracted for each of the following elements.

- Fabric stress
- Catenary cable
- Fabric attachment link
- End column
- End foundation
- Mid column
- Mid foundation
- End rafter
- Mid rafter
- End strut
- Mid strut
- End Brace
- Mid Brace
- Tonnage of steelwork

The data is analysed by AS4100-1998 steel structures design code to determine the required structural element property size and tonnage of steel required to support each of the 20 barrel vault profiles. (Figure 4.5)

The data from each barrel vault free roof profile is compiled in Table 4.1 & Table 4.2 for comparison.

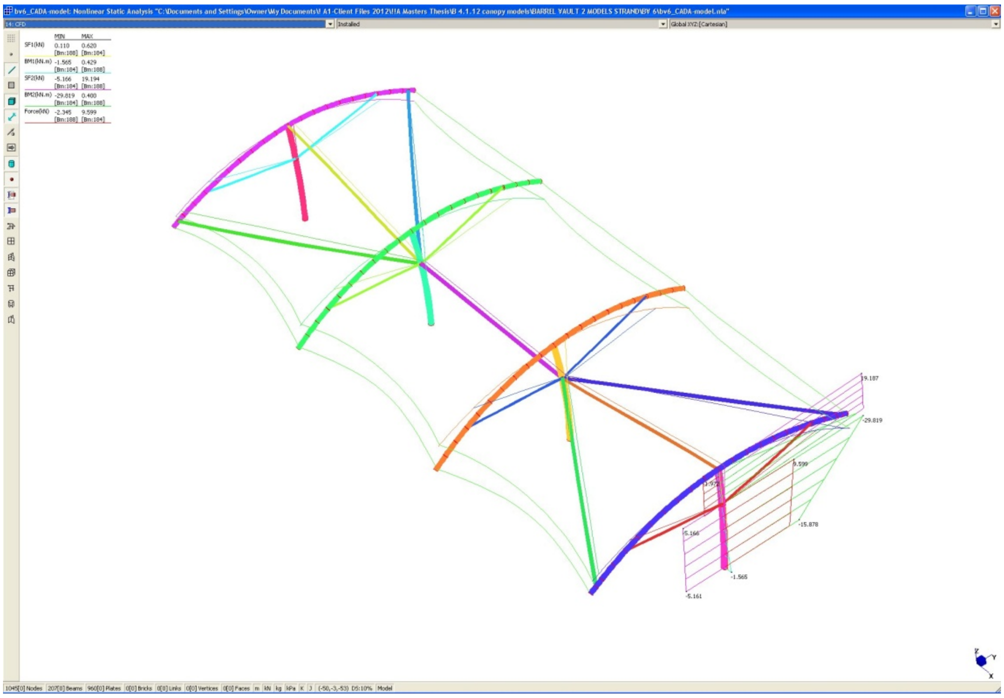

Figure 4.5 Structural analysis BV6 (typical for all barrel vault profile shapes)

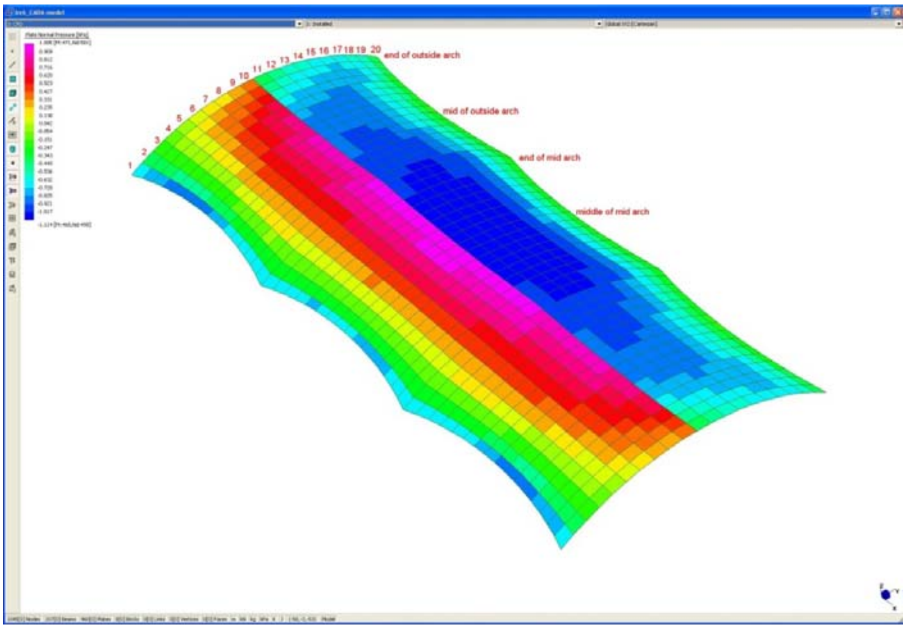

Figure 4.6 *Zones for* table, pressure coefficients for BV6 (Typical all profiles)

4.4 Summary of data collected- Structural analysis of all profile configurations

In order to answer **Q1: Is there is an optimum height to span ratio for a barrel vault free roof profile.** The following tables have been complied. The table has been divided into 2 sections for ease of placement in the research paper.

Legend for data from the tables.

Table 4.1

- 'Profile' — defines each of the Barrel Vault profile shapes BV1 to BV20
- 'Height to span ratio' — defines the h/s ratio for each of the barrel vault profile shapes
- 'Rise of Rafter' — defines in metres the rise of the barrel vault profile on the 10 metre width of the test canopy
- 'Fabric Stress' — defines in kN/m the highest stressed plate value within the barrel vault canopy determined during the analysis process Figure 4.7
- 'Catenary Cable' — defines in kN the highest value within the canopy perimeter cable determined during the analysis process Figure 4.8
- 'Fabric Link' — defines in kN the highest value within the canopy attachment link to the structural member determined during the analysis process Figure 4.9
- 'End Column' — defines the diameter and wall thickness of the test structure end columns Figure 4.10
- 'End Foundation' — defines in metres the 450mm diameter pier foundation depth required for the end column of the structure
- 'Mid Column' — defines the diameter and wall thickness of the test structure middle columns Figure 4.11

- ‘Mid Foundation’ defines in metres the 450mm diameter pier foundation depth required for the middle columns of a structure

Table 4.2

- ‘Profile’ defines each of the Barrel Vault profile shapes BV1 to BV20
- ‘End Rafter’ defines the diameter and wall thickness of the test structure end rafters Figure 4.12
- ‘Mid Rafter’ defines the diameter and wall thickness of the test structure middle rafters Figure 4.13
- ‘End Strut’ defines the diameter and wall thickness of the test structure end strut Figure 4.14
- ‘Mid Strut’ defines the diameter and wall thickness of the test structure middle strut Figure 4.15
- ‘End Brace’ defines the diameter and wall thickness of the test structure end brace Figure 4.16
- ‘Mid Brace’ defines the diameter and wall thickness of the test structure middle brace Figure 4.17
- ‘Tonnage steelwork’ defines in Tonnes the total weight of the structural steel members of each Barrel Vault profile shape

Profile	Height to Span Ratio	Rise of Rafter	Fabric Stress	Catenary Cable	Fabric Link	End Column	End Foundation	Mid Column	Mid Foundation
		mts	kN/m	kN	kN	Chs Gr350	450 diam	Chs Gr350	450 diam
BV1	0.025	0.25	2.54	15.835	9.735	101x3.2	1.3	114x3.2	1.25
BV2	0.050	0.50	4.082	22.762	14.283	114x3.2	1.45	165x3.5	1.8
BV3	0.075	0.75	4.894	29.899	18.686	139x3.5	1.7	168x4.8	2.15
BV4	0.100	1.00	7.351	33.34	21.491	165x3.5	1.8	168x6.4	2.35
BV5	0.125	1.25	8.211	36.166	23.43	168x4.8	1.75	273x4.8	2.45
BV6	**0.150**	**1.50**	**9.024**	**37.24**	**24.75**	**168x4.8**	**1.7**	**168x6.4**	**2.45**
BV7	0.175	1.75	9.468	36.755	24.694	168x4.8	1.45	168x6.4	2.4
BV8	0.200	2.00	10.388	35.581	24.125	168x4.8	1.45	219x6.4	2.35
BV9	0.225	2.25	10.978	34.508	23.297	165x3.5	1.1	168x6.4	2.0
BV10	0.250	2.50	11.101	31.758	21.486	139x3.5	1.1	168x4.8	1.7
BV11	0.275	2.75	11.879	29.858	19.722	139x3.5	1.05	168x4.8	1.25
BV12	0.300	3.00	12.243	27.12	17.558	114x3.2	1.1	114x6.0	0.75
BV13	**0.325**	**3.25**	**11.868**	**23.12**	**14.44**	**101x2.6**	**1.26**	**114x6.0**	**1.15**
BV14	0.350	3.50	12.791	21.801	13.878	101x3.2	1.15	114x6.0	1.4
BV15	0.375	3.75	12.912	20.038	13.566	114x3.2	1.15	114x6.0	1.6
BV16	0.400	4.00	13.117	20.898	14.573	114x3.2	1.2	165x3.5	1.65
BV17	0.425	4.25	13.325	22.359	15.812	114x3.2	.13	165x3.5	1.65
BV18	0.450	4.50	13.418	23.574	17.096	114x3.6	1.45	165x3.5	1.6
BV19	0.475	4.75	13.821	24.819	18.09	114x6.0	1.6	168x4.8	1.5
BV20	0.500	5.00	13.705	20.105	13.207	114x6.0	1.0	168x4.8	1.45

Table 4.1 Results for all profiles

Profile	End Rafter	Mid Rafter	End Strut	Mid Strut	End Brace	Mid Brace	Tonnage steelwork
	Chs Gr350	Chs Gr350	Chs Gr350	Chs Gr350	Chs Gr350	Chs Gr350	T
BV1	89x2.6	89x2.6	76x2.3	76x2.3	114x3.2	114x3.6	0.955
BV2	89x4.8	101x3.2	76x3.2	76x3.2	114x3.2	114x4.8	1.207
BV3	114x4.8	114x3.6	89x2.6	89x3.2	114x4.8	114x6.0	1.606
BV4	114x6.0	114x3.2	89x3.2	89x2.6	114x4.8	139x3.5	1.677
BV5	165x3.5	114x3.6	89x3.2	89x2.6	114x4.8	139x3.5	1.824
BV6	**168x4.8**	**114x3.6**	**101x2.6**	**89x2.6**	**114x4.8**	**139x3.5**	**1.919**
BV7	168x4.8	114x3.6	89x3.2	89x2.6	114x4.8	139x3.5	1.964
BV8	168x4.8	114x4.8	114x3.2	89x2.6	114x4.8	139x3.5	2.181
BV9	168x4.8	114x3.6	89x3.2	76x3.2	114x3.6	139x3.5	1.838
BV10	168x4.8	114x3.6	89x2.6	76x3.2	114x3.6	114x6.0	1.810
BV11	168x4.8	114x3.6	89x2.6	76x3.2	114x3.2	114x6.0	1.793
BV12	168x4.8	114x3.6	89x2.6	76x2.3	114x3.2	114x6.0	1.736
BV13	**165x3.5**	**114x3.6**	**76x3.2**	**76x2.3**	**114x3.2**	**114x6.0**	**1.613**
BV14	168x4.8	114x4.8	76x3.2	76x2.3	114x3.2	114x6.0	1.872
BV15	168x4.8	114x4.8	89x2.6	76x2.3	114x3.2	114x6.0	1.929
BV16	168x6.4	114x4.8	89x2.6	76x2.3	114x3.2	114x6.0	2.133
BV17	168x6.4	114x4.8	89x2.6	76x2.3	114x3.2	114x6.0	2.185
BV18	168x6.4	114x4.8	89x2.6	76x2.3	114x3.2	114x6.0	2.254
BV19	219x6.4	114x6.0	89x3.2	76x2.3	114x3.6	114x6.0	2.647
BV20	168x6.4	114x6.0	89x3.2	89x3.2	114x4.8	114x4.8	2.919

Table 4.2 Results for all profiles continued

Review and analysis of the Table 4.1 and Table 4.2 highlight the point that BV6 utilizes 1.919 Tonnes of structural steel members to be able to resist the applied wind force of 38.18 m/s.

The optimum barrel vault profile shape is BV13, which utilizes 1.613 Tonnes of structural steel members to be able to resist the applied wind force of 38.18 m/s.

The BV13 profile can be used by a project designer with the knowledge that the project cost inputs, the increased height of the structural steel members, and construction costs will not increase the overall project cost. The BV13 profile is the most cost effective.

