DRAFT REPORT

CAUSEWAY PEDESTRIAN BRIDGES

PERTH, WESTERN AUSTRALIA

DESKTOP STABILITY ASSESSMENT REPORT
RWDI # 2100795
September 14, 2022

SUBMITTED TO

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EXECUTIVE SUMMARY

RWDI Australia Pty Ltd (RWDI) was retained by Causeway Link Alliance, in collaboration with WSP Australia, to undertake wind engineering studies for the proposed cable-stayed pedestrian bridges across the Swan River in Perth, Western Australia. This report presents the background, objectives, results, and findings from RWDI's desktop aerodynamic stability assessment of the completed bridge. The following is a summary of the main findings:

- Flutter of the deck is considered unlikely below the 10,000 year stability speed for each bridge;
- galloping may occur at a wind speed below the 10,000 year stability speed for each bridge if the aerodynamics of the deck are unfavorable;
- there is a risk of vertical vortex-induced oscillations (VIO) of the deck exciting multiple modes up to the design wind speed for both McCallum Park and Fraser Point bridges. For the lowest vertical modes of vibration, VIO could occur at relatively common wind speeds less than 10 m/s. The susceptibility to VIO is driven by the low mass and low damping of the deck, and the corresponding lock-in wind speed range is driven by the frequency of a given vertical mode of vibration. It is possible that the acceleration of the deck associated with VIO could exceed the comfort criterion and could be of concern with regards to fatigue and strength loading;
- there is a risk of torsional VIO of the deck exciting multiple modes up to the design wind speed for the McCallum park bridge. For the Point Fraser bridge, torsional VIO is unlikely at wind speeds below the design speed; and,
- the risk of VIO of the pylons is low for both McCallum Park and Fraser Point during the completed bridge phase. This is due to the fact that the modes with pylon motion also involve the participation of other components (deck, cables).

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1 INTRODUCTION

RWDI Australia Pty Ltd (RWDI) was retained by Causeway Link Alliance, in collaboration with WSP Australia, to undertake wind engineering studies for the pair of pedestrian bridges that will span the Swan River, linking McCallum Park to Point Fraser near the Perth central business district (CBD) in Western Australia. This report documents the background, objectives, and main findings of the aerodynamic stability assessment phase of the wind engineering studies.

1.1 Project Description

The Causeway Pedestrian Bridges project consists of two unique bridges: the McCallum Park bridge, linking McCallum Park to Heirisson Island, and the Point Fraser Bridge, linking Heirisson Island to Point Fraser. The bridges will provide both pedestrian and cyclist access across the Swan River. The McCallum Park bridge is a cable-stayed bridge with a 155 m long main span and 60 m long side spans, with a maximum deck elevation of 8 m above the Swan River. The curved bridge deck is supported by asymmetrically arranged stay cables connected to two 47 m tall pylons. Figure 1-1 shows general plan and elevation views of the proposed McCallum Park bridge. The typical deck cross-section, shown in Figure 1-3, is asymmetric in form and is composed of a closed box girder and a cantilevered deck plate. On the McCallum Park bridge, the deck is also asymmetric in orientation: from Heirisson Island to midspan the deck is oriented with the cantilever on the North side, and from midspan to McCallum Park the deck is oriented with the cantilever on the South side. The McCallum Park pylons are cylindrical and constant in cross-section for the majority of the elevation, except for a short tapered section near the tip (Figure 1-4).

The Point Fraser bridge is cable-stayed bridge with a 96.5 m long main span and a 48 m long back span, with a maximum elevation of 9 m above the river. The bridge deck is curved and is supported by asymmetrically arrange stay cable connected to a single 53 m tall pylon. Several shorter, curved back spans join Pier 3 to the abutment on the Point Fraser side. Figure 1-2 shows plan and elevation views of the proposed Point Fraser bridge. The same deck cross-section is employed on the Point Fraser bridge, however the orientation of the deck is constant over its length, with the cantilevered plate being on the North side. The shape of the Point Fraser pylon in the lateral-vertical plane resembles a that of a boomerang, while in the longitudinal-vertical plane the width of the pylon is constant (Figure 1-5).

The wind engineering studies herein were carried out based on information provided by WSP between August 8, 2022 and August 24, 2022. Table 1-1 details the key information used by RWDI. Through discussions with WSP, the following parameters have been considered in the current studies:

- Modal deflections and natural frequencies based on WSP's finite element models of the completed bridges;
- mass and mass moment of inertia properties for the deck and the other bridge elements (pylons, cables, etc.);
- the completed bridge will be studied up to 10,000-year return period wind speed for the evaluation of aerodynamic stability while the design wind speed will be based on the 2,000-year return wind speed; and,
- a structural damping ratio of 0.3% of critical.

1.2 Objectives

The complete scope of wind engineering services includes:

- wind climate analysis;
- aerodynamic stability assessment;
- free standing pylon force balance tests;
- deck sectional model test; and
- full bridge aeroelastic model studies.

The current report details the desktop aerodynamic stability assessment, which considers the susceptibility of the bridge to aerodynamic instabilities such as vortex-shedding induced oscillations (VIO), galloping and flutter.

2 DESKTOP AERODYNAMIC STABILITY ASSESSMENT

2.1 Aerodynamic Instabilities

A desktop aerodynamic stability assessment of the bridges has been carried out considering the deck and the pylons for each bridge. For the initial desktop stability assessment of wind-sensitive bridges, the following types of wind-induced instabilities need to be considered:

1. **Flutter**: a self-excited aerodynamic instability that can grow to destructive amplitudes in torsion or coupled torsion-vertical motion and is to be avoided at all cost.

2. **Galloping**: an instability involving across-wind vibrations. Similar to flutter, galloping-induced vibrations can theoretically grow to large amplitudes with increasing wind speed and therefore are also to be avoided at all costs.

3. **Vortex-shedding Induced Oscillations**: A phenomenon that involves limited amplitude motions caused by alternate and regular vortices shed from either side of a bluff body – such as a bridge deck or a pylon. This phenomenon occurs only over limited wind speed and amplitude ranges and can be tolerated if the frequency of occurrence, amplitudes, and accelerations are not excessive.

Experience and data obtained from previous projects, as well as relevant literature, were used to estimate aerodynamic properties for the bridge for the preliminary desktop assessment and to guide the definition of the scope of planned wind tunnel tests.

2.2 Structural Properties

2.2.1 Deck Section Geometry and Mass

Figure 1-3 presents a typical cross-section of the deck. The mass per unit length varies between 2,030 kg/m and 2,920 kg/m over the main span of either bridge, and the mass moment of intertia (MMI) per unit length varies between 7,050 kg-m^2/m and 11,000 kg-m^2/m. Due to the asymmetry of the deck section, the center of mass is located approximately 700 mm off-center in the lateral direction towards the box girder side of the deck.

The overall width of the typical deck section is 6.7 m and the depth (measured from the top of the deck surface to the base of the box girder) is 1.2 m for a deck width-to-depth ratio of 5.6. Parapets are included on each side of the deck and are composed of a 1.4 m tall balustrade and stainless steel mesh up to 1.2 m off the deck surface. The porosity of the stainless steel mesh is approximately 83%.

2.2.2 Dynamic Properties

All analyses in this report are based on the generalized coordinate theory where mass and stiffness are represented by vibrational modes. For the stability assessment, WSP provided dynamic properties for the two completed bridges. Appendices A1 and A2 show renderings of the mode shapes for the McCallum Park and Point Fraser bridges, respectively, based on RWDI's simplified numerical models of the bridges. RWDI's numerical models are based directly on the geometry, mass distribution and mode shapes and frequencies provided by WSP and have been used to calculate the equivalent mass and mass moment of inertia per unit length (defined in Section 2.3) of the modes of vibration of interest, as well as visualizing the mode shapes.

2.2.3 Structural Damping

High structural damping can suppress vibrations. However, unless supplementary damper devices are added, it is difficult to increase damping on a bridge. A damper device typically can control only one mode of vibration, this option is only efficient if vibrations of one or two modes need to be controlled.

The inherent structural damping of bridges varies depending on their structural scheme, material, and methods of construction. Various references (Refs. 1, 2, 3, 4, 5) report structural damping ratios as a percent of critical.

It is noted that the wind excitation mechanisms differ from the excitation from an earthquake. For example, the wind gusts excite mainly the deck at lower frequencies than the much higher frequency motions starting at the bridge base due to ground motions. Therefore, the level of energy dissipated in the structure is lower for wind excitations when compared to sudden seismic events.

A damping ratio of 0.3% of critical was selected for this desktop assessment since the deck and pylons are composed primarily of steel members.

2.3 Parameters Controlling Dynamic and Aerodynamic Responses

The aerodynamic stability of the proposed bridge is governed by the typical cross-section of the deck and will depend on each of the following:

i) section geometry,

ii) mass and mass moment of inertia per unit length, and

iii) structural properties such as stiffness and damping.

For any section, the dependence on overall dimensions, mass, and damping can be described by its Scruton number:

$$Sc = \frac{m_{eqv}\zeta}{\rho DB} \tag{2-1}$$

for translation modes, and

$$Sc = \frac{I_{eqv}\zeta}{\rho (DB)^2} \tag{2-2}$$

for rotational modes, where,

- m_{eqv} and I_{eqv} are the equivalent mass and MMI per unit length, respectively;
- D is the depth, a measure of section frontal face exposed to wind;
- B is the width representing the exposed lifting area to wind;
- ζ is the structural damping ratio; and,
- ρ is the air density.

In general, lower Scruton numbers imply that sections might be more susceptible to aerodynamic instabilities due to low mass and/or damping relative to its overall dimensions exposed to the wind. However, the Scruton number does not account for the influence of the section shape on its aerodynamic properties.

The equivalent mass or MMI of a deck with length L (S is the length of the entire structure) for any mode j and degree of freedom k are calculated based on the mass, $m(s)$, and the MMI, $I_{xx}(s)$ and $I_{yy}(s)$, distributions and the mode shapes $\Phi(s)$ as:

$$m_{eqv,j,k} = \frac{\mathrm{M}_{gen,j}}{\int_0^L \Phi_{j,k}(\mathrm{s})^2 ds},$$

$$\mathrm{M}_{gen,j} = \int_0^S \left[m(s)\left(\Phi_{\mathrm{j,x}}(\mathrm{s})^2 + \Phi_{\mathrm{j,y}}(\mathrm{s})^2 + \Phi_{\mathrm{j,z}}(\mathrm{s})^2\right) + \mathrm{I_{xx}}(s)\Phi_{j,xx}(s)^2 + \mathrm{I}_{yy}(s)\Phi_{j,yy}(s)^2\right] ds, \tag{2-3}$$

It should be noted that in this equivalent mass definition, wind excitations are considered correlated only over the bridge deck. A similar equivalent mass may be defined for each element of interest, e.g. pylons, that might be enveloped by a strongly correlated wind flow. The equivalent modal mass is a measure of how much structural mass a correlated aerodynamic excitation attempts to displace.

2.4 Assessment Results

2.4.1 Flutter

All bridge decks are susceptible to aerodynamic instability known as flutter, which results in a dramatic increase in torsional oscillations once a certain wind speed is reached. This response is said to be “divergent” because it continues to increase rapidly with increasing wind speed. Flutter occurs due to a coupling of paired torsional and vertical modes, and the critical onset speed is thus a function of the ratio of the torsion and vertical frequencies. In general, the larger the torsion frequency relative to the vertical frequency, the larger the critical speed.

The critical speed for flutter depends on the ratio of the first torsion-to-vertical frequencies, which are summarized for each deck configuration in Table 2-1. Both the McCallum Park and Point Fraser decks are unlikely to experience flutter below the 10,000 year stability speed due relatively high torsional stiffness of the bridge decks and coupling with motion in other degrees of freedom.

2.4.2 Galloping

Galloping is a divergent instability that causes motion in the across-wind direction (i.e., in the vertical direction for a horizontal member). The critical onset speed for galloping is a function of the Scruton number and the aerodynamic behavior of the body. Long, slender bodies (i.e., large *B/D*) are typically not susceptible to galloping, whereas more bluff bodies with slenderness ratios between 1 and 5 (i.e., 1 < B/D < 5) may be susceptible. The critical wind speed for galloping can be estimated based on the Den Hartog equation (Ref. 6):

$$U_{crit} = \frac{8\pi Scf D}{-\left(\frac{dC_L}{d\alpha}+C_D\right)} \qquad (2\text{-}4)$$

where f is the modal frequency, C_L is the lift coefficient, C_D is the drag coefficient and α is the angle of attack. Examining the above equation, it can be noted that for galloping to occur, the rate of change of the lift coefficient with angle of wind incidence needs to be negative and larger than the drag coefficient. Due to the unique, asymmetric design of the deck cross-section, it is difficult to predict what the aerodynamic behavior will be for each wind direction. If a moderately negative C_L slope were to occur, it is possible that galloping could occur at a wind speed below the 10,000-year stability speed. This conclusion is summarized in Table 2-1.

2.4.3 Vortex-shedding Induced Oscillations

Vortex-shedding induced oscillations (VIO) are frequently observed on bridge decks in the vertical and torsional degrees of freedom. On pylons or other vertical members, VIO can cause vibrations in a horizontal direction normal to the wind or along-wind. The occurrence of VIO is characterized by two primary factors:

(i) the onset wind speed,
(ii) the amplitude of vibrations; and,

if it occurs, then its wind speed can be predicted by a characteristic constant called Strouhal number:

$$St = \frac{fD}{U}, \qquad (2\text{-}5)$$

where U is the wind speed at which the shedding frequency of the vortices would synchronize with the frequency of a mode of vibration of the deck. It is also known that turbulence often acts to suppress vortex shedding excitation by disturbing the coherence of the vortices shed in the wake.

The amplitudes of the response are partially governed by the Scruton number (Equations 2-1 and 2-2), which is dependent on either the equivalent mass (considering translational motions) or equivalent mass moment of inertia (for torsional motions). As a point of reference, the Scruton number below which oscillation amplitude become large for a circular cylinder is 2.5. Other geometries (such as a bridge deck) will have a different Scruton number at which oscillations become large, however the 2.5 value gives a sense of the order of magnitude for a "low" Scruton number.

The assessment of VIO entails calculating the critical wind speed range (based on an assumed Strouhal number range) and the Scruton number for each mode of vibration. Considering the McCallum Park bridge deck, there is a risk of vertical VIO occurring for multiple modes of vibration. Table 2-2 shows the modes susceptible to VIO of the deck, where Scruton numbers less than 5 are highlighted to indicate which degree of freedom may be excited. The results demonstrate that the majority of the first 20 modes may be susceptible to vertical VIO. The most susceptible is the 1st vertical mode, mode 2, which has a Scruton number of 1.0 and an estimated critical speed range of 4 m/s to 9 m/s. This speed range is well below the design speed and represents relatively common wind speeds at the site. The estimated critical speed range increases with increasing modal frequency, however the majority of the highlighted modes have a critical speed range that could fall below the design speed. If VIO were to be observed, it is likely that one or more modes could have accelerations that would exceed the comfort criterion of 0.5 m/s^2 (5%g) up to 15 m/s deck level wind speed. Similarly, there are several modes susceptible to VIO in the torsional degree of freedom. The most susceptible is the 1st torsion mode, mode 18, which has a Scruton number of 0.9 and an estimated critical speed range of 30 m/s to 59 m/s.

Table 2-3 shows the results for the Point Fraser bridge. Similar to the McCallum Park bridge, there are multiple modes that show susceptibility to vertical VIO. However, only modes up to mode 10 have an estimated critical wind speed range that falls below the design wind speed. The 1st vertical mode, mode 3, has a Scruton number of 1.3 and an critical speed range of 7 m/s to 14 m/s, which represents relatively common wind speeds at the site. There are several modes that may be susceptible to torsional VIO, however the estimated critical wind speed ranges are above the design speed.

If VIO is observed during the sectional model test and the amplitudes are such that the comfort criterion is exceeded below the 15 m/s threshold or if the VIO amplitude would be a source of concern for strength design, then mitigation options will be explored. Given the fact that there are multiple modes susceptible to vertical VIO and with comparable Scruton number, the addition of supplementary damping to suppress VIO would prove challenging since dampers would be required in multiple locations along the deck. The preferable method for mitigating VIO is to modify the cross-sectional geometry to one that is more favorable aerodynamically. In order to gain insight into what geometry modifications may be beneficial in reducing VIO, CFD simulations were performed for the baseline deck section for each wind direction. Figure 2-1 shows images of instantaneous vortificty contours from the simulation. Note that the barriers were included and modelled as porous elements. Figure 2-2 presents a numer of mitigation options that can be explored during the sectional model test should they be required. The first three options are intended to address VIO for the direction with wind approaching the box girder, while the latter two are intended for the opposite direction. It is also possible that a combination of these options could be required.

A similar VIO assessment was performed for the pylon of the McCallum Park bridge. Due to the circular cross-section of this pylon, the $Sc = 2.5$ threshold is appropriate for determining modes susceptible to VIO. No modes have a Scruton number less than 2.5, therefore the risk of VIO is low. This is primarily due to the large equivalent mass associated with pylon motion since it is coupled with motion of the deck and/or cables. For the Point Fraser pylon, the Scruton number for all modes is relatively large and thus susceptibility to VIO is low. It would be prudent however to consider the risk of VIO for the pylons during construction if the sequencing includes free-standing pylon stages.

2.5 Summary

The aerodynamic stability of the proposed McCallum Park and Point Fraser bridges at the completed phase has been examined based on our experience and available analytical and empirical formulae. Below is the summary of the main findings based on this assessment:

- Flutter of the deck is considered unlikely below the 10,000 year stability speed for each bridge;
- galloping may occur at a wind speed below the 10,000 year stability speed for each bridge if the aerodynamics of the deck are unfavorable;
- there is a risk of vertical VIO of the deck exciting multiple modes up to the design wind speed for both McCallum Park and Fraser Point bridges. For the lowest vertical modes of vibration, VIO could occur at relatively common wind speeds less than 10 m/s. The susceptibility to VIO is driven by the low mass and low damping of the deck, and the corresponding lock-in wind speed range is driven by the frequency of a given vertical mode of vibration. It is possible that the acceleration of the deck associated with VIO could exceed the comfort criterion and could be of concern with regards to fatigue and strength loading;
- there is a risk of torsional VIO of the deck exciting multiple modes up to the design wind speed for the McCallum park bridge. For the Point Fraser bridge, torsional VIO is unlikely at wind speeds below the design speed; and,
- the risk of VIO of the pylons is low for both McCallum Park and Fraser Point during the completed bridge phase. This is due to the fact that the modes with pylon motion also involve the participation of other components (deck, cables). However, if there are stages during the construction sequence where the pylons are free-standing, these could be at risk for VIO. We recommend providing dynamic properties for the free-standing pylon configurations for RWDI to assess.

A sectional model wind tunnel test of the deck is planned and will investigate further the aerodynamic stability behavior of the deck for each wind direction. Full bridge aeroelastic model studies are also planned to verify the stability behaviour of the deck and pylons for each bridge.

3 REFERENCES

1. ESDU 77032 Fluctuating loads and dynamic response of bodies and structures in fluid flows – background information, last update December 1985, Endorsed by The Royal Aeronautical Society Institution of Chemical Engineers Institution of Mechanical Engineers, UK.

2. BD 49/01, Design Rules for Aerodynamic Effects on Bridges, Design manual for Roads and Bridges, ISBN 0115523286, 2001.

3. CAN/CSA-S6-06, A National Standard of Canada, Canadian Highway Bridge Design Code, ISBN 1554362520, 2006.

4. Practical guidelines. CEB, B. I. 209, August 1991.

5. SÉTRA, Technical guide Footbridges. Assessment of vibrational behaviour of footbridges under pedestrian loading, 2006.

6. Den Hartog J.P (1932). Transmission line vibration due to sleet. Trans. AIEE 51, 1074-1086.

TABLES

Table 1-1: Summary of Information Provided

Information	File Name	Date Received
Bridge drawings	Various	August 8, 2022
Dynamic properties	MPB_Dyn_Data_20220822.xlsx PFB_Dyn_Data_20220824.xlsx	August 24, 2022
Mass and MMI properties	MPB Section Data 20220819.xlsx PFB Section Data 20220819.xlsx	August 19, 2022
Deck barrier details	Causeway_Handrail_20220819.pdf SS mesh.pdf	August 23, 2022

Table 2-1: Deck Flutter and Galloping Preliminary Assessment

Configuration	Aerodynamic stability criterion wind speed, 10-minute mean at deck level (m/s)	Frequency ratio f_T/f_V	Flutter criterion ($V_{flutter} > V_{stability}$)	Galloping criterion ($V_{gallop} > V_{stability}$)
McCallum Park	28.6	6.7[1]	Likely to pass	Potential for failure
Point Fraser	31.4	7.5[2]	Likely to pass	Potential for failure

[1] 1st vertical mode: mode 2; 1st torsion mode: mode 18
[2] 1st vertical mode: mode 3; 1st torsion mode: mode 17