In order to answer **Q2: What are the cost implications or significant percentage increase/decrease in construction costs when designing a barrel vault free roof structure which varies above or below the optimum profile shape.**

As stated in Chapter 1.2, Page 14

"The barrel vault free roof profile will have an optimum height to span ratio (h/s) which is the ideal configuration for the barrel vault canopy as far as cost - tonnage of steel to support the tensile membrane fabric roof. An increase in height to span ratio may positively influence the form and aesthetic appeal of the structure while not significantly increasing the cost - tonnage of steel. The aim of the research is to provide designers with data which will be of assistance during the design phase of a tensile membrane project.

The review of the project data highlights that the BV6 profile which is utilized for an array of built structures is not an optimum profile shape. The BV13 profile is the optimum, with the advantage that the use of the BV9 to BV14 profiles will increase the aesthetics of the built tensile membrane structure. For the research, a nominal cost of $4000 per Tonne has been used for the manufacture for the structural steelwork.

Profile	Tonnage steelwork	Cost to manufacture steelwork
	T	$4000/Tonne
BV1	0.955	$3980
BV2	1.207	$4828
BV3	1.606	$6424
BV4	1.677	$6708
BV5	1.824	$7296
BV6	**1.919**	**$7676**
BV7	1.964	$7856
BV8	2.181	$8724
BV9	1.838	$7352
BV10	1.810	$7240
BV11	1.793	$7172
BV12	1.736	$6944
BV13	**1.613**	**$6452**
BV14	1.872	$7488
BV15	1.929	$7716
BV16	2.133	$8532
BV17	2.185	$8740
BV18	2.254	$9016
BV19	2.647	$10588
BV20	2.919	$11676

Table 4.3 Cost to manufacture steel work for each profile BV1 to BV20

The data in Table 4.3 reveals the construction cost of BV13 to be $6452, with BV11 and BV12 within 12% of the optimum profile shape.

BV9 to BV14 are within 16% of the optimum profile shape.

The data in Table 4.3 reveals the construction cost of BV6 $7676 to be 19% higher that BV13 $6452.

The Table 4.3 will be very useful to the designer when determining a barrel vault profile shape for a specific project.

Figures 4.7 to 4.17 highlight the elements of the FEA model with the output data which was used to determine the information for the Table 4.1 and 4.2 results