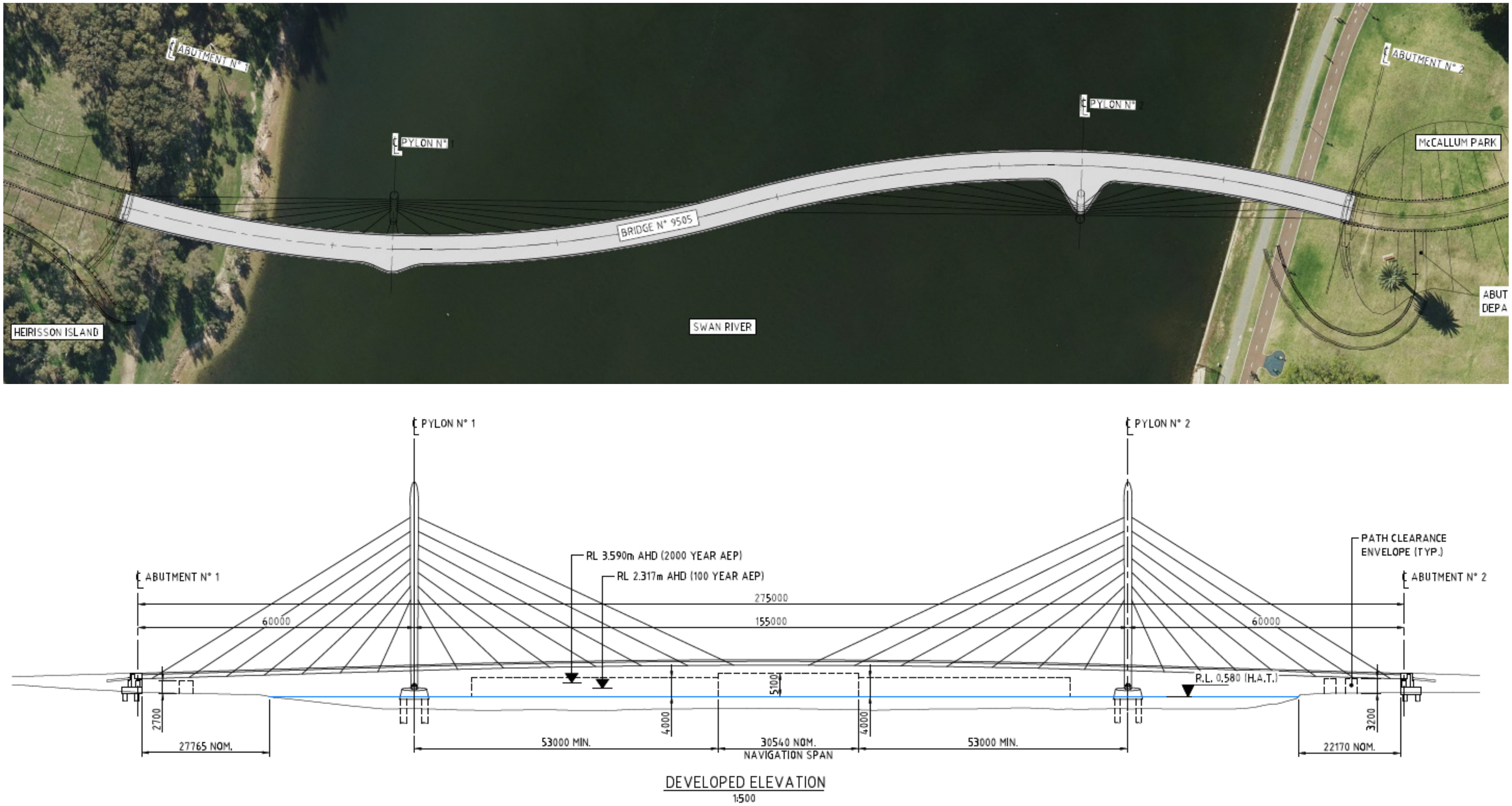
Table 2-2: McCallum Park Deck VIO Preliminary Assessment, Vertical and Torsional Modes

Mode	f (Hz)	Critical wind speed range (m/s)		Scruton number	
		Minimum	Maximum	Vertical	Torsion
2	0.439	4	9	1.0	792.7
4	0.644	6	13	1.6	27.7
5	0.678	7	14	2.9	125.4
6	0.868	9	17	2.1	22.2
7	1.154	12	23	0.9	58.5
8	1.190	12	24	1.0	3.1
10	1.400	14	28	0.9	5.8
11	1.649	16	33	2.0	7.9
12	1.732	17	35	1.4	11.0
14	2.070	21	41	0.9	3.9
15	2.257	23	45	1.1	4.0
16	2.561	26	51	2.1	12.6
17	2.671	27	53	0.9	11.4
18	2.960	30	59	1.5	0.9

Table 2-3: Point Fraser Deck VIO Preliminary Assessment, Vertical and Torsional Modes

Mode	f (Hz)	Critical wind speed range (m/s)		Scruton number	
		Minimum	Maximum	Vertical	Torsion
1	0.552	6	11	3.2	1382.2
3	0.693	7	14	1.3	255.9
5	1.375	14	28	1.0	189.5
6	1.694	17	34	1.6	8.0
7	1.932	19	39	2.2	10.4
8	2.304	23	46	1.0	18.0
9	2.548	25	51	3.4	28.9
10	2.636	26	53	2.8	33.3

FIGURES



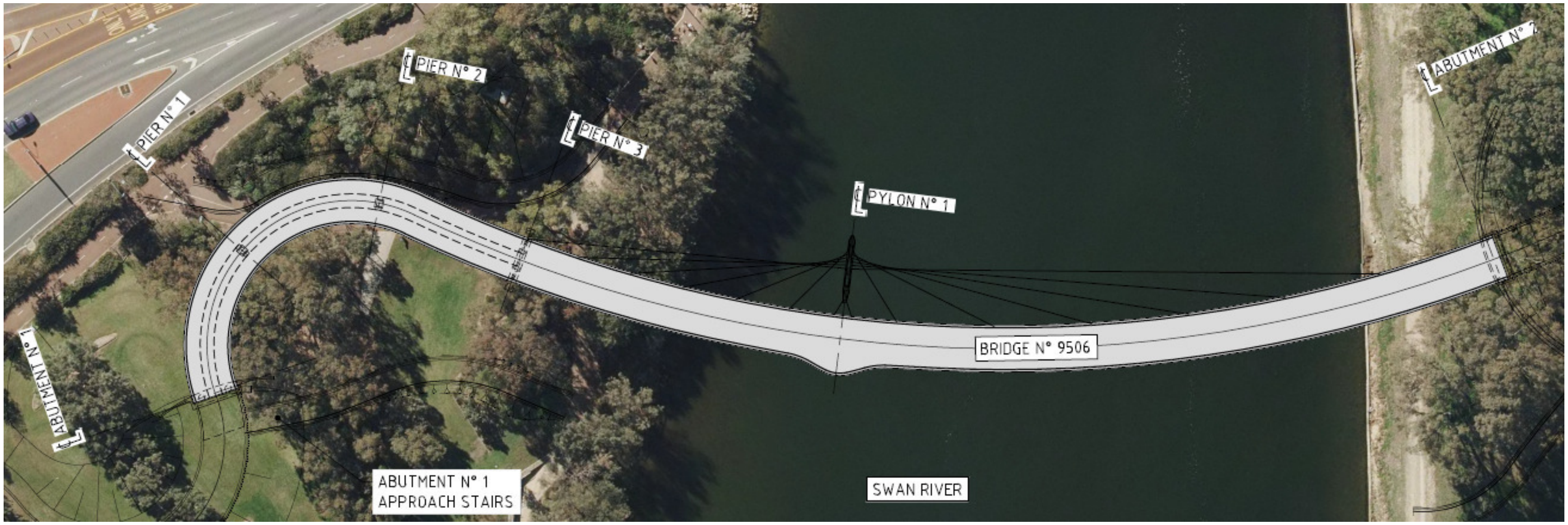
Plan and Elevation Views of the McCallum Park Bridge

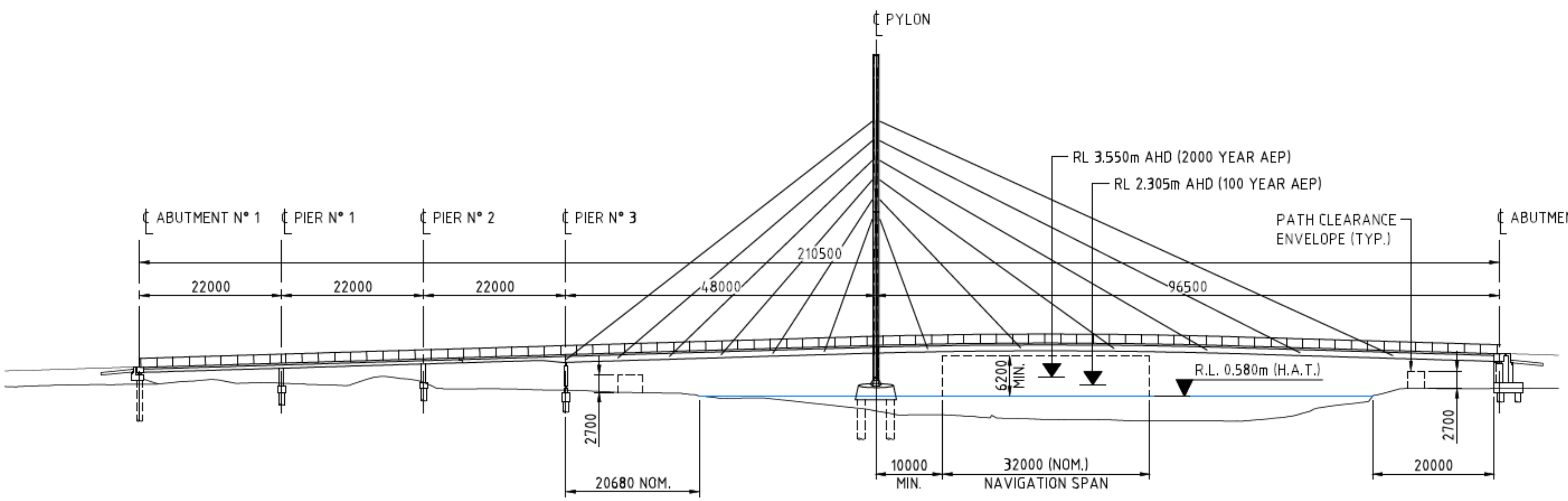
Causeway Pedestrian Bridges, Perth, Australia

Project #2100975

Figure No. 1-1

Date: September 15, 2022





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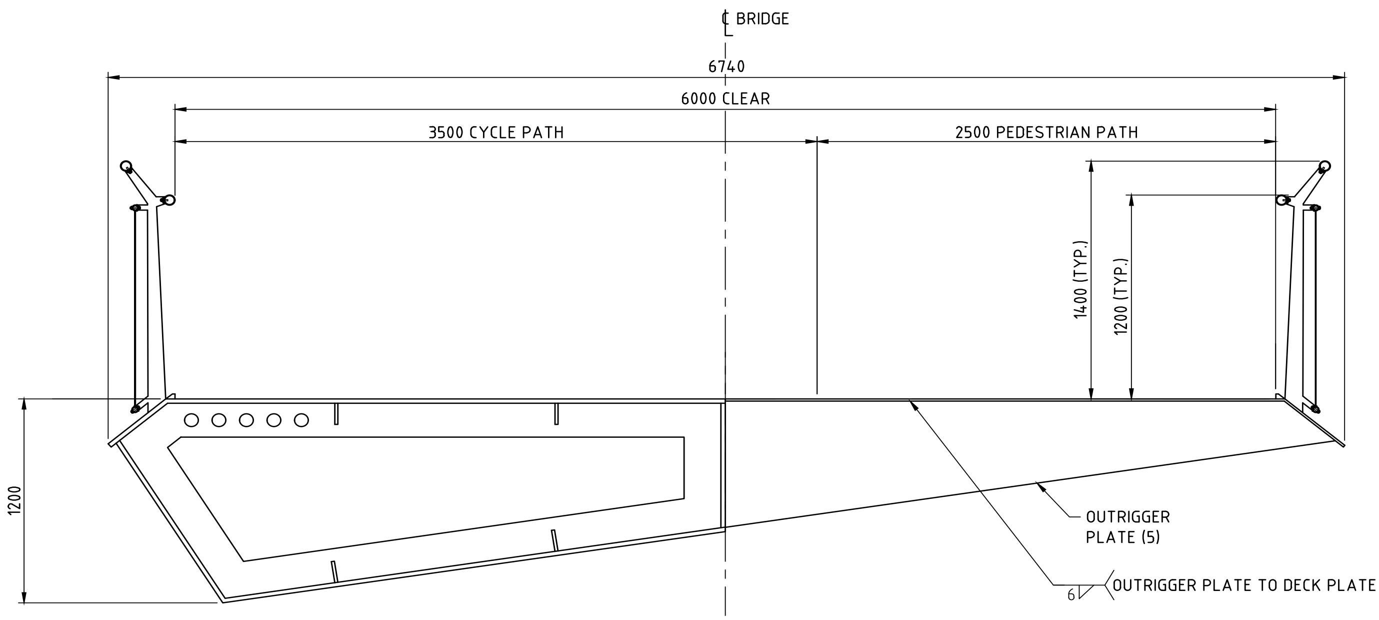
Plan and Elevation Views of the Point Fraser Bridge Causeway Pedestrian Bridges, Perth, Australia — Project #2100975	Figure No. 1-2 Date: September 15, 2022	