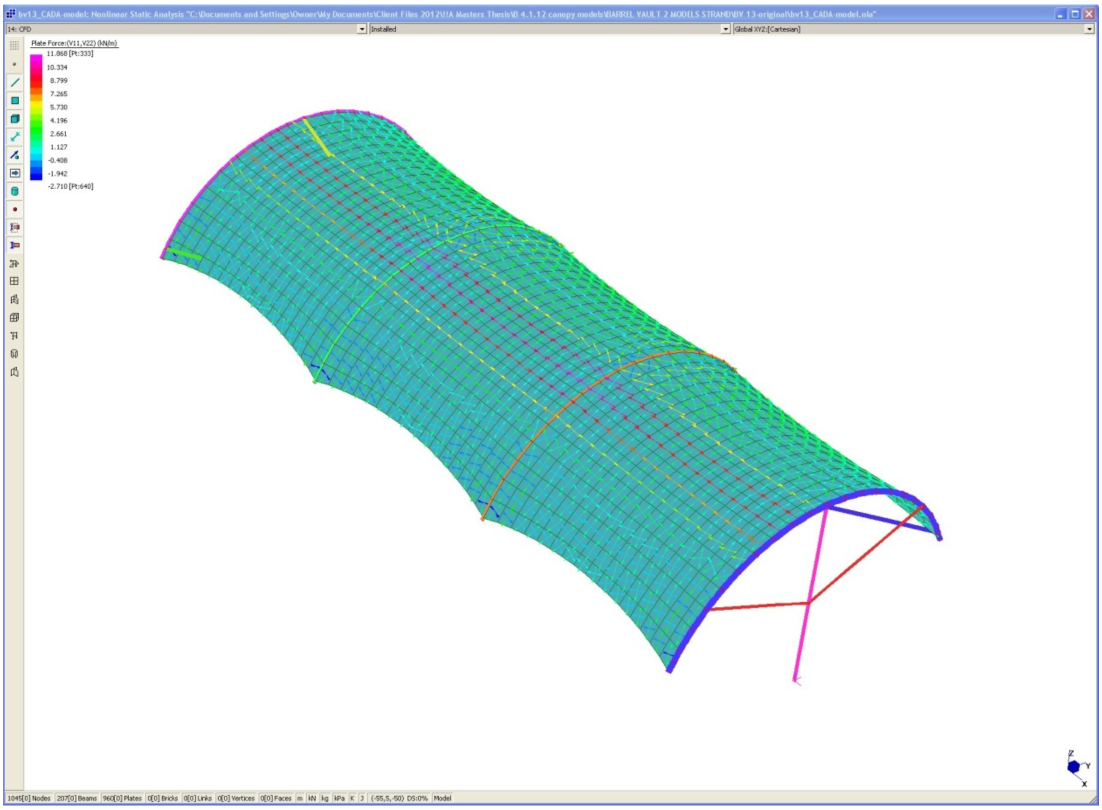

Figure 4.7 BV13 Fabric stress 11.868kN/m

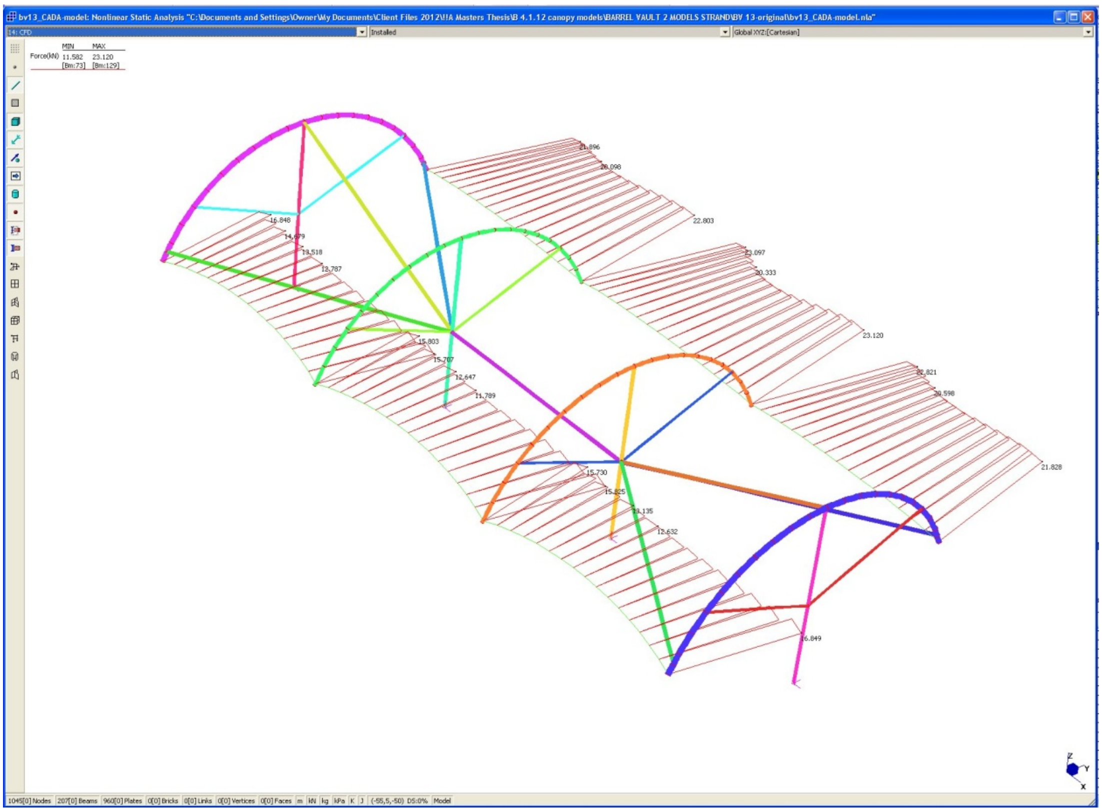

Figure 4.8 BV13 Catenary Cable 23.12kN

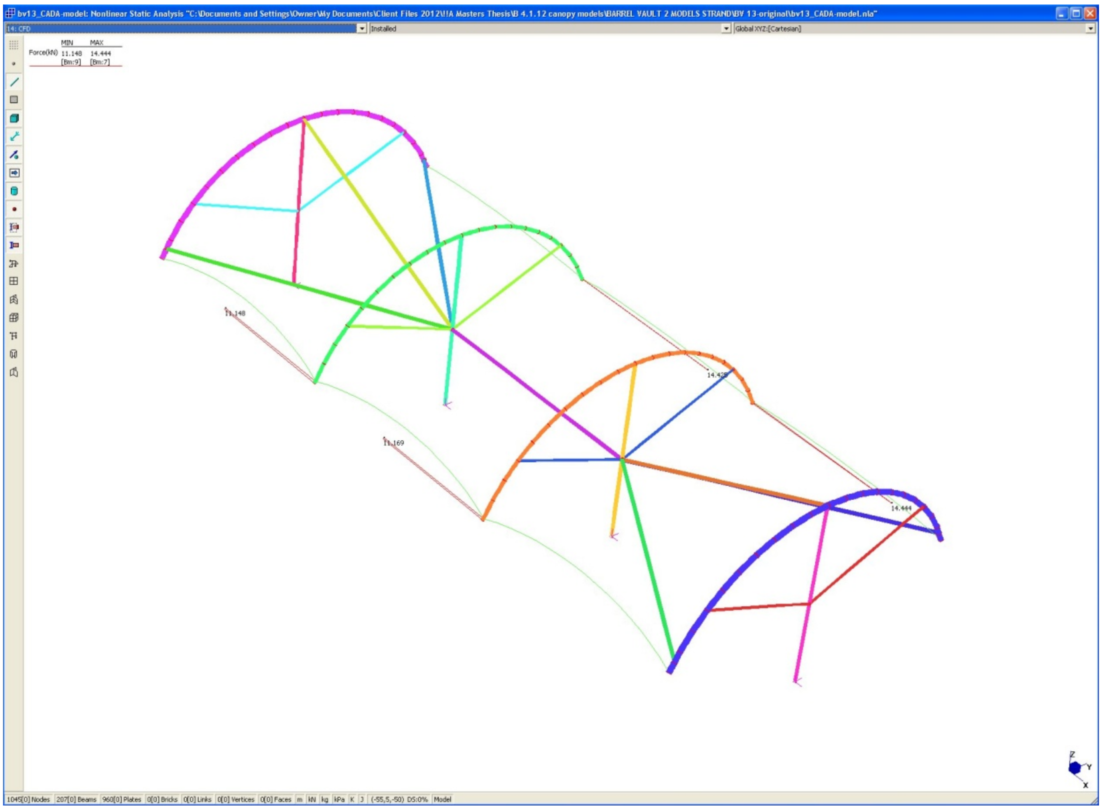

Figure 4.9 BV13 Fabric Attachment Link 14.44kN

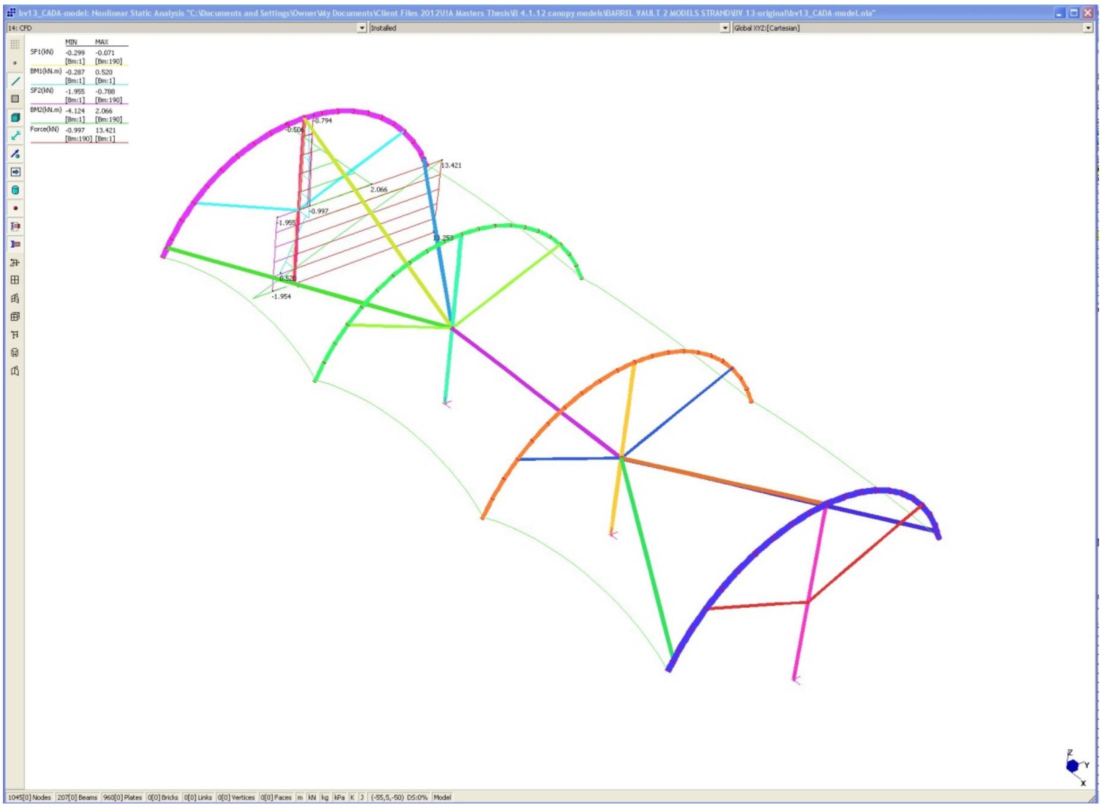

Figure 4.10 BV13 End Column FEA output file

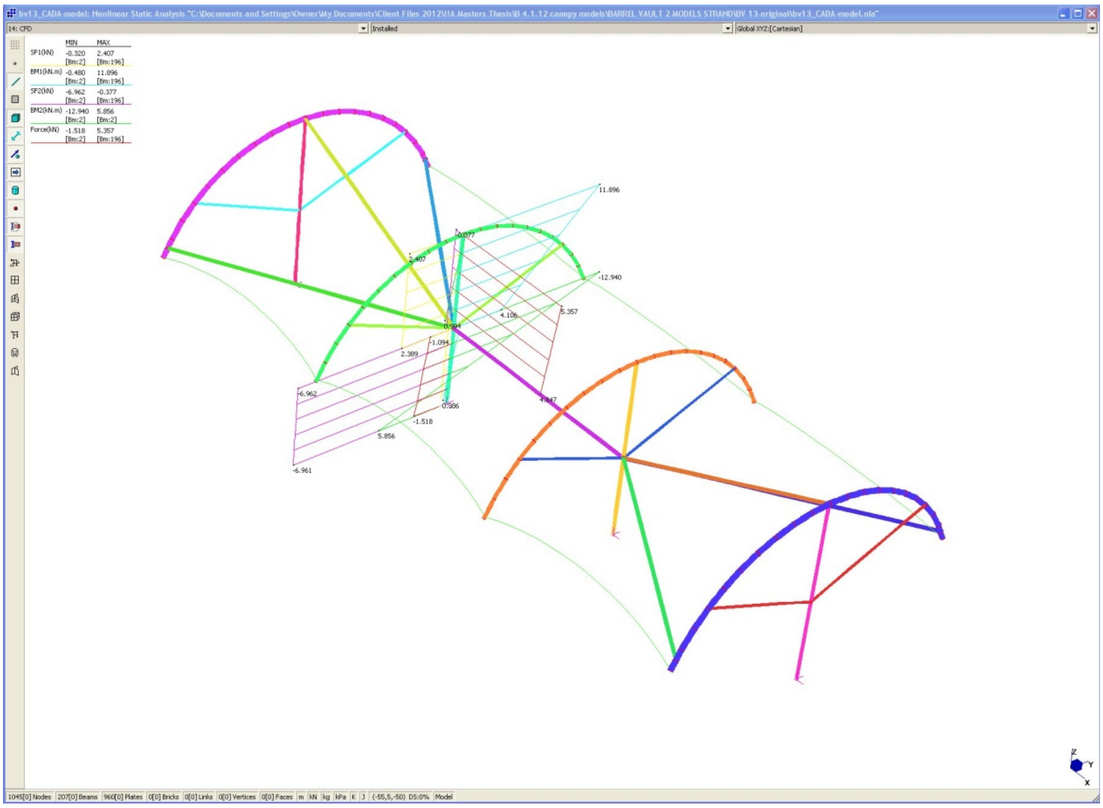

Figure 4.11 BV13 Middle Column FEA output file

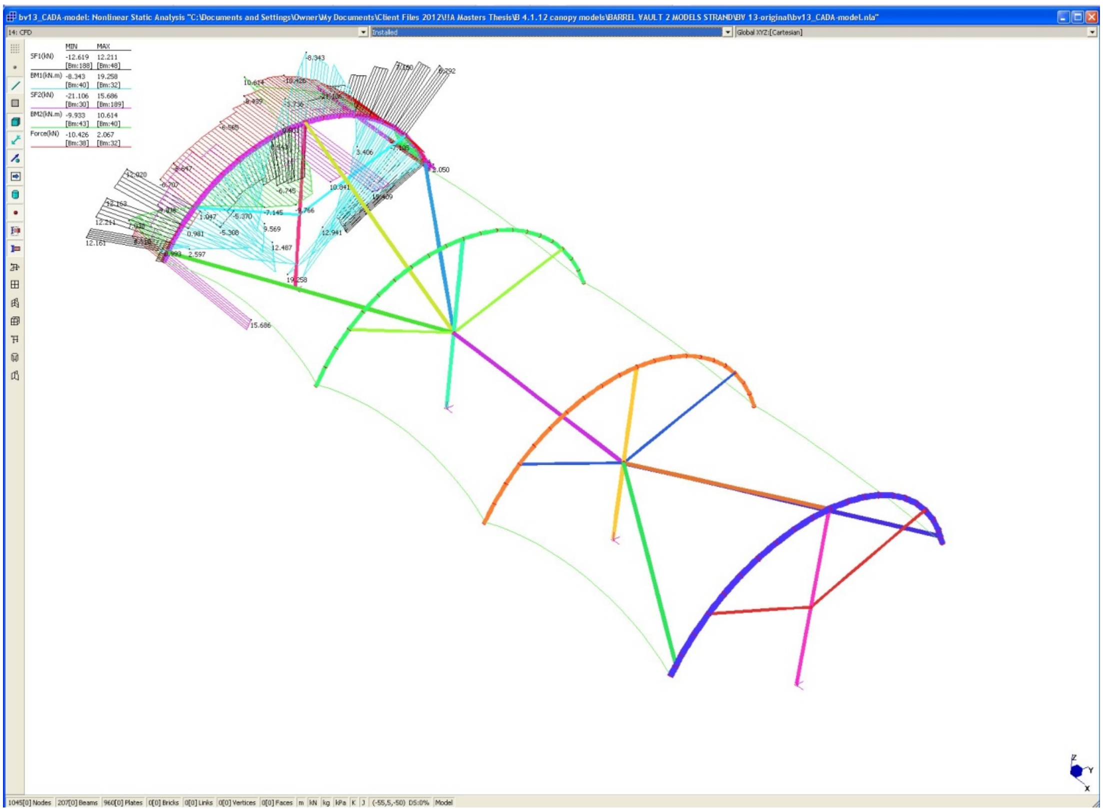

Figure 4.12 BV13 End Rafter FEA output file

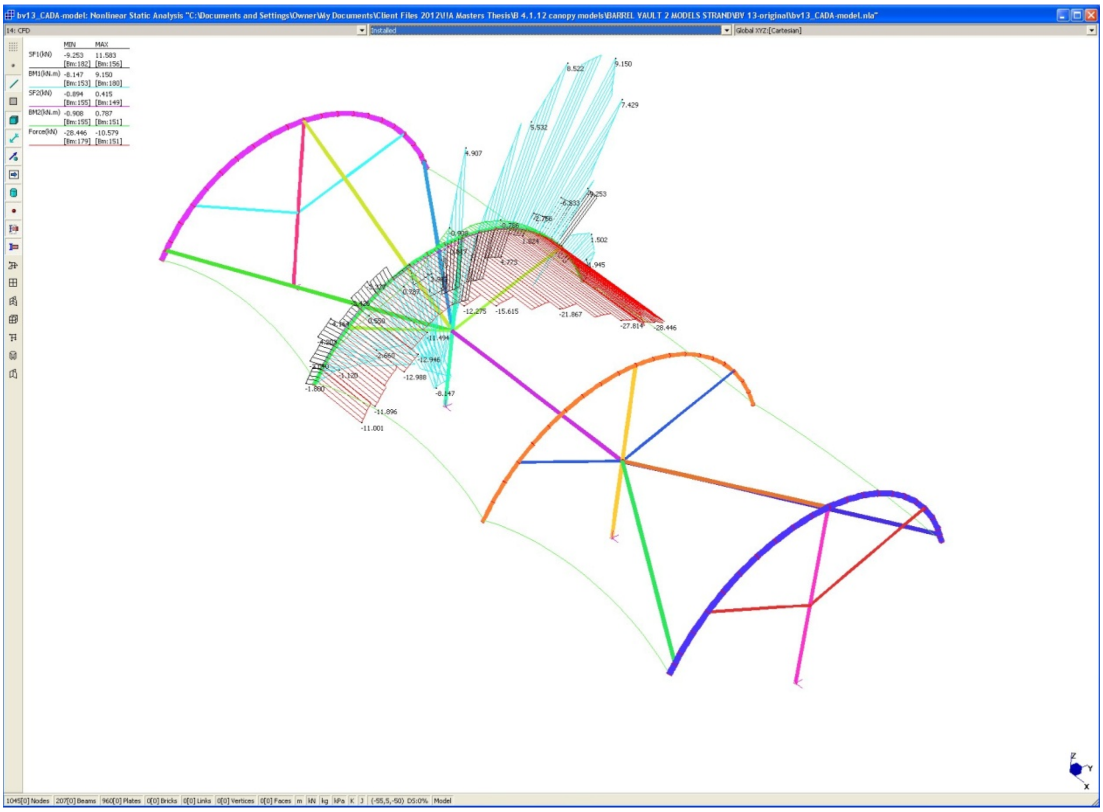

Figure 4.13 BV13 Middle Rafter FEA output file

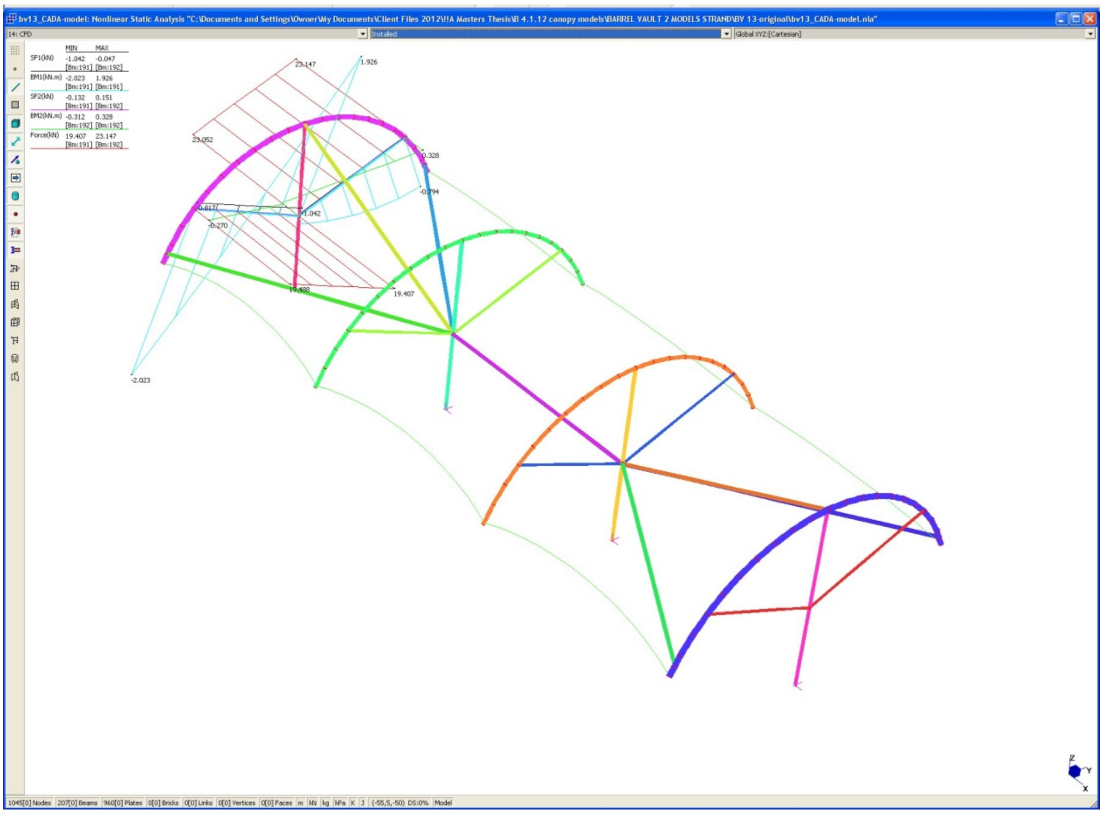

Figure 4.14 BV13 End Strut FEA output file

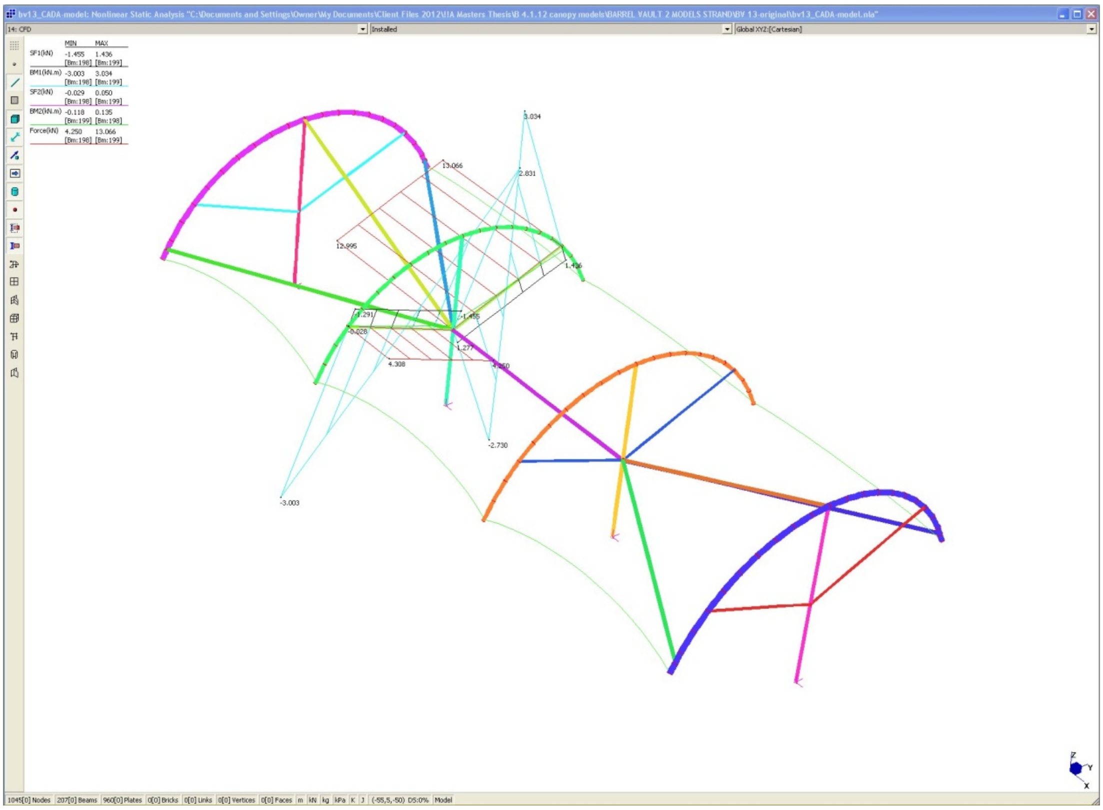

Figure 4.15 BV13 Middle Strut FEA output file

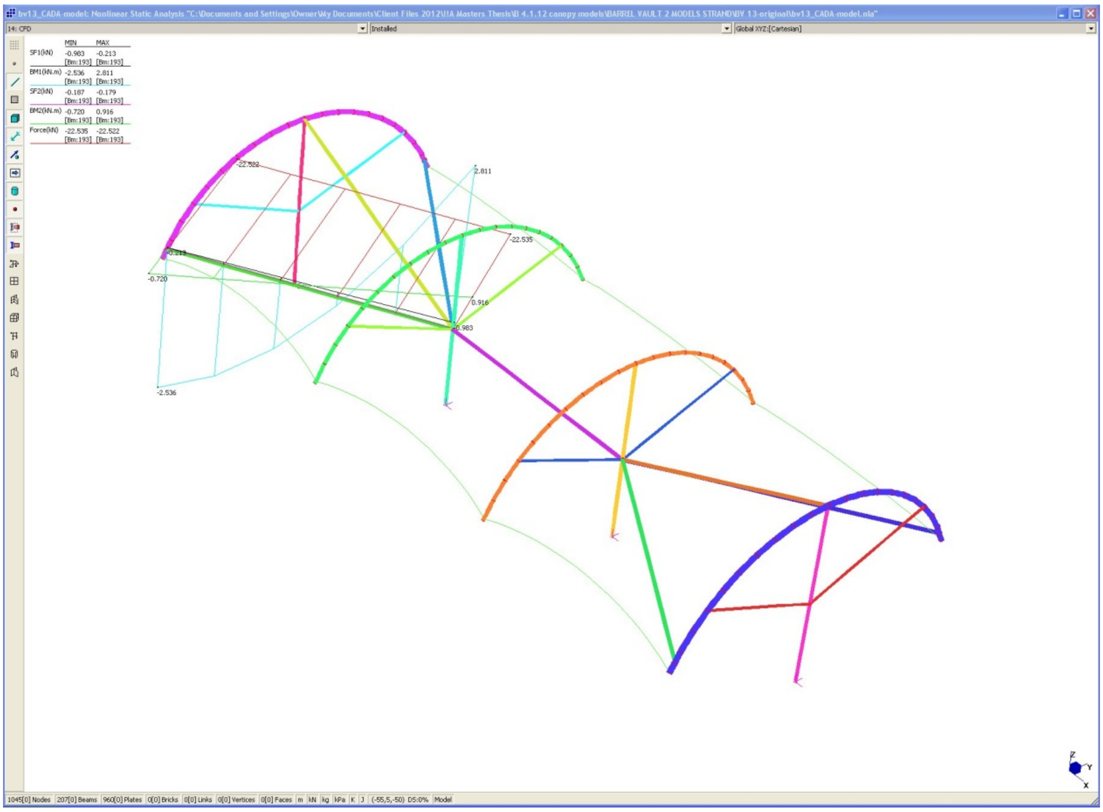

Figure 4.16 BV13 End Brace FEA output file

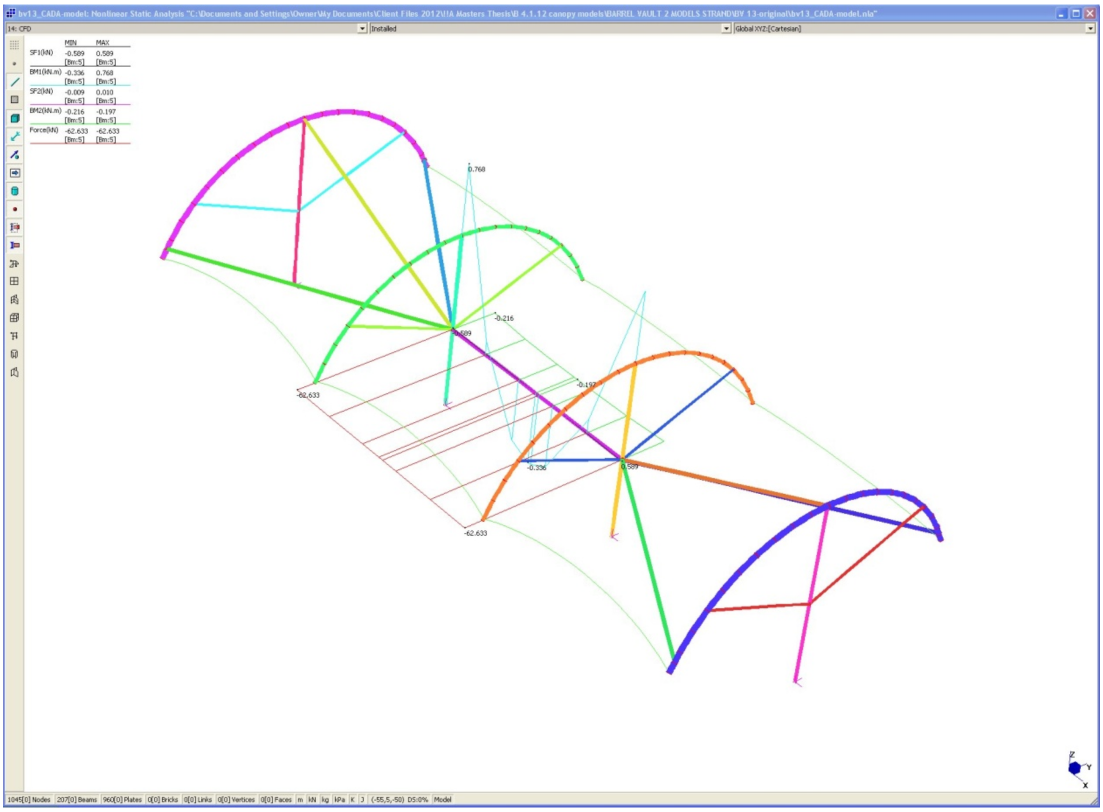

Figure 4.17 BV13 Middle Brace FEA output file

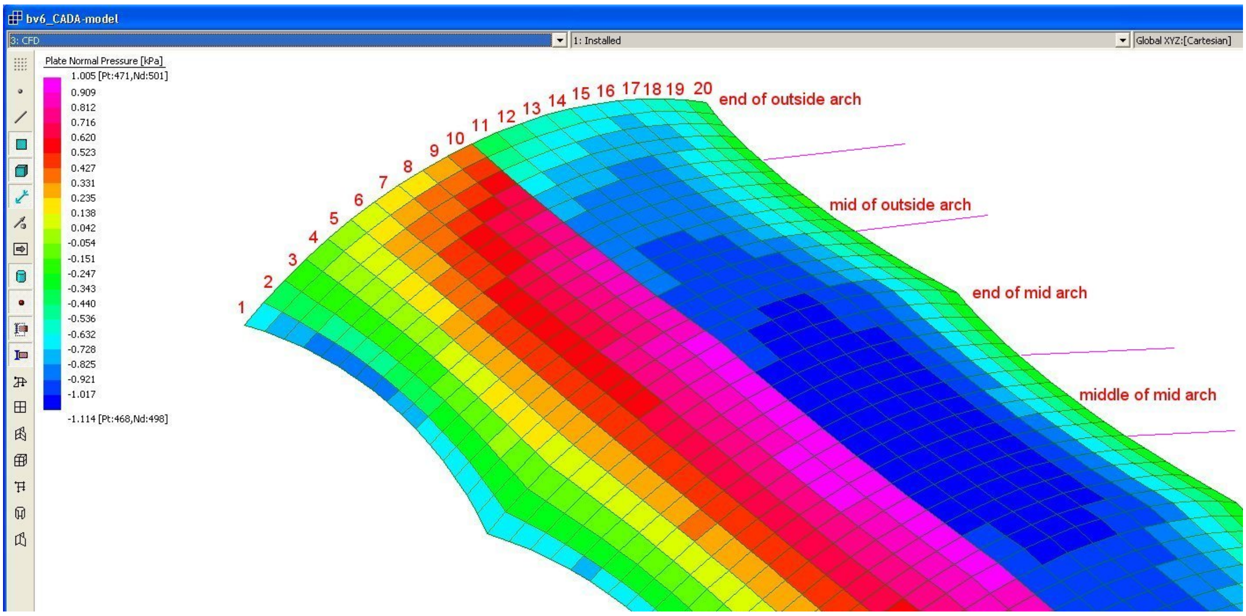

Figure 4.18 Enlarged Cropped View, *Zones for* table, pressure coefficients for BV6 (Typical all profiles)

Each of the mesh geometries (BV1 to BV20) have been created by a formfinding software program. The BV6 profile (Figure 4.18) has the mesh geometry dimension of 22.5 mts long x 10 mts wide with a rise of 1.50 mts being a height to span ratio 0.15. The mesh geometry over the 22.5 mt length is divided into 3 increments by the structural steel curved rafter members with each increment 7.5 mts. The mesh geometry consists of 48 plate elements long x 20 plate elements wide. Over the length of the canopy, on Figure 4.18 the zones have been designated as,

- End of outside arch 5 plates in length
- Middle of outside arch 6 plates in length
- End of middle arch 5 plates in length, each side of the curved rafter
- Middle of middle arch 6 plates in length

Over the width of the canopy, on Figure 4.18 the zones have been numbered and designated as, 1 to 20.

To document a concise table of each barrel vault profile, average pressure coefficients were determined for each zone.

Example, BV6 profile, “Plate position 20”,” End of end arch” pressure coefficient was determined by the averaging the pressure of the Zone 20 plates x 5 plates in length.

-0.398 + -0396 + -0.358 + -0.323 + -0.289 = -1.764/5 = -0.353 (Table 4.8)

4.5 Summary of data collected- Pressure Coefficients of all profile configurations

In order to answer **Q3: What is the pressure distribution on each of the profile shapes.**

The following tables of pressure coefficients for profiles BV1 to BV20, have been compiled to assist the designer of a barrel vault structure, be able to concisely apply the relevant pressure coefficients to the FEA analysis model, zone by zone with the knowledge the analysis result will closely mirror a FEA model with pressure coefficients pressure mapped from a CFD simulation.

Plate position	End of end arch	Middle of end arch	End of middle arch	Middle of mid arch
20	-0.052	-0.038	-0.054	-0.039
19	-0.078	-0.071	-0.097	-0.080
18	-0.090	-0.098	-0.127	-0.110
17	-0.095	-0.119	-0.149	-0.134
16	-0.097	-0.135	-0.166	-0.153
15	-0.095	-0.148	-0.179	-0.168
14	-0.108	-0.157	-0.188	-0.179
13	-0.091	-0.163	-0.194	-0.186
12	-0.086	-0.166	-0.196	-0.189
11	-0.082	-0.165	-0.195	-0.189
10	0.077	0.161	0.190	0.185
9	0.070	0.154	0.182	0.178
8	0.060	0.143	0.171	0.166
7	0.052	0.127	0.155	0.150
6	0.041	0.107	0.134	0.130
5	0.029	0.184	0.107	0.103
4	-0.011	0.047	0.071	0.070
3	-0.060	-0.000	0.019	0.026
2	-0.069	-0.068	-0.067	-0.038
1	-0.224	-0.230	-0.310	-0.169

Table 4.4 Pressure coefficients for barrel vault free roof profile BV1

Plate position	End of end arch	Middle of end arch	End of middle arch	Middle of mid arch
20	-0.126	-0.080	-0.105	-0.087
19	-0.188	-0.146	-0.192	-0.163
18	-0.210	-0.198	-0.253	-0.221
17	-0.221	-0.239	-0.297	-0.269
16	-0.223	-0.273	-0.332	-0.307
15	-0.220	-0.299	-0.358	-0.338
14	-0.212	-0.317	-0.375	-0.359
13	-0.202	-0.327	-0.384	-0.373
12	-0.189	-0.333	-0.393	-0.381
11	-0.175	-0.331	-0.393	-0.380
10	0.161	0.323	0.384	0.373
9	0.144	0.307	0.367	0.357
8	0.126	0.285	0.340	0.333
7	0.105	0.254	0.306	0.301
6	0.081	0.213	0.271	0.260
5	0.054	0.161	0.210	0.207
4	0.017	0.095	0.140	0.144
3	-0.036	0.004	0.035	0.057
2	-0.130	-0.133	-0.131	-0.070
1	-0.425	-0.444	-0.585	-0.318

Table 4.5 Pressure coefficients for barrel vault free roof profile BV2

Plate position	End of end arch	Middle of end arch	End of middle arch	Middle of mid arch
20	-0.201	-0.122	-0.140	-0.138
19	-0.306	-0.227	-0.253	-0.251
18	-0.349	-0.306	-0.340	-0.340
17	-0.367	-0.375	-0.410	-0.414
16	-0.371	-0.419	-0.471	-0.472
15	-0.367	-0.463	-0.515	-0.519
14	-0.349	-0.489	-0.550	-0.553
13	-0.332	-0.506	-0.576	-0.575
12	-0.306	-0.509	-0.585	-0.584
11	-0.279	-0.506	-0.585	-0.582
10	0.253	0.489	0.567	0.569
9	0.227	0.463	0.541	0.542
8	0.192	0.428	0.506	0.504
7	0.157	0.375	0.454	0.451
6	0.122	0.306	0.384	0.384
5	0.070	0.227	0.306	0.301
4	0.009	0.113	0.201	0.197
3	-0.079	-0.017	0.061	0.065
2	-0.218	-0.218	-0.131	-0.132
1	-0.663	-0.629	-0.498	-0.498

Table 4.6 Pressure coefficients for barrel vault free roof profile BV3

Plate position	End of end arch	Middle of end arch	End of middle arch	Middle of mid arch
20	-0.263	-0.166	-0.191	-0.179
19	-0.398	-0.298	-0.360	-0.326
18	-0.482	-0.402	-0.478	-0.443
17	-0.484	-0.486	-0.570	-0.540
16	-0.492	-0.553	-0.642	-0.618
15	-0.489	-0.603	-0.696	-0.680
14	-0.470	-0.637	-0.733	-0.725
13	-0.446	-0.655	-0.755	-0.752
12	-0.412	-0.662	-0.762	-0.765
11	-0.374	-0.652	-0.754	-0.760
10	0.332	0.627	0.731	0.737
9	0.288	0.586	0.690	0.696
8	0.243	0.527	0.631	0.636
7	0.197	0.450	0.556	0.558
6	0.145	0.349	0.458	0.457
5	0.078	0.233	0.327	0.340
4	-0.012	0.093	0.162	0.201
3	-0.133	-0.072	-0.041	0.031
2	-0.307	-0.280	-0.303	-0.186
1	-0.765	-0.657	-0.792	-0.576

Table 4.7 Pressure coefficients for barrel vault free roof profile BV4

Plate position	End of end arch	Middle of end arch	End of middle arch	Middle of mid arch
20	-0.314	-0.201	-0.227	-0.216
19	-0.454	-0.349	-0.419	-0.387
18	-0.515	-0.471	-0.559	-0.525
17	-0.550	-0.567	-0.663	-0.642
16	-0.559	-0.646	-0.742	-0.736
15	-0.559	-0.707	-0.803	-0.831
14	-0.524	-0.742	-0.847	-0.859
13	-0.489	-0.760	-0.864	-0.888
12	-0.437	-0.760	-0.856	-0.891
11	-0.393	-0.733	-0.838	-0.874
10	0.340	0.698	0.794	0.835
9	0.297	0.637	0.725	0.774
8	0.244	0.567	0.646	0.694
7	0.183	0.480	0.550	0.590
6	0.122	0.367	0.428	0.463
5	0.044	0.218	0.297	0.307
4	-0.052	0.052	0.122	0.146
3	-0.175	-0.122	-0.061	-0.031
2	-0.323	-0.332	-0.288	-0.237
1	-0.681	-0.690	-0.681	-0.604

Table 4.8 Pressure coefficients for barrel vault free roof profile BV5

Plate position	End of end arch	Middle of end arch	End of middle arch	Middle of mid arch
20	-0.353	-0.212	-0.251	-0.262
19	-0.486	-0.367	-0.456	-0.437
18	-0.547	-0.498	-0.606	-0.586
17	-0.586	-0.606	-0.724	-0.718
16	-0.589	-0.691	-0.813	-0.833
15	-0.567	-0.752	-0.872	-0.900
14	-0.529	-0.787	-0.905	-0.952
13	-0.479	-0.799	-0.912	-0.971
12	-0.425	-0.793	-0.897	-0.966
11	-0.366	-0.765	-0.859	-0.933
10	0.308	0.719	0.803	0.873
9	0.253	0.658	0.730	0.790
8	0.204	0.581	0.641	0.698
7	0.154	0.487	0.535	0.567
6	0.097	0.374	0.415	0.437
5	0.025	0.237	0.277	0.288
4	-0.065	0.058	0.115	0.106
3	-0.181	-0.135	-0.071	-0.074
2	-0.321	-0.347	-0.284	-0.262
1	-0.626	-0.706	-0.633	-0.611

Table 4.9 Pressure coefficients for barrel vault free roof profile BV6

Plate position	End of end arch	Middle of end arch	End of middle arch	Middle of mid arch
20	-0.384	-0.218	-0.262	-0.279
19	-0.471	-0.375	-0.471	-0.480
18	-0.506	-0.506	-0.637	-0.655
17	-0.524	-0.620	-0.760	-0.799
16	-0.524	-0.698	-0.847	-0.910
15	-0.506	-0.768	-0.908	-0.989
14	-0.471	-0.803	-0.943	-1.031
13	-0.437	-0.812	-0.943	-1.041
12	-0.384	-0.812	-0.925	-1.017
11	-0.340	-0.786	-0.882	-0.973
10	0.288	0.742	0.829	0.904
9	0.244	0.681	0.751	0.812
8	0.192	0.594	0.663	0.707
7	0.148	0.498	0.550	0.585
6	0.096	0.375	0.419	0.437
5	0.017	0.227	0.271	0.279
4	-0.070	0.052	0.096	0.070
3	-0.183	-0.148	-0.113	-0.140
2	-0.332	-0.358	-0.349	-0.358
1	-0.620	-0.725	-0.690	-0.725

Table 4.10 Pressure coefficients for barrel vault free roof profile BV7

Plate position	End of end arch	Middle of end arch	End of middle arch	Middle of mid arch
20	-0.410	-0.201	-0.262	-0.280
19	-0.454	-0.349	-0.454	-0.484
18	-0.462	-0.480	-0.611	-0.656
17	-0.467	-0.594	-0.742	-0.808
16	-0.462	-0.690	-0.829	-0.924
15	-0.454	-0.751	-0.899	-1.001
14	-0.437	-0.803	-0.943	-1.041
13	-0.410	-0.829	-0.960	-1.054
12	-0.375	-0.838	-0.952	-1.039
11	-0.340	-0.821	-0.917	-0.998
10	0.297	0.777	0.864	0.938
9	0.244	0.716	0.794	0.847
8	0.201	0.629	0.698	0.738
7	0.148	0.515	0.576	0.602
6	0087	0.375	0.428	0.445
5	0.009	0.218	0.262	0.262
4	-0.096	0.026	0.061	0.049
3	-0.218	-0.192	-0.157	-0.175
2	-0.375	-0.428	-0.402	-0.411
1	-0.663	-0.751	-0.725	-0.743

Table 4.11 Pressure coefficients for barrel vault free roof profile BV8

Plate position	End of end arch	Middle of end arch	End of middle arch	Middle of mid arch
20	-0.428	-0.183	-0.236	-0.272
19	-0.437	-0.323	-0.402	-0.459
18	-0.419	-0.445	-0.550	-0.625
17	-0.423	-0.567	-0.681	-0.772
16	-0.425	-0.663	-0.794	-0.890
15	-0.421	-0.742	-0.882	-0.975
14	-0.410	-0.812	-0.943	-1.035
13	-0.393	-0.856	-0.978	-1.063
12	-0.375	-0.873	-0.986	-1.067
11	-0.340	-0.864	-0.969	-1.041
10	0.297	0.829	0.925	0.986
9	0.253	0.760	0.847	0.901
8	0.201	0.663	0.733	0.786
7	0.148	0.533	0.602	0.637
6	0.079	0.375	0.437	0.457
5	-0.017	0.192	0.244	0.249
4	-0.131	-0.017	0.026	0.018
3	-0.262	-0.244	-0.210	-0.228
2	-0.437	-0.489	-0.480	-0.481
1	-0.707	-0.803	-0.768	-0.816

Table 4.12 Pressure coefficients for barrel vault free roof profile BV9

Plate position	End of end arch	Middle of end arch	End of middle arch	Middle of mid arch
20	-0.437	-0.148	-0.218	-0.242
19	-0.402	-0.262	-0.349	-0.402
18	-0.375	-0.384	-0.489	-0.558
17	-0.358	-0.498	-0.620	-0.698
16	-0.349	-0.602	-0.742	-0.822
15	-0.349	-0.707	-0.847	-0.928
14	-0.358	-0.794	-0.934	-1.010
13	-0.358	-0.856	-0.986	-1.065
12	-0.349	-0.899	-1.013	-1.090
11	-0.332	-0.899	-1.004	-1.075
10	0.306	0.873	0.960	1.029
9	0.253	0.794	0.873	0.938
8	0.201	0.690	0.760	0.812
7	0.140	0.541	0.602	0.647
6	0.061	0.367	0.419	0.448
5	-0.044	0.166	0.210	0.223
4	-0.166	-0.061	-0.026	0.253
3	-0.306	-0.297	-0.279	-0.285
2	-0.480	-0.541	-0.550	-0.548
1	-0.742	-0.829	-0.812	-0.851

Table 4.13 Pressure coefficients for barrel vault free roof profile BV10

Plate position	End of end arch	Middle of end arch	End of middle arch	Middle of mid arch
20	-0.437	-0.113	-0.183	-0.213
19	-0.384	-0.201	-0.253	-0.327
18	-0.340	-0.314	-0.384	-0.458
17	-0.323	-0.428	-0.524	-0.601
16	-0.306	-0.550	-0.672	-0.744
15	-0.314	-0.672	-0.803	-0.877
14	-0.314	-0.777	-0.917	-0.993
13	-0.323	-0.864	-1.004	-1.078
12	-0.332	-0.925	-1.048	-1.125
11	-0.323	-0.943	-1.048	-1.130
10	0.297	0.917	0.1004	1.083
9	0.262	0.838	0.917	0.990
8	0.201	0.716	0.786	0.849
7	0.131	0.559	0.611	0.663
6	0.044	0.358	0.410	0.443
5	-0.079	0.140	0.175	0.193
4	-0.210	-0.105	-0.079	-0.073
3	-0.358	-0.358	-0.349	-0.347
2	-0.533	-0.602	-0.611	-0.613
1	-0.777	-0.864	-0.838	-0.891