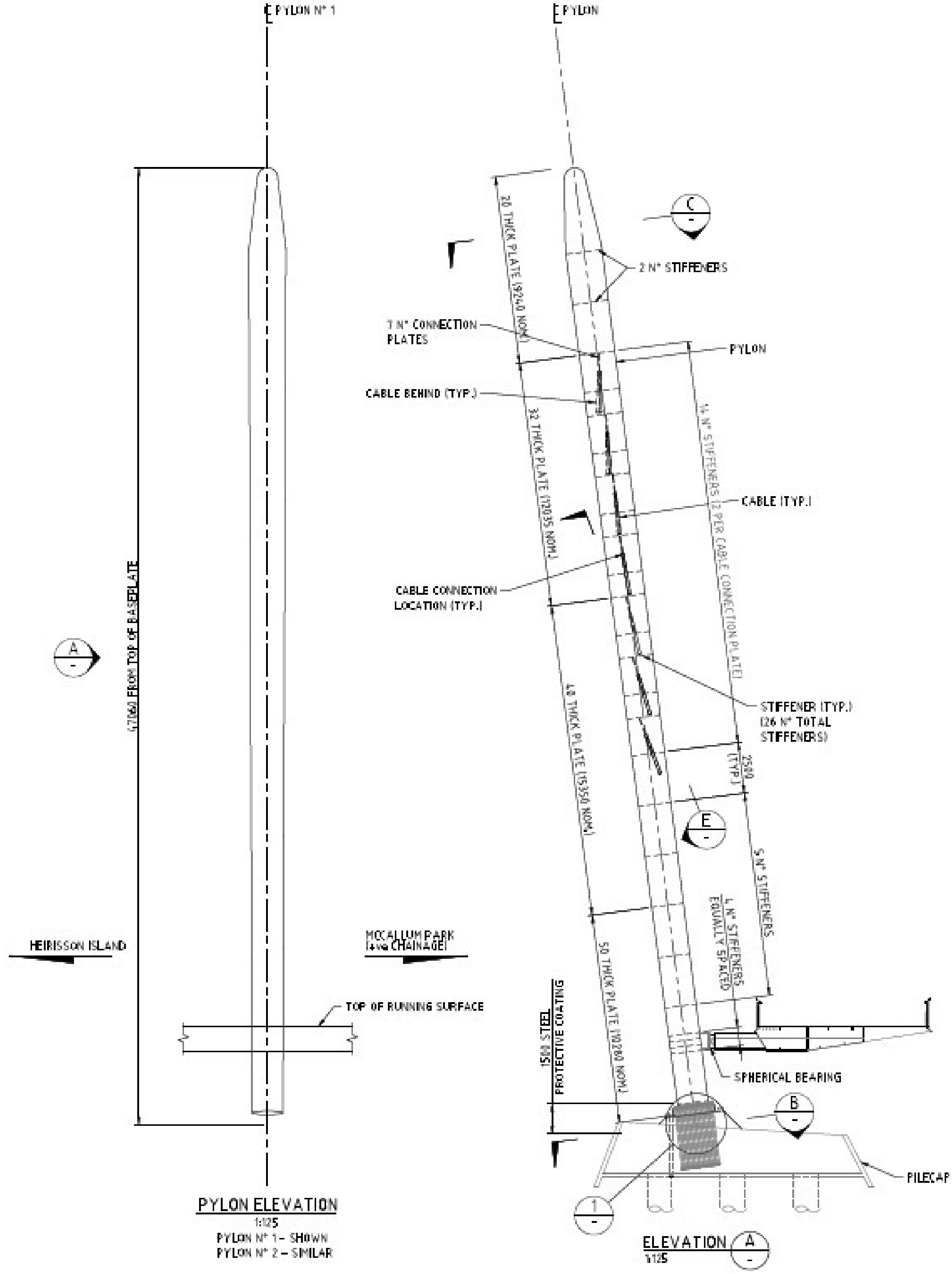
Typical Deck Cross-Section

Figure No. 1-3

September 15, 2022

Causeway Pedestrian Bridges, Perth, Australia

Project #2100975



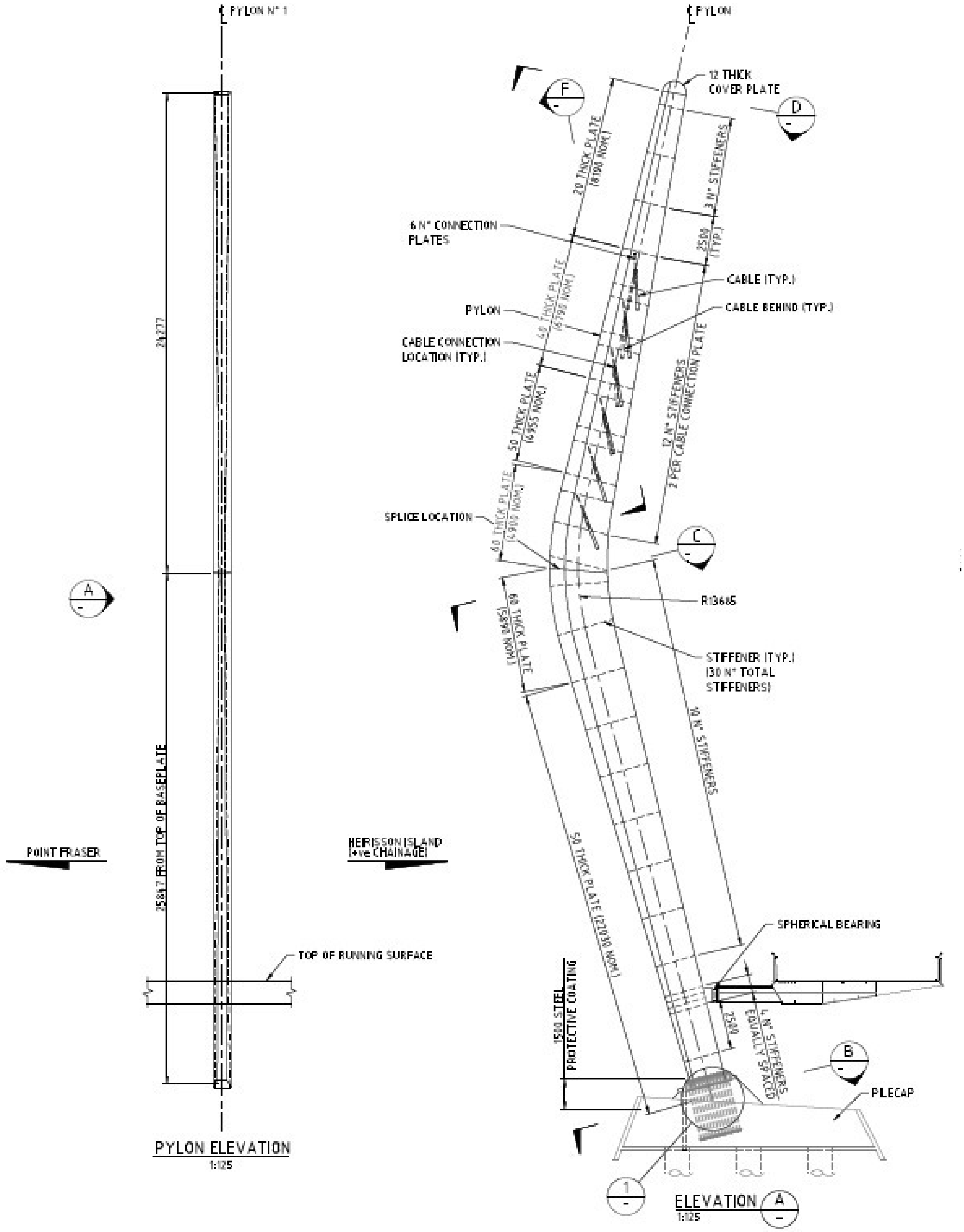
Elevation Views of the McCallum Park Bridge Pylon

Causeway Pedestrian Bridges, Perth, Australia

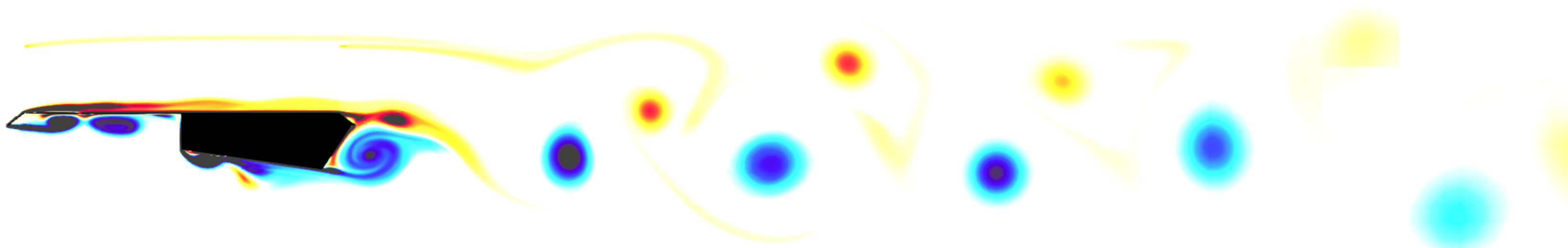
Project #2100975

Figure No. 1-4

September 15, 2022



Elevation Views of the Point Fraser Bridge Pylon Causeway Pedestrian Bridges, Perth, Australia — Project #2100975	Figure No. 1-5
	September 15, 2022