Table 4.14 Pressure coefficients for barrel vault free roof profile BV11

Plate position	End of end arch	Middle of end arch	End of middle arch	Middle of mid arch
20	-0.465	-0.086	-0.144	-0.171
19	-0.390	-0.155	-0.152	-0.227
18	-0.346	-0.253	-0.254	-0.333
17	-0.317	-0.368	-0.412	-0.482
16	-0.301	-0.501	-0.586	-0.648
15	-0.299	-0.641	-0.756	-0.818
14	-0.302	-0.774	-0.904	-0.973
13	-0.309	-0.885	-1.014	-1.092
12	-0.314	-0.960	-1.080	-1.166
11	-0.319	-0.986	-1.093	-1.184
10	0.298	0.959	1.051	1.142
9	0.256	0.876	0.956	1.040
8	0.196	0.743	0.811	0.883
7	0.115	0.561	0.621	0.677
6	0.011	0.343	0.394	0.433
5	-0.115	0.099	0.140	0.163
4	-0.260	-0.158	-0.129	-0.120
3	-0.416	-0.419	-0.402	-0.404
2	-0.590	-0.668	-0.661	-0.672
1	-0.807	-0.879	-0.849	-0.917

Table 4.15 Pressure coefficients for barrel vault free roof profile BV12

Plate position	End of end arch	Middle of end arch	End of middle arch	Middle of mid arch
20	-0.475	-0.045	-0.121	-0.143
19	-0.382	-0.091	-0.072	-0.142
18	-0.330	-0.174	-0.148	-0.217
17	-0.298	-0.286	-0.312	-0.366
16	-0.280	-0.430	-0.507	-0.556
15	-0.272	-0.592	-0.705	-0.761
14	-0.272	-0.753	-0.882	-0.951
13	-0.282	-0.890	-1.020	-1.104
12	-0.300	-0.984	-1.103	-1.200
11	-0.304	-1.024	-1.127	-1.231
10	0.292	1.003	1.090	1.193
9	0.254	0.916	0.989	1.086
8	0.188	0.769	0.829	0.912
7	0.097	0.569	0.619	0.685
6	-0.017	0.330	0.372	0.418
5	-0.153	0.065	0.097	0.124
4	-0.308	-0.210	-0.191	-0.176
3	-0.468	-0.474	-0.472	-0.465
2	-0.636	-0.717	-0.725	-0.732
1	-0.822	-0.893	-0.865	-0.928

Table 4.16 Pressure coefficients for barrel vault free roof profile BV13

Plate position	End of end arch	Middle of end arch	End of middle arch	Middle of mid arch
20	-0.512	-0.009	-0.111	-0.150
19	-0.391	-0.032	-0.023	-0.107
18	-0.331	-0.103	-0.067	-0.140
17	-0.297	-0.217	-0.230	-0.283
16	-0.275	-0.377	-0.446	-0.494
15	-0.267	-0.563	-0.670	-0.729
14	-0.268	-0.752	-0.876	-0.952
13	-0.279	-0.918	-1.040	-1.134
12	-0.300	-1.032	-1.141	-1.249
11	-0.306	-1.085	-1.174	-1.290
10	0.293	1.063	1.135	1.250
9	0.248	0.970	1.025	1.132
8	0.174	0.807	0.848	0.939
7	0.072	0.586	0.618	0.688
6	-0.056	0.321	0.347	0.393
5	-0.203	0.035	0.051	0.077
4	-0.361	-0.255	-0.251	-0.241
3	-0.520	-0.523	-0.540	-0.538
2	-0.681	-0.753	-0.780	-0.794
1	-0.845	-0.897	-0.879	-0.950

Table 4.17 Pressure coefficients for barrel vault free roof profile BV14

Plate position	End of end arch	Middle of end arch	End of middle arch	Middle of mid arch
20	-0.505	0.034	-0.119	-0.190
19	-0.358	0.017	0.002	-0.127
18	-0.291	-0.036	-0.003	-0.118
17	-0.257	-0.142	-0.162	-0.246
16	-0.232	-0.309	-0.392	-0.465
15	-0.218	-0.519	-0.638	-0.718
14	-0.220	-0.734	-0.866	-0.960
13	-0.238	-0.928	-1.049	-1.161
12	-0.275	-1.065	-1.165	-1.287
11	-0.299	-1.132	-1.200	-1.331
10	0.285	1.115	1.161	1.284
9	0.238	1.015	1.036	1.151
8	0.159	0.839	0.844	0.937
7	0.053	0.601	0.594	0.663
6	-0.081	0.317	0.300	0.344
5	-0.233	0.012	-0.014	0.005
4	-0.392	0.289	-0.328	-0.327
3	-0.548	-0.556	-0.616	-0.629
2	-0.692	-0.767	-0.839	-0.876
1	-0.822	-0.862	-0.897	-0.993

Table 4.18 Pressure coefficients for barrel vault free roof profile BV15

Plate position	End of end arch	Middle of end arch	End of middle arch	Middle of mid arch
20	-0.553	0.093	-0.082	-0.195
19	-0.386	0.078	0.066	-0.127
18	-0.313	0.021	0.092	-0.091
17	-0.278	-0.096	-0.062	-0.197
16	-0.257	-0.281	-0.312	-0.418
15	-0.245	-0.510	-0.588	-0.687
14	-0.253	-0.749	-0.847	-0.952
13	-0.277	-0.963	-1.055	-1.172
12	-0.303	-1.120	-1.193	-1.320
11	-0.313	-1.196	-1.243	-1.373
10	0.287	1.179	1.203	1.327
9	0.226	1.072	1.076	1.184
8	0.137	0.882	0.871	0.955
7	0.016	0.621	0.600	0.656
6	-0.131	0.315	0.285	0.316
5	-0.292	-0.010	-0.051	-0.044
4	-0.451	-0.323	-0.378	-0.392
3	-0.604	-0.593	-0.666	-0.699
2	-0.744	-0.791	-0.875	-0.944
1	-0.833	-0.848	-0.895	-1.028

Table 4.19 Pressure coefficients for barrel vault free roof profile BV16

Plate position	End of end arch	Middle of end arch	End of middle arch	Middle of mid arch
20	-0.562	0.113	-0.012	-0.172
19	-0.379	0.094	0.154	-0.081
18	-0.300	0.055	0.185	-0.012
17	-0.269	-0.055	0.031	-0.101
16	-0.246	-0.244	-0.241	-0.337
15	-0.233	-0.491	-0.546	-0.635
14	-0.241	-0.752	-0.834	-0.932
13	-0.273	-0.989	-1.067	-1.186
12	-0.306	-1.158	-1.220	-1.350
11	-0.317	-1.244	-1.282	-1.418
10	0.291	1.227	1.244	1.373
9	0.225	1.110	1.109	1.223
8	0.124	0.903	0.886	0.980
7	-0.010	0.623	0.595	0.662
6	-0.170	0.292	0.258	0.295
5	-0.341	-0.053	-0.098	-0.085
4	-0.515	-0.380	-0.438	-0.450
3	-0.665	-0.655	-0.728	-0.775
2	-0.791	-0.842	-0.924	-1.007
1	-0.860	-0.868	-0.906	-1.053

Table 4.20 Pressure coefficients for barrel vault free roof profile BV17

Plate position	End of end arch	Middle of end arch	End of middle arch	Middle of mid arch
20	-0.551	0.082	0.030	-0.148
19	-0.359	0.072	0.193	-0.038
18	-0.281	0.064	0.234	0.052
17	-0.254	-0.021	0.101	-0.015
16	-0.234	-0.203	-0.176	-0.258
15	-0.217	-0.457	-0.503	-0.581
14	-0.218	-0.739	-0.814	-0.910
13	-0.251	-0.997	-1.072	-1.189
12	-0.292	-1.187	-1.242	-1.376
11	-0.310	-1.281	-1.311	-1.451
10	0.288	1.262	1.269	1.406
9	0.218	1.137	1.124	1.248
8	0.112	0.912	0.888	0.988
7	-0.031	0.613	0.577	0.655
6	-0.204	0.263	0.221	0.272
5	-0.388	-0.100	-0.151	-0.138
4	-0.560	-0.438	-0.500	-0.539
3	-0.711	-0.712	-0.787	-0.856
2	-0.822	-0.888	-0.966	-1.053
1	-0.862	-0.879	-0.918	-1.065

Table 4.21 Pressure coefficients for barrel vault free roof profile BV18

Plate position	End of end arch	Middle of end arch	End of middle arch	Middle of mid arch
20	-0.523	0.003	0.050	-0.097
19	-0.323	0.024	0.207	0.061
18	-0.250	0.034	0.248	0.163
17	-0.228	-0.004	0.127	0.119
16	-0.205	-0.157	-0.147	-0.137
15	-0.175	-0.410	-0.475	-0.496
14	-0.156	-0.705	-0.795	-0.864
13	-0.180	-0.983	-1.063	-1.179
12	-0.240	-1.194	-1.246	-1.397
11	-0.294	-1.301	-1.320	-1.492
10	0.289	1.286	1.279	1.454
9	0.223	1.158	1.131	1.295
8	0.113	0.924	0.883	0.025
7	-0.040	0.606	0.560	0.670
6	-0.220	0.237	0.189	0.259
5	-0.415	-0.142	-0.198	-0.177
4	-0.569	-0.491	-0.558	-0.578
3	-0.749	-0.770	-0.845	-0.883
2	-0.860	-0.936	-1.008	-1.075
1	-0.864	-0.892	-0.928	-1.062

Table 4.22 Pressure coefficients for barrel vault free roof profile BV19

Plate position	End of end arch	Middle of end arch	End of middle arch	Middle of mid arch
20	-0.577	-0.031	0.108	-0.052
19	-0.381	0.007	0.249	0.116
18	-0.308	0.020	0.288	0.216
17	-0.293	-0.006	0.184	0.203
16	-0.278	-0.150	-0.088	-0.038
15	-0.249	-0.403	-0.432	-0.419
14	-0.225	-0.707	-0.776	-0.817
13	-0.232	-0.999	-1.071	-1.164
12	-0.269	-1.220	-1.277	-1.409
11	-0.306	-1.335	-1.371	-1.529
10	0.293	1.322	1.339	1.505
9	0.217	1.186	1.188	1.350
8	0.093	0.936	0.933	1.073
7	-0.079	0.596	0.595	0.705
6	-0.275	0.208	0.206	0.267
5	-0.481	-0.189	-0.191	-0.203
4	-0.672	-0.550	-0.553	-0.609
3	-0.822	-0.827	-0.834	-0.885
2	-0.915	-1.037	-0.982	-1.039
1	-0.904	-0.908	-0.891	-0.999

Table 4.23 Pressure coefficients for barrel vault free roof profile BV20

4.6 Refinement of profile shape utilizing research data

The next phase of the research is to determine if, the designer of a barrel vault tensile membrane canopy is required to add more shape to the profile to improve the aesthetics, will the increasing of the dip between the curved support rafters, which will change the canopy geometry, significantly affect the wind loading onto the canopy, and adversely influence the required structural steel member sizes, thereby altering the construction cost.

The refinement of profile shape research focuses on 2 profiles, BV6 and BV13.

BV6 because of the use of this profile on shopping mall carparking structures, and BV13 because the research has highlighted the profile as the optimium shape.

Geometry Design Specifications BV6 from present research

The BV6 profile (Figure 4.1) has a mesh geometry dimension of 22.5 mts long x 10 mts wide with a rise of 1.50 mts being a height to span ratio 0.15. The mesh geometry is set with the low edge of the canopy 2.7 mts and highest point at the centre of the curved rafter 4.2 mts from the ground level. The 22.5 mt length is divided into 3 increments each of 7.5 mts. The mesh geometry consists of 48 plate elements long x 20 plate elements wide. The dip between the curved support rafters is 140mm. (Figure 4.19)

Figure 4.19 Conceptual image of BV6 with 140mm dip

Geometry Design Specifications BV6A for further research

The BV6A profile, has a mesh geometry dimension identical to BV6 with the design variation of the dip between the curved support rafters has been increased to 283mm. (Figure 4.20)

Figure 4.20 Conceptual image of BV6A with 283mm dip

Geometry Design Specifications BV6B for further research

The BV6B profile, has a mesh geometry dimension identical to BV6 with the design variation of the dip between the curved support rafters has been increased to 391mm. (Figure 4.21)

Figure 4.21 Conceptual image of BV6B with 391mm dip

Geometry Design Specifications BV13 from present research

The BV13 profile has a mesh geometry dimension of 22.5 mts long x 10 mts wide with a rise of 3.25 mts being a height to span ratio 0.325. The mesh geometry is set with the low edge of the canopy 2.7 mts and highest point at the centre of the curved rafter 5.95 mts from the ground level. The 22.5 mt length is divided into 3 increments each of 7.5 mts. The mesh geometry consists of 48 plate elements long x 20 plate elements wide.

The dip between the curved support rafters is 222mm. (Figure 4.22)

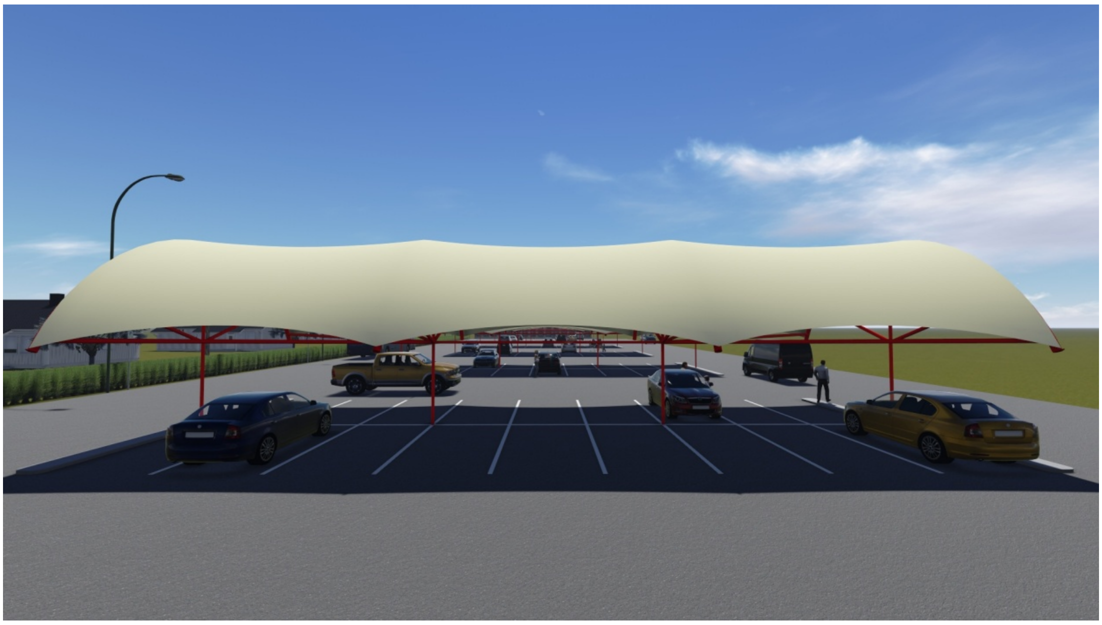

Figure 4.22 Conceptual image of BV13 with 222mm dip

Geometry Design Specifications BV13A for further research

The BV13A profile, has a mesh geometry dimension identical to BV13 with the design variation of the dip between the curved support rafters has been increased to 448mm. (Figure 4.23)

Figure 4.23 Conceptual image of BV13A with 448mm dip

Geometry Design Specifications BV13B for further research

The BV13B profile, has a mesh geometry dimension identical to BV13 with the design variation of the dip between the curved support rafters has been increased to 667mm. (Figure 4.24)

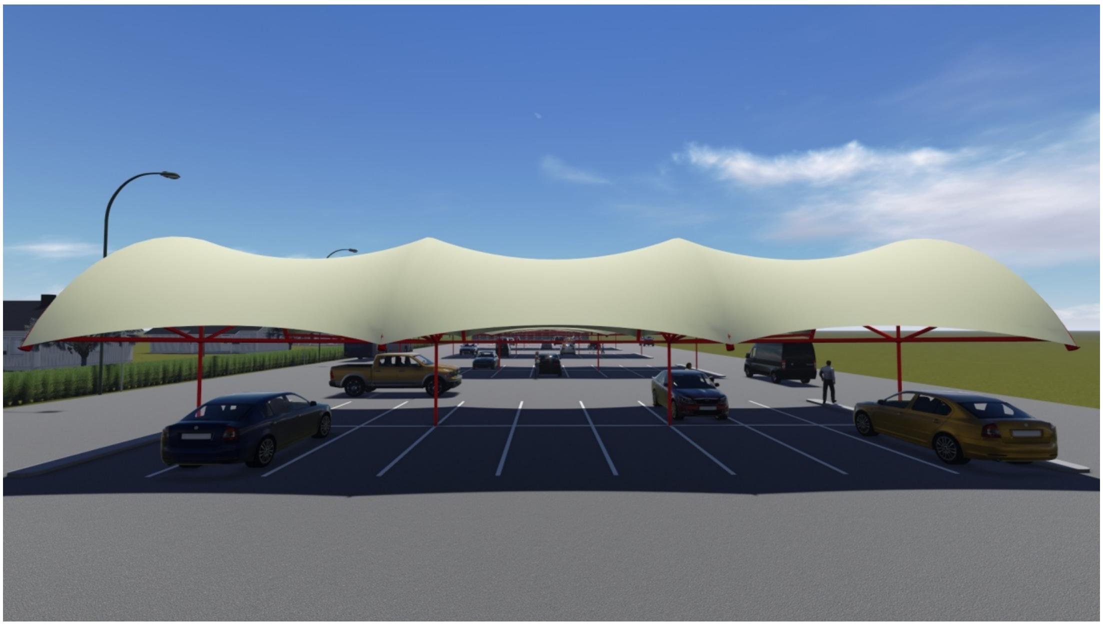

Figure 4.24 Conceptual image of BV13B with 667mm dip

The research of the BV6A, BV6B and BV13A, BV13B profiles followed the identical procedure which is outlined in 4.1 Modeling, 4.2 Research process, and 4.3 Data Analysis.

4.7 Summary of data collected- Structural analysis of BV6, BV6A, BV6B, and BV13, BV13A, BV13B profile configurations

In order to answer **Q4: Will an increase of the dip ratio between the support rafters, compromise the optimum height to span ratio for the sake of aesthetics**

The analysis data of the BV6, BV6A, BV6B, and BV13, BV13A, BV13B profiles is compiled in the following Tables 4.24 and 4.25 which are formatted in identical layout to the tables of the initial research. Tables 4.1 and 4.2

Profile	Dip of canopy between rafters	Rise of Rafter	Fabric Stress	Catenary Cable	Fabric Link	End Column	End Foundation	Mid Column	Mid Foundation
		mts	kN/m	kN	kN	Chs Gr350	450 diam	Chs Gr350	450 diam
BV6	**0.14**	**1.50**	**9.024**	**37.24**	**24.75**	**168x4.8**	**1.7**	**168x6.4**	**2.45**
BV6A	0.391	1.5	7.591	37.93	25.12	168x4.8	1.9	168x6.4	2.3
BV6B	0.283	1.5	8.081	37.60	24.895	168x4.8	1.85	168x6.4	2.35
BV13	**0.222**	**3.25**	**11.868**	**23.12**	**14.44**	**101x2.6**	**1.26**	**114x6.0**	**1.15**
BV13A	0.447	3.25	10.709	23.72	14.66	101x2.6	1.26	114x6.0	1.15
BV13B	0.667	3.25	9.264	27.25	16.89	101x2.6	1.26	114x6.0	1.15

Table 4.24 Results for BV6, BV6A, BV6B and BV13, BV13A, BV13B profiles

Profile	End Rafter	Mid Rafter	End Strut	Mid Strut	End Brace	Mid Brace	Tonnage steelwork
	Chs Gr350	Chs Gr350	Chs Gr350	Chs Gr350	Chs Gr350	Chs Gr350	T
BV6	**168x4.8**	**114x3.6**	**101x2.6**	**89x2.6**	**114x4.8**	**139x3.5**	**1.919**
BV6A	168x4.8	114x3.6	101x2.6	89x2.6	114x4.8	139x3.5	1.919
BV6B	168x4.8	114x3.6	101x2.6	89x2.6	114x4.8	139x3.5	1.919
BV13	**165x3.5**	**114x3.6**	**76x3.2**	**76x2.3**	**114x3.2**	**114x6.0**	**1.613**
BV13A	165x3.5	114x3.6	76x3.2	76x2.3	114x3.2	114x6.0	1.613
BV13B	165x3.5	114x3.6	76x3.2	76x2.3	114x3.2	114x6.0	1.613

Table 4.25 Results for BV6, BV6A, BV6B and BV13, BV13A, BV13B profiles continued

The data tables 4.24 and 4.25 highlight that the structural steel members sizes do not alter with the increase of the dip between the curved rafters, therefore the cost to construct each of the BV6 or the BV13 profiles will not alter.

The data tables 4.24 and 4.25 highlight the decrease in fabric stress with the increase in the dip.

The data tables 4.24 and 4.25 highlight the slight increase in Catenary Cable and Fabric Link tension. The designer will have to be aware that an increase in cable size and fabric attachments may be required when the dip of the barrel vault canopy profile is increased.

4.8 Limitations of the research

To find an optimum Height to Span ratio for barrel vault free roof profile. The only considered method of comparison is to complete an analysis of the structural steel required to support the canopy of each of the barrel vault free roof profiles

The tonnage of steel is compiled Table 4.1 and 4.2 for comparison of each of the barrel vault profiles. The tonnage of steel for each profile will determine construction cost of the structures, ultimately determining the optimum barrel vault free roof profile.

BV6 profile requires 1.919 tonnes of structure steel to support the structure for the designated design wind speed, and BV13 profile requires 1.613 tonnes of structural steel

5 CONCLUSIONS

The research project has highlighted the importance of testing a theory, and that the final results, enable the researcher to be able to make informed choice when moving forward with the design of a Barrel Vault Structure. The research project also has emphasized the importance of allowing the designer and engineer of a Tensile Membrane Structure, the required time to implement testing into the initial design phase of the project to allow optimization of the proposed design

5.1 What was attempted and what was achieved

Question 1 **Is there is an optimum height to span ratio for a barrel vault free roof profile.**

Question 2 **Is there is a cost premium or significant percentage increase in construction costs when designing a barrel vault free roof structure which varies above or below the optimum profile shape.**

Question 3 **What are the pressure coefficients for the 4 main zones of a barrel vault free roof profile.**

Question 4 **Will an increase of the dip ratio between the support rafters, compromise the optimum height to span ratio for the sake of aesthetics**

5.1.1 Question 1 The research project has highlighted the direct relation of height to span ratio and tonnage of steel to support each of the barrel vault free roof profiles. The optimum height to span ratio profile is BV13 with BV11 and BV12 within 12% of the optimum. The profile range of BV9 to BV14 is within 16% of the optimum.

5.1.2 Question 2 When the designer of a tensile membrane structure utalising a barrel vault free roof canopy varies from the optimum profile there is a cost penalty of 19% increase in the tonnage of structural steelwork. Comparison between BV13 and BV6. Usually the shopping mall car park structures which are constructed in Australia and USA use the BV6 & BV7 canopy profiles. The research data shows that these profiles are not as cost effective as the BV 13 profile.

To increase the height to span ratio from the BV13 to BV20 the cost penalty increase is 81%.

BV1 to BV3 would not be used as canopy profiles for a PVC barrel vault structure due to the low angle windward and leeward edge of the canopy. The low angle would increase the tendency for the canopy to pond with water during a storm event.

5.1.3 Question 3 Each of the research models have been divided into 4 zones and each zone into 20 incremental plates across the width of the model. The coefficient values which have been documented for each incremental plate (Figure 4.18 and Tables 4.4 to 4.23) will assist the designer and the engineer when analyzing barrel vault free roof canopies. The reference wind codes do not include information on barrel vault free roof canopies.

5.1.4 Question 4 The dip between the curved support rafters of a barrel vault canopy does not significantly affect the wind load onto the structure, nor change the structural member sizes. Therefore the cost to construct does not alter.

5.2 Theory, methods and analysis

The barrel vault free roof profile will have an optimum height to span ratio which is the ideal configuration for the barrel vault canopy as far as cost - tonnage of steel to support the tensile membrane fabric roof. An increase in height to span ratio may positively influence the form and aesthetic appeal of the structure while not significantly increasing the cost - tonnage of steel.