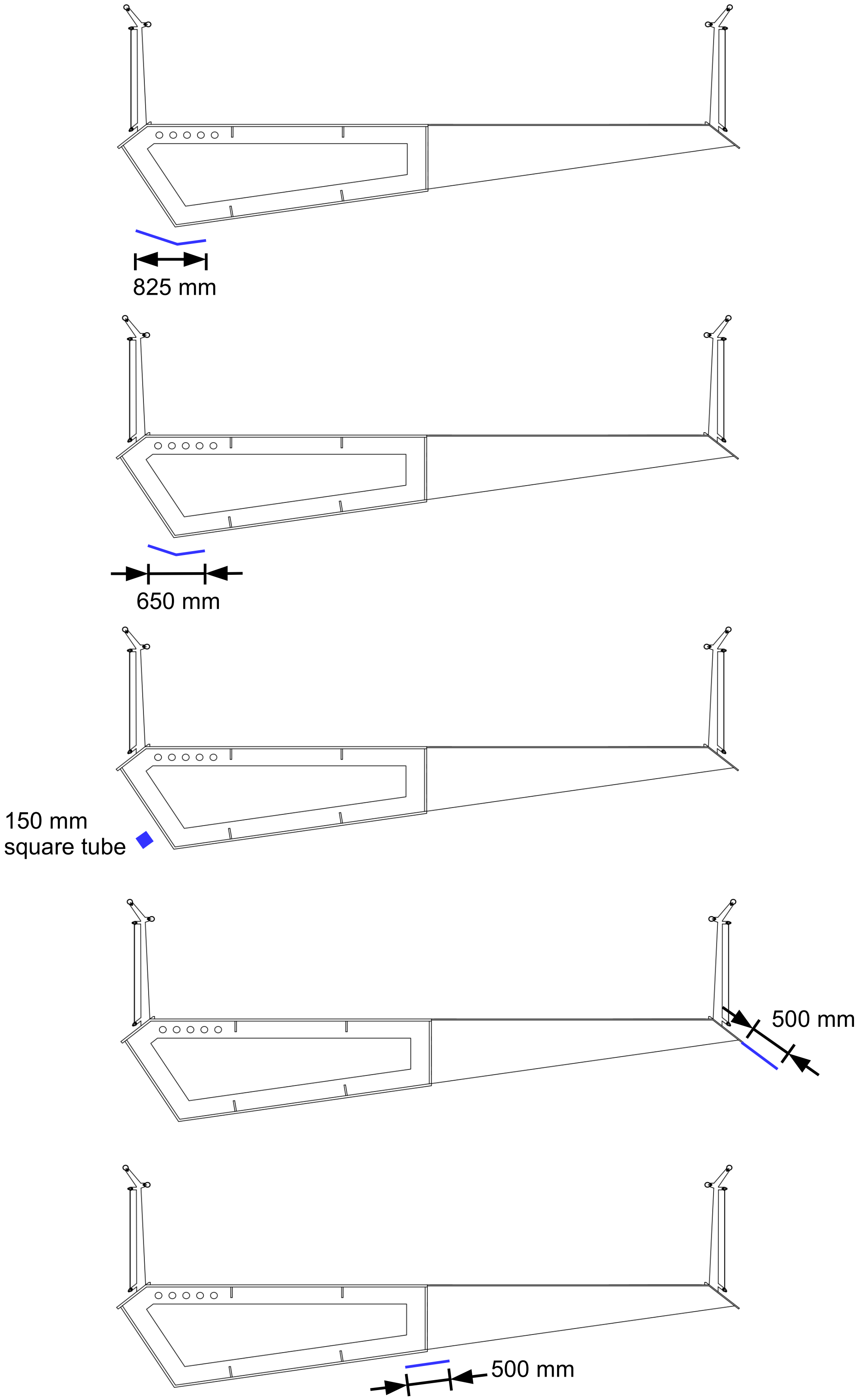
CFD Simulations of Flow Over the Baseline Deck
Top: wind approaching the box girder
Bottom: flow approaching the cantilever

Causeway Pedestrian Bridges, Perth, Australia

Project #2100975

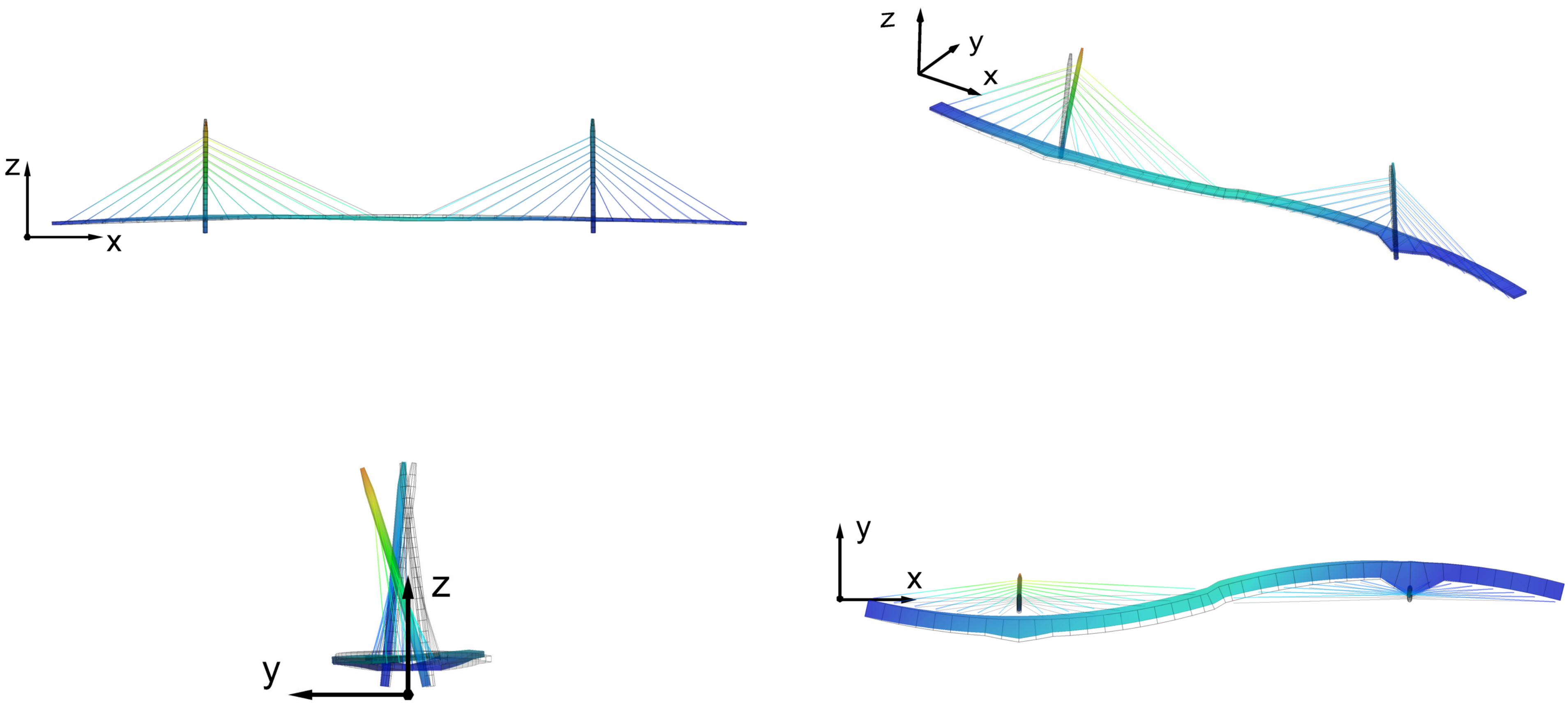
Figure No. 2-1

Date: September 15, 2022



Proposed Deck Mitigation Options	Figure No. 2-2	
Causeway Pedestrian Bridges, Perth, Australia — Project #2100975	September 15, 2022	

APPENDIX A



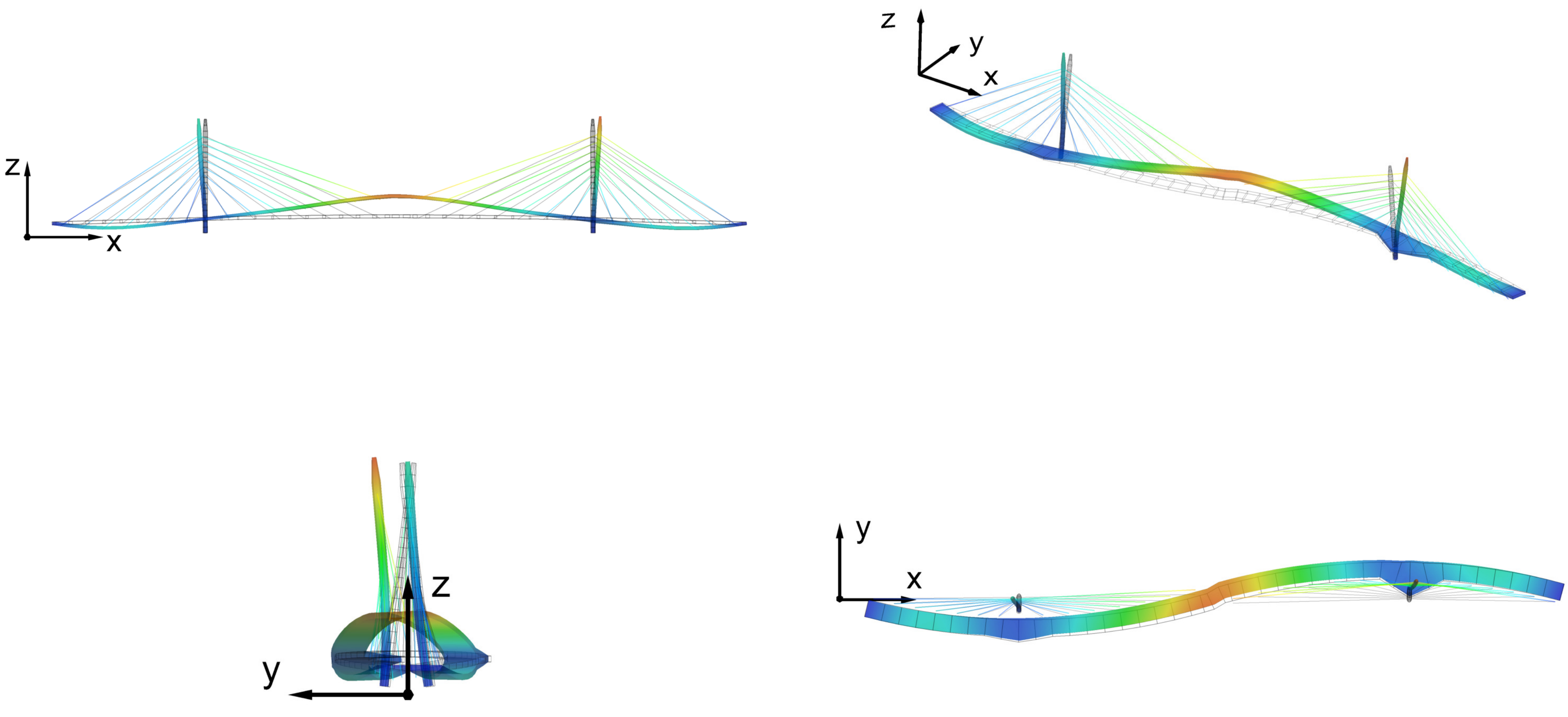
Dynamic Properties - McCallum Park Bridge
Mode 1, f = 0.424 Hz

Appendix A1-1

Date: September 15, 2022

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795



Dynamic Properties - McCallum Park Bridge

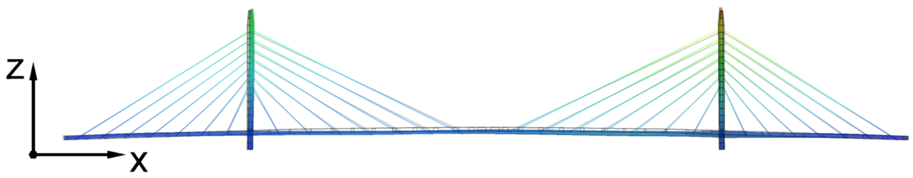
Mode 2, f = 0.439 Hz

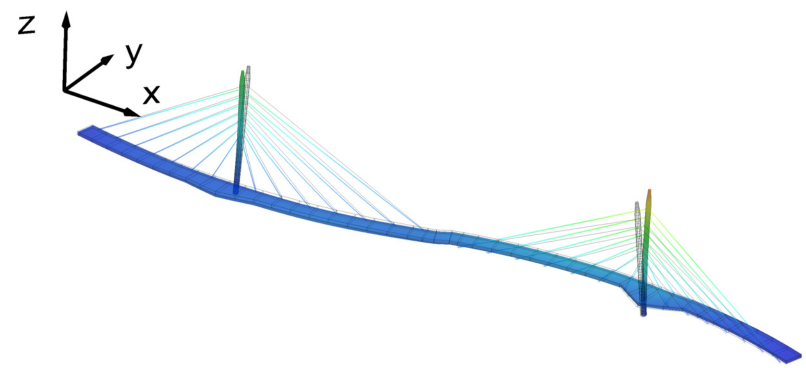
Causeway Pedestrian Bridges, Perth, Australia