Due to advances in software technology Computational Fluid Dynamics (CFD) is a viable aid in the design process of tensile membrane structures. CFD is able to quickly produce visualizations of the wind effect and wind turbulence created by each of the barrel vault roof profiles. Wind tunnel testing would be a time and cost prohibitive process. This research project consists of 20 individual profile variations, BV1 to BV20, of the barrel vault free roof canopy. And a further 4 variations to the profile shape BV6A, BV6B, and BV13A, BV13B

Each of the initial mesh geometries (BV1 to BV20, inclusive of BV6A, BV6B, BV13A, BV13B) have been created within industry specific form finding software with the parameters set to optimize each profile shape. Once created each of the profile shapes have been subjected to an identical wind load and analysis environment, to compile the data required for the research.

The CFD model was exported to the FEA software, identical structural supports added to each of the 24 profile configurations, and analysis completed of the steel required to support the roof profile.

5.3 Result

The aim of the research was to find the optimum barrel vault free roof canopy profile height to span ratio, and to compile data which would be of significant use to the designer of a tensile membrane structure when determining an appropriate profile configuration for a project structure.

The research project has successfully answered Question 1 and Question 2 showing that canopy profile BV13 is the optimum and most cost effective configuration, (steel tonnage required to support the tensile membrane roof), and BV13 has greater aesthetic appeal due to the added height of the canopy profile with the added bonus of reduced wind loading. Designers of tensile membrane projects will be able to use the data compiled to make an educated appraisal of all profiles and determine the most appropriate profile configuration for the individual structure.

The data compiled during the research to answer Question 1 and Question 2 has allowed the formatting of the tables to answer Question 3. The tables are an available reference in addition to the regional wind codes data the engineer has at hand.

The limited testing of the BV6 and BV13 profiles in regard to varying the dip between the support rafters, has highlighted that the wind action onto the main support structure does not significantly affect the structural member sizes

5.4 Limitations of the study

To find an optimum Height to Span ratio for barrel vault free roof profile. The only considered method of comparison has been to complete an analysis of the structural steel required to support the canopy of each of the barrel vault free roof profiles. The tonnage of steel for each profile has been used to determine construction cost of the structures, ultimately determining the optimum barrel vault free roof profile. All profile variations were modeled in CFD software for determination of wind action onto the canopy surface.

This research project only studied the barrel vault free roof canopy profile which is symmetrical across its width. Often barrel vault profiles have one raised side. (Figure 5.1) This research project does not look at this profile variation of the barrel vault free roof canopy.

Figure 5.1 Barrel vault structure with one raised side

5.5 Contribution of the study to knowledge and practice

The data compiled by the research project will be of significant assistance to designers when in the first instance determining the preferred height to span ratio for a given project, and secondly the cost implications of utilizing the preferred profile.

Figures 5.2 and 5.3 are 3D conceptual images of a car park project. Figure 5.4 utilizes the height to span ratio of 0.15. The research project has shown that a car park project could successfully use a height to span ration of 0.3 for no extra cost consideration while the benefit would be the construction of a project with increased aesthetic appeal.

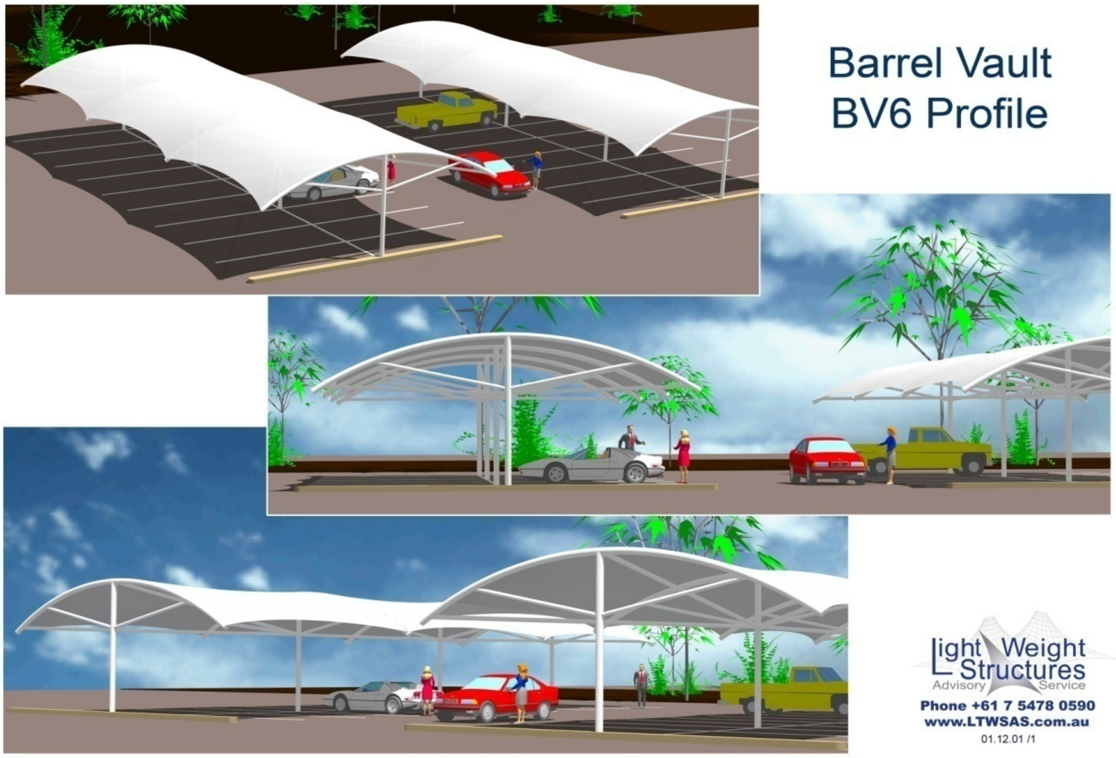

Figure 5.2 Conceptual image of a project with a BV6 height to Span ratio

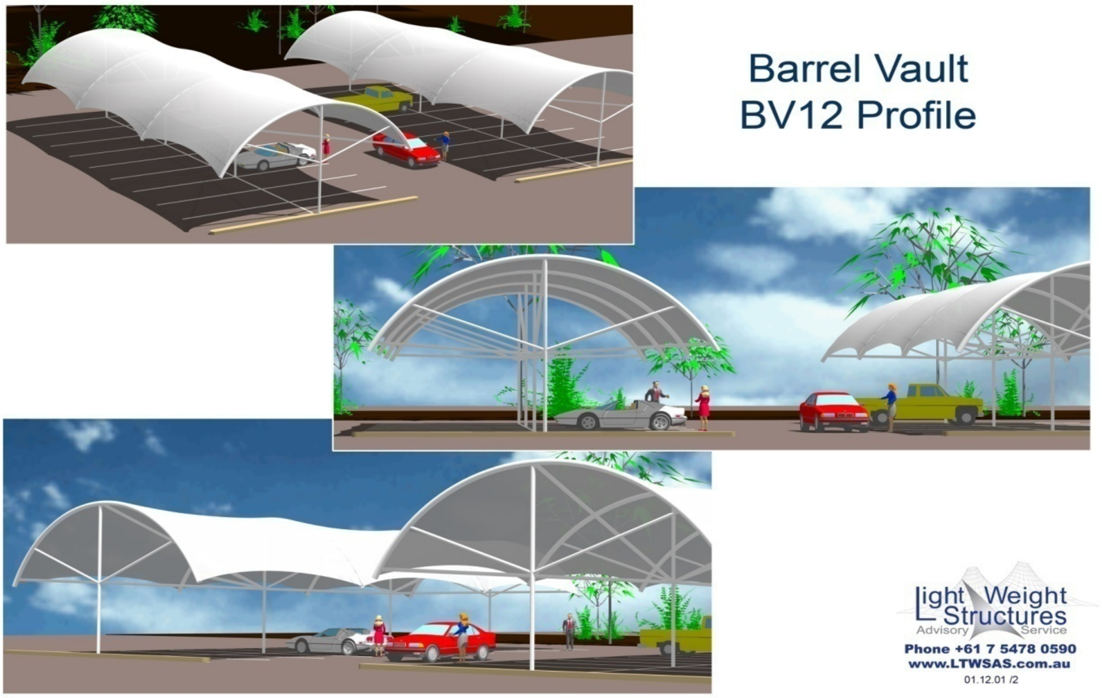

Figure 5.3 Conceptual image of a project with a BV12 height to span ratio

Figure 5.4 Car parking project- design profile BV6

Figures 5.5 and 5.6 utalise the height to span ration of 0.2 BV8. The canopy geometry of the middle canopy on the resort tower with 11 units (rear building), 6.1 mts long x 6.8 mts wide, with a rise of 1.345mm and a dip of 573mm. Figure 5.6 highlights the exaggerated profile of the canopy which provided the increased aesthetic appeal and the ability to resist high wind load from the exposed location.

Further research is required on all profile configurations utilized in the design of tensile membrane structures. Hypar, Conic, Saddle, and Barrel Vault profiles are the basis of design for a tensile membrane structure and at present there is limited information available. Future research will allow for a greater understanding of the behavior of the profiles under high wind loading, snow loading, and severe weather conditions.

Figure 5.5 Rooftop area project- design profile BV8

Figure 5.6 Rooftop area project- design profile BV8

BIBLIOGRAPHY

Arnout S., Lombaert G., Degrande G., De Roeck G. (2012): *The optimal Design of a barrel vault in the conceptual design stage.* Journal of Computers and structures 92-93,308-316

AS/NZS 1170.2:2002 *Structural design actions Part 2 Wind Actions*

AS/NZS 1170.2:2011 *Structural design actions Part 2 Wind Actions*

AS 4100-1998 *Steel Structures*

ASCE 7-05 *Minimum Design Loads for Buildings and Other Structures*

Barnard R. H., (2000) *Predicting dynamic wind loading on cantilevered canopy roof structures*. Journal of Wind Engineering and Industrial Aerodynamics 85, 47-57

Berger Horst, (1999) *Form and function of tensile structures for permanent buildings.* Journal of Engineering Structures 21 669-679

Blackmore. P. A., Tsokri. E., (2006) *Wind Loads on curved roofs.* Journal of Wind Engineering and Industrial Aerodynamics 94, 833-844

Bletzinger Kai-Uwe, Ramm Ekkehard, (2001) *Structural optimization and form finding of light weight structures*. Journal Computers and Structures 79, 2053-2062

BS 6399 : Part 1 : 1996 *Loadings for Buildings Part 1. Code of practice for dead and imposed loads*

Burton Jennifer, Gosling Peter, (2004) *Wind loading pressure coefficients on a conic shaped fabric roof-Experimental methods,* Journal of the international association for shell and spacial structures IASS, Phd Thesis

Burton Jennifer (2006): *Wind Loading on Conic Roofs*. PhD Thesis, University of Newcastle, Tyne.

Eurocode 1, ENV 1991-1-4 :1996, *Actions on structures Part 1.4: General Actions – Wind Actions*

Forster Brian & Mollaert Marijke (2004); *European Design Guide for Tensile Surface Structures*

Holmes J.D., (2007) *Wind Loading of Structures,* Taylor and Francis

Huntington Craig G., (2004) *The Tensioned Fabric Roof,* Americian Society of Civil Engineers, Reston.

Palmer Garry, Vazquez Bernardo, Knapp Graham, Wright Nigel, Happold Buro (2003). *The practical application of CFD to wind engineering problems*, University of Nottingham, Eighth International IBPSA Conference

Pun Peter K.F., (1993) *Analysis of a tension membrane hypar subjected to fluctuating wind loads*, Master Thesis, University of Queensland, Brisbane

Sivaprasad Neha, (2006),*Wind design of fabric structures determination of gust factors for fabric structures*. Master Thesis University of Southern California

The Australian Wind Engineer, newsletters

Tian Di., (2011) *Membrane Materials and Membrane Structures in Architecture*, Masters Thesis, University of Sheffield

Uematsu Yasushi, Stathopoulos Theodore, Iizumi Eri, (2007) *Wind Loads on free-standing canopy roofs.* Journal of Wind Engineering and Industrial Aerodynamics 95, 1486-1510

Uematsu Yasushi, Stathopoulos Theodore, Iizumi Eri, (2008) *Wind Loads on free-standing canopy roofs: Part 1 local wind pressures.* Journal of Wind Engineering and Industrial Aerodynamics 96, 1015-1028

Uematsu Yasushi, Stathopoulos Theodore, Iizumi Eri, (2008) *Wind Loads on free-standing canopy roofs: Part 2 overall wind forces.* Journal of Wind Engineering and Industrial Aerodynamics 96, 1029-1042

Valdes J. G., Miquel J., Onate E., (2009) *Nonlinear Finite element analysis of orthotropic and prestressed membrane structures*. Journal Finite Elements in Analysis and Design 45, 395-405

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