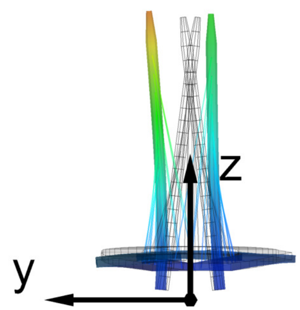
Project #2100795

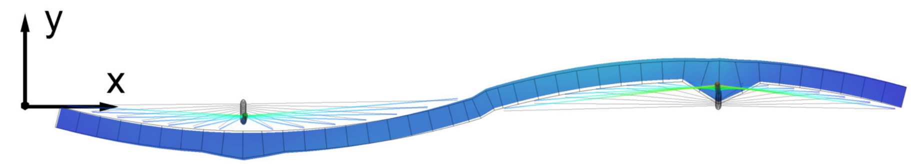
Appendix A1-2

Date: September 15, 2022









Dynamic Properties - McCallum Park Bridge

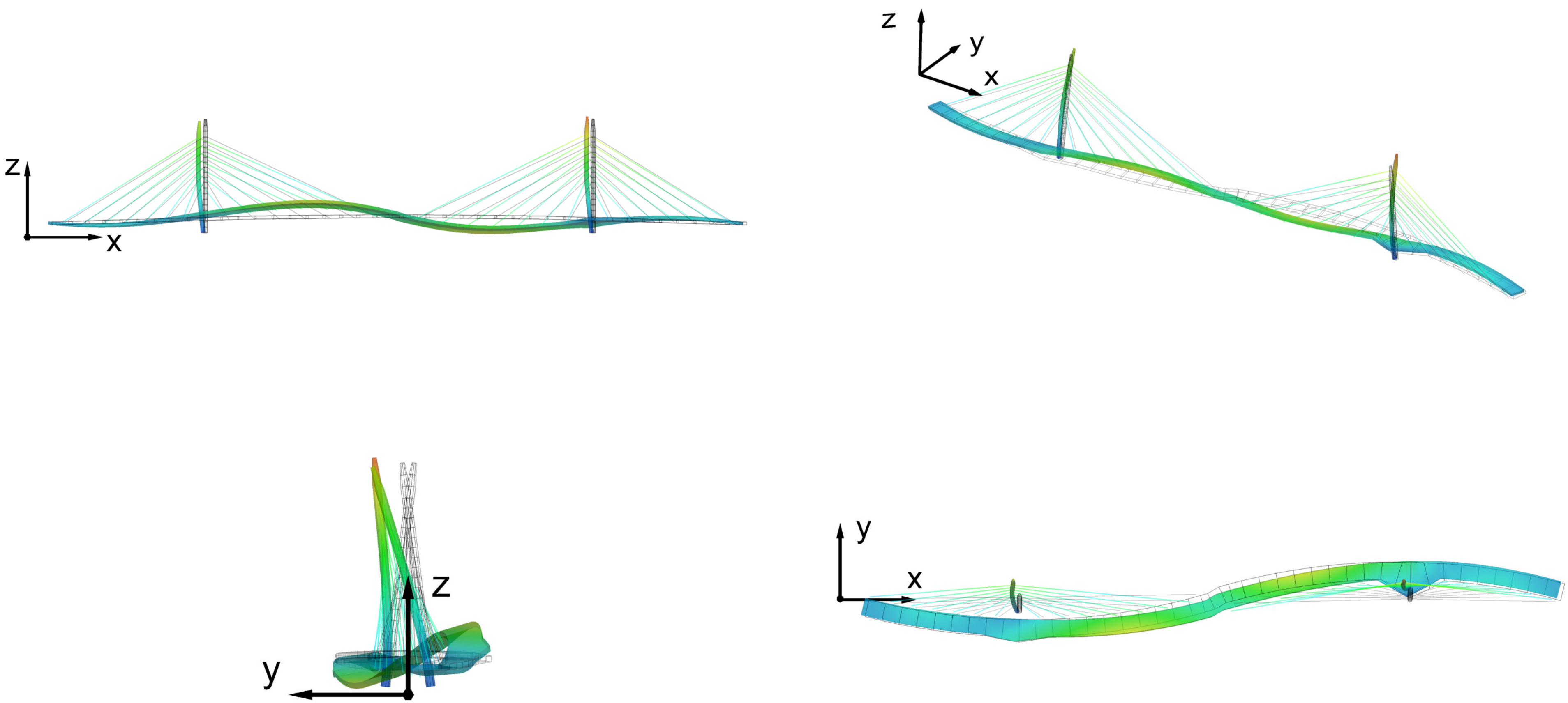
Mode 3, f = 0.569 Hz

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795

Appendix A1-3

Date: September 15, 2022



Dynamic Properties - McCallum Park Bridge

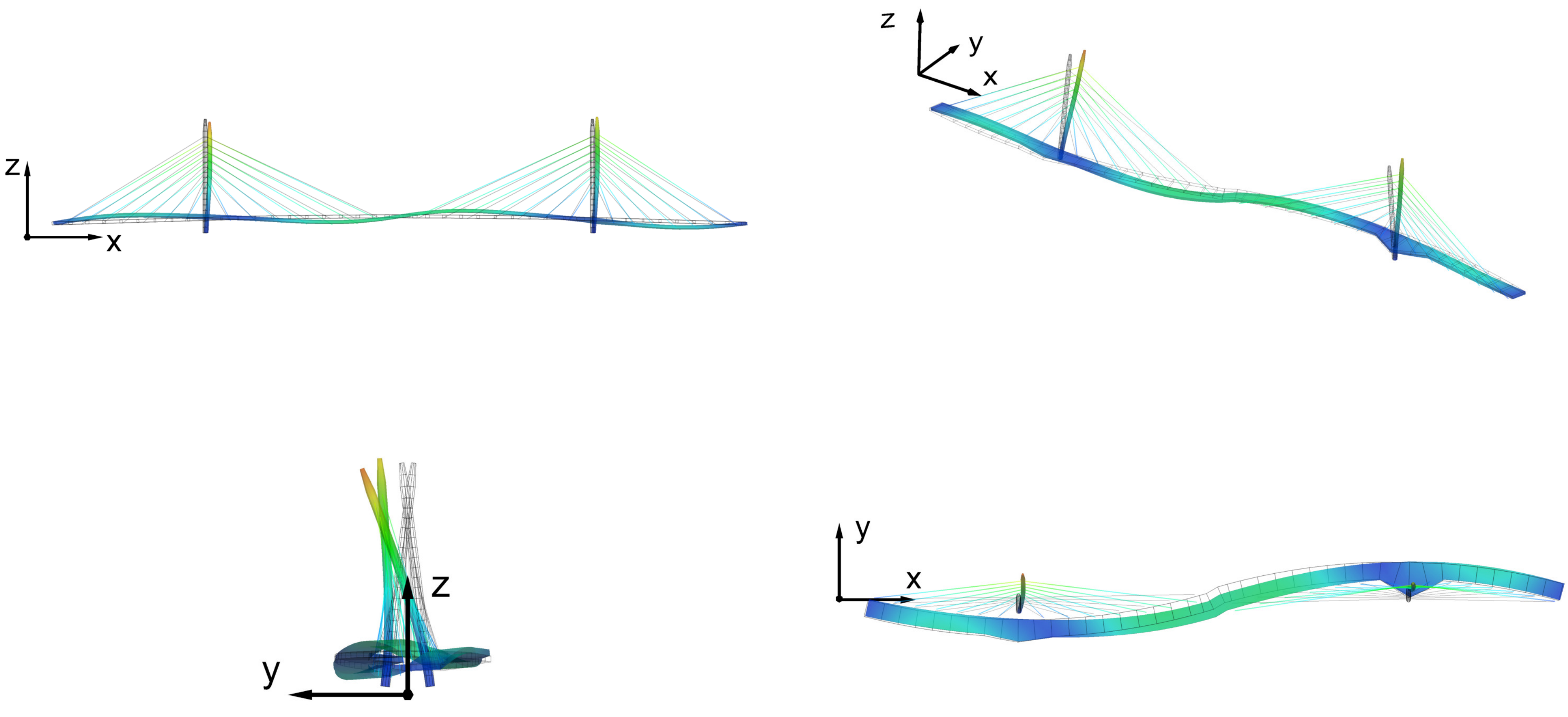
Mode 4, f = 0.644 Hz

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795

Appendix A1-4

Date: September 15, 2022



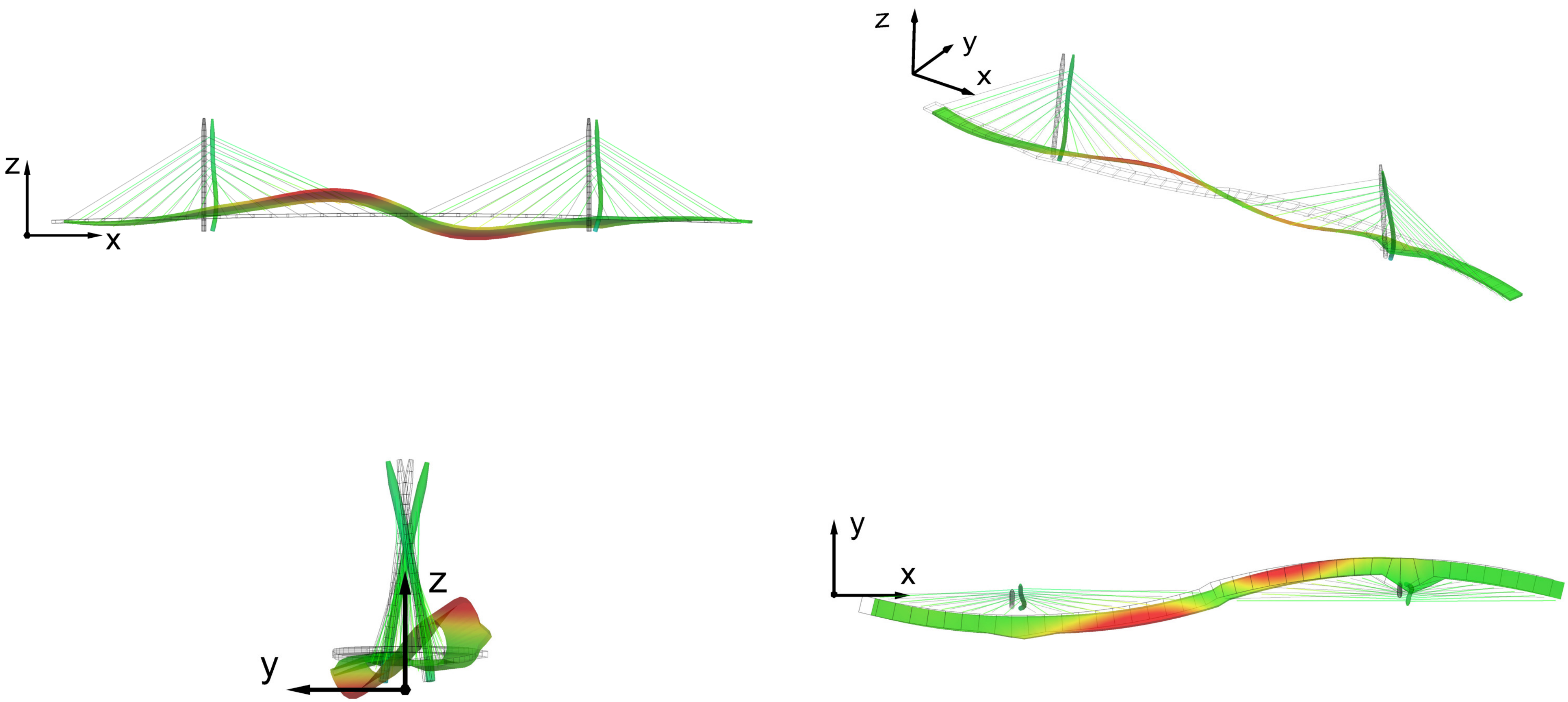
Dynamic Properties - McCallum Park Bridge
Mode 5, f = 0.678 Hz

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795

Appendix A1-5

Date: September 15, 2022



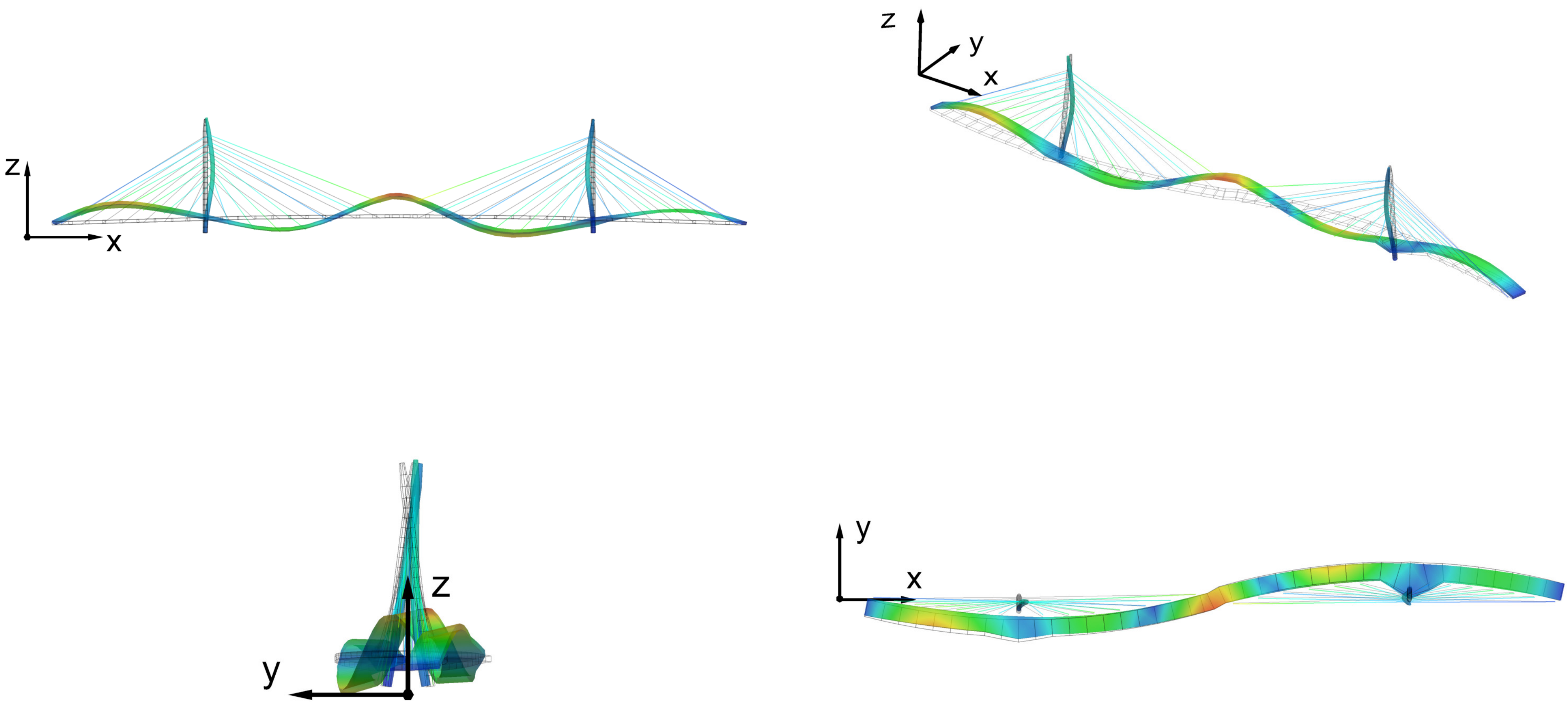
Dynamic Properties - McCallum Park Bridge
Mode 6, f = 0.868 Hz

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795

Appendix A1-6

Date: September 15, 2022



Dynamic Properties - McCallum Park Bridge

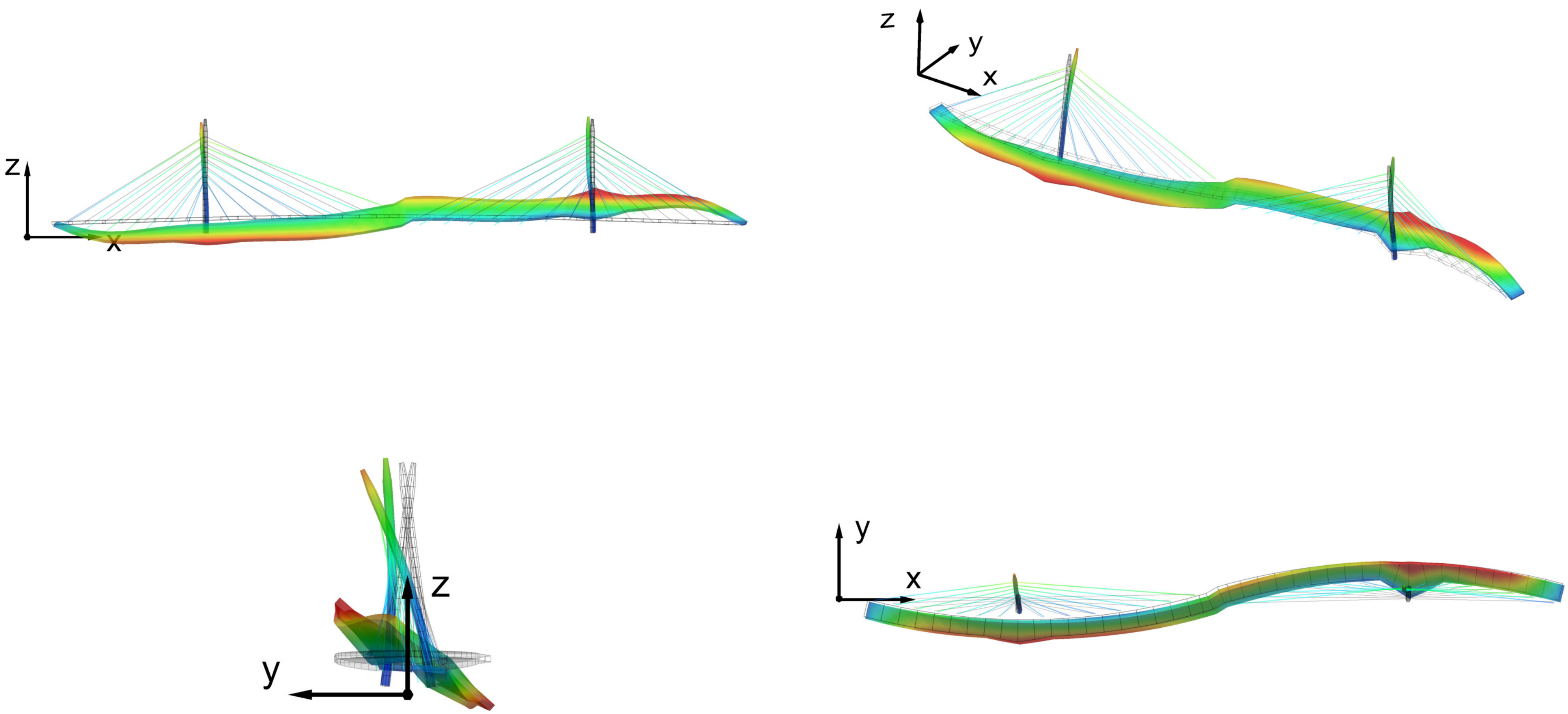
Mode 7, f = 1.154 Hz

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795

Appendix A1-7

Date: September 15, 2022



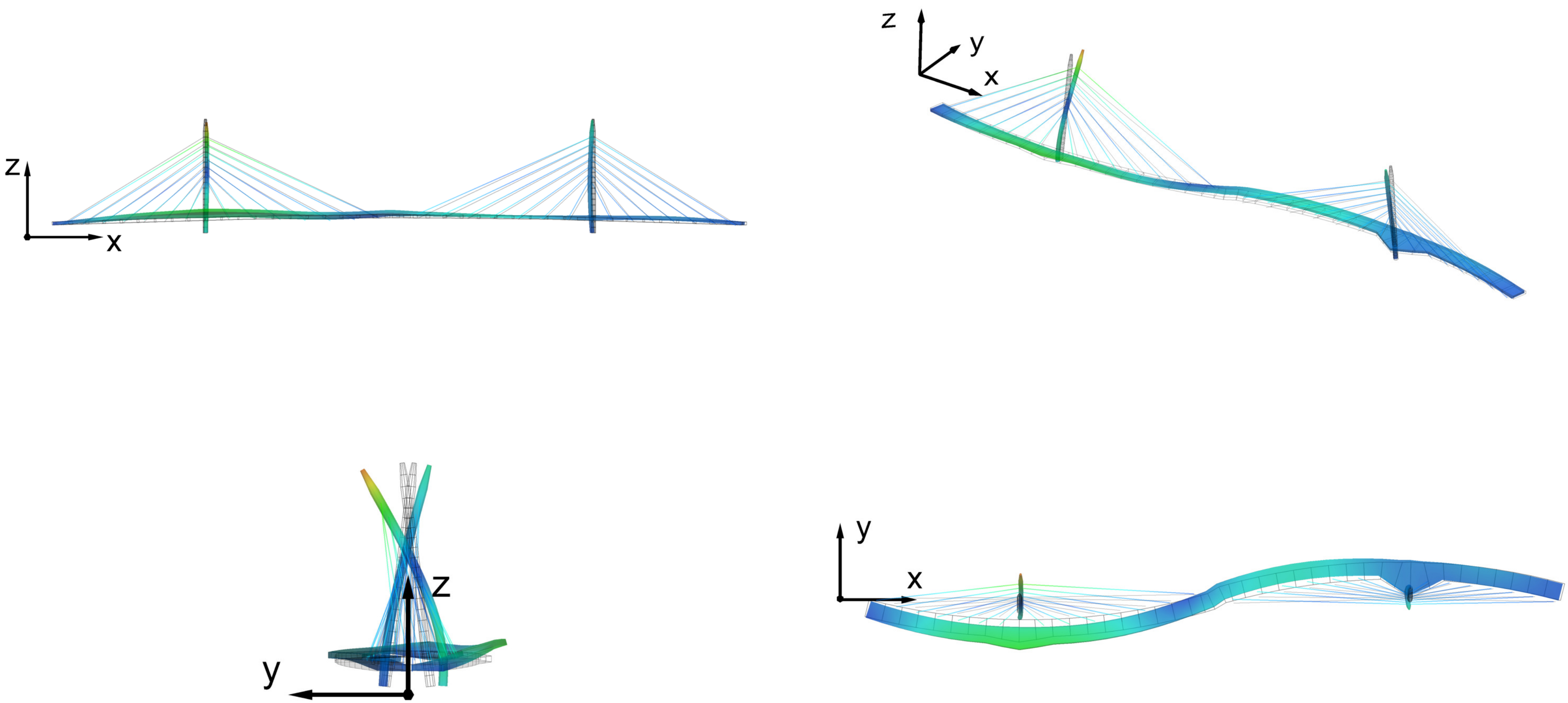
Dynamic Properties - McCallum Park Bridge
Mode 8, f = 1.190 Hz

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795

Appendix A1-8

Date: September 15, 2022



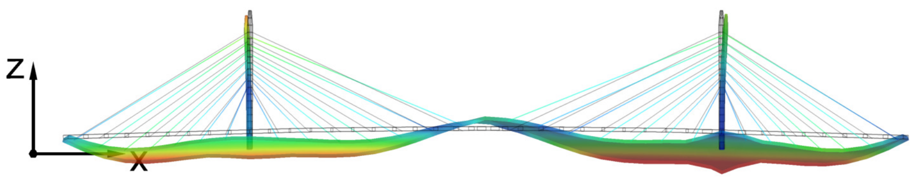
Dynamic Properties - McCallum Park Bridge
Mode 9, f = 1.324 Hz

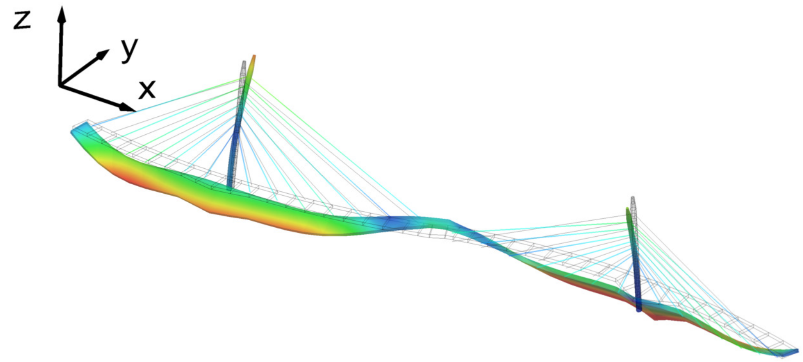
Causeway Pedestrian Bridges, Perth, Australia

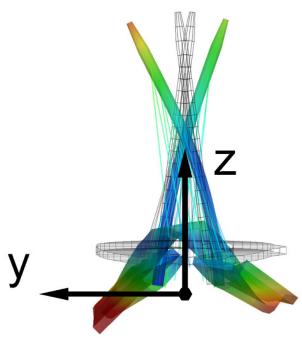
Project #2100795

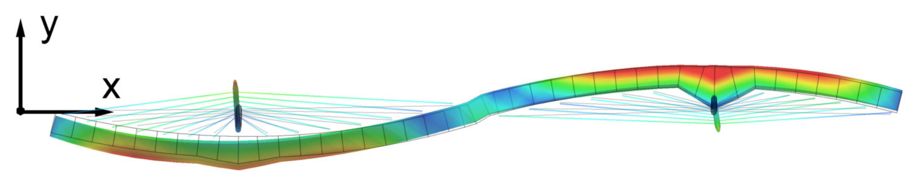
Appendix A1-9

Date: September 15, 2022









Dynamic Properties - McCallum Park Bridge

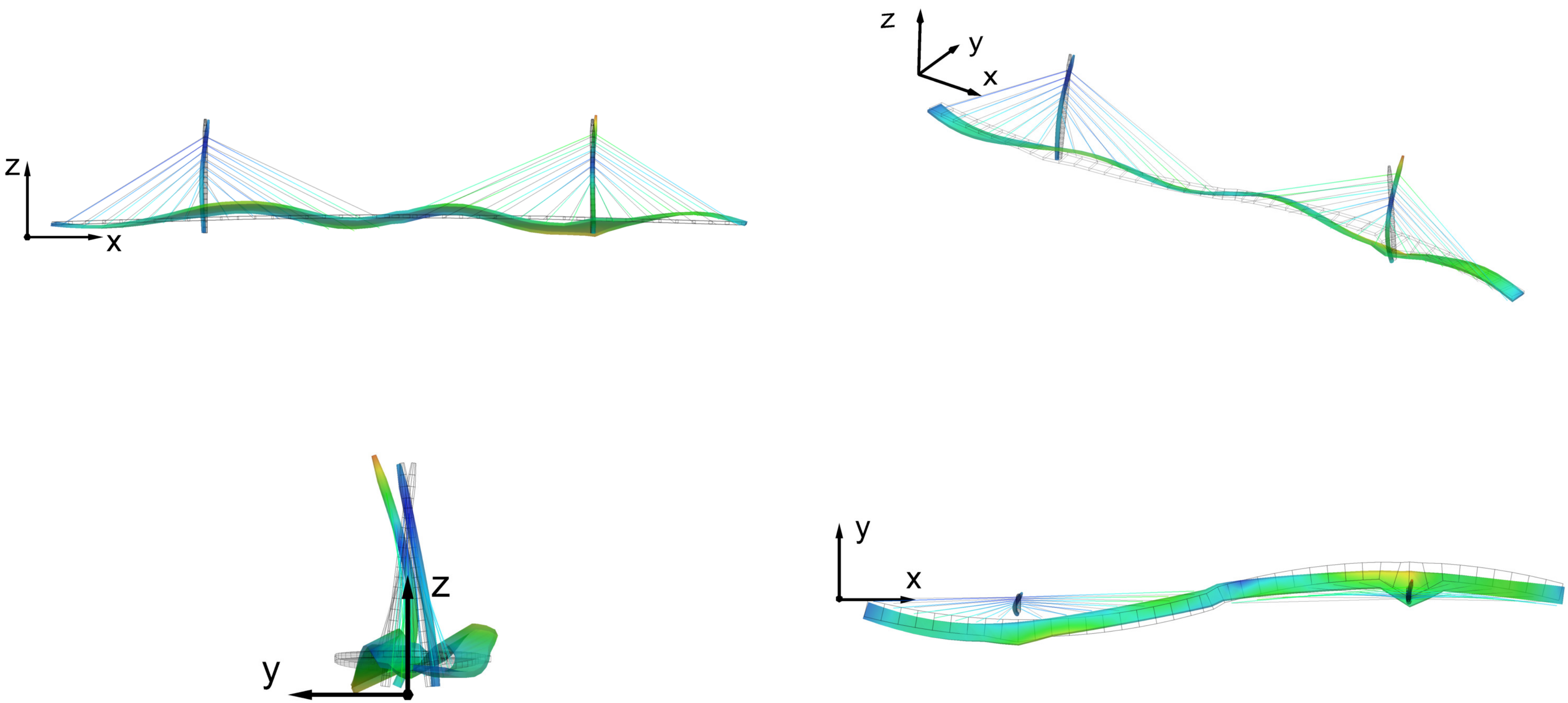
Mode 10, f = 1.400 Hz

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795

Appendix A1-10

Date: September 15, 2022



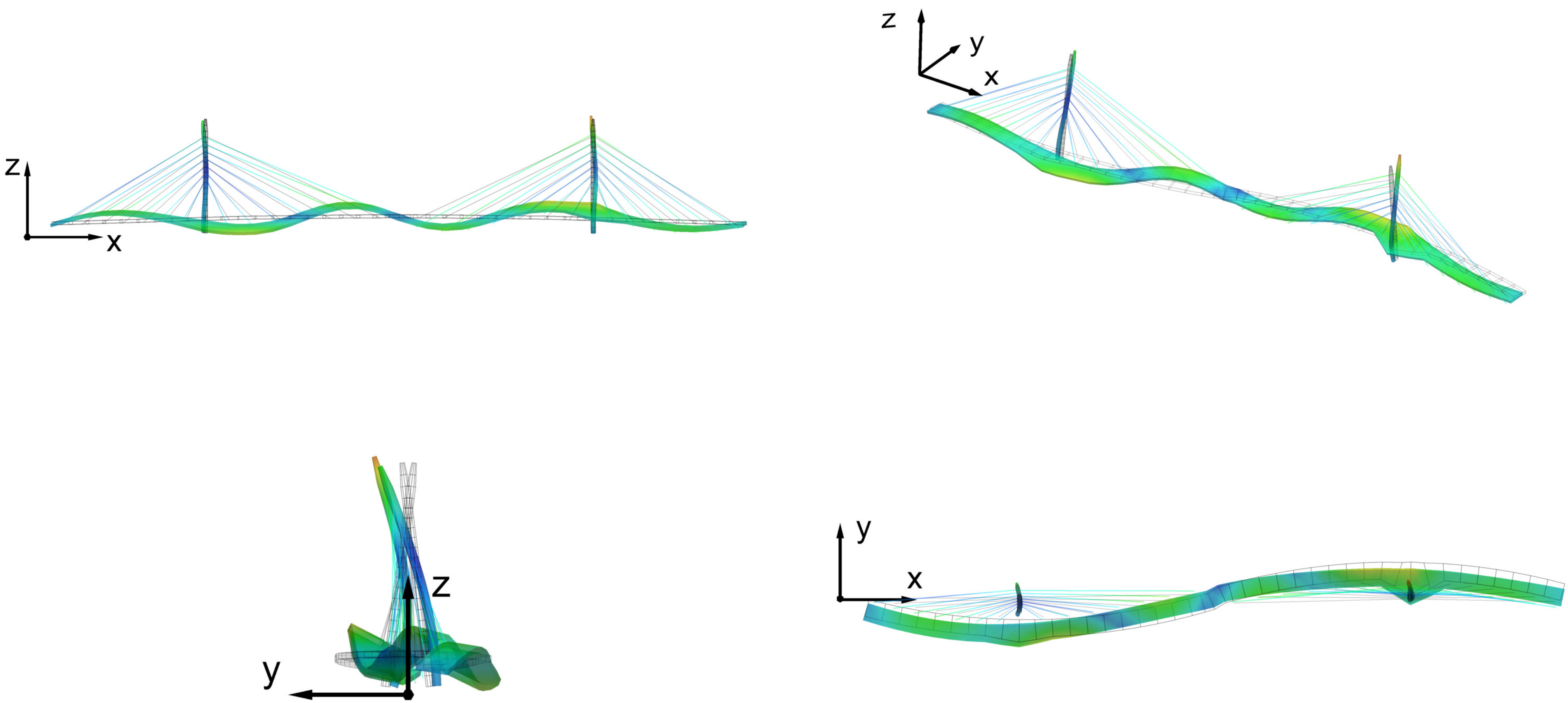
Dynamic Properties - McCallum Park Bridge
Mode 11, f = 1.649 Hz

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795

Appendix A1-11

Date: September 15, 2022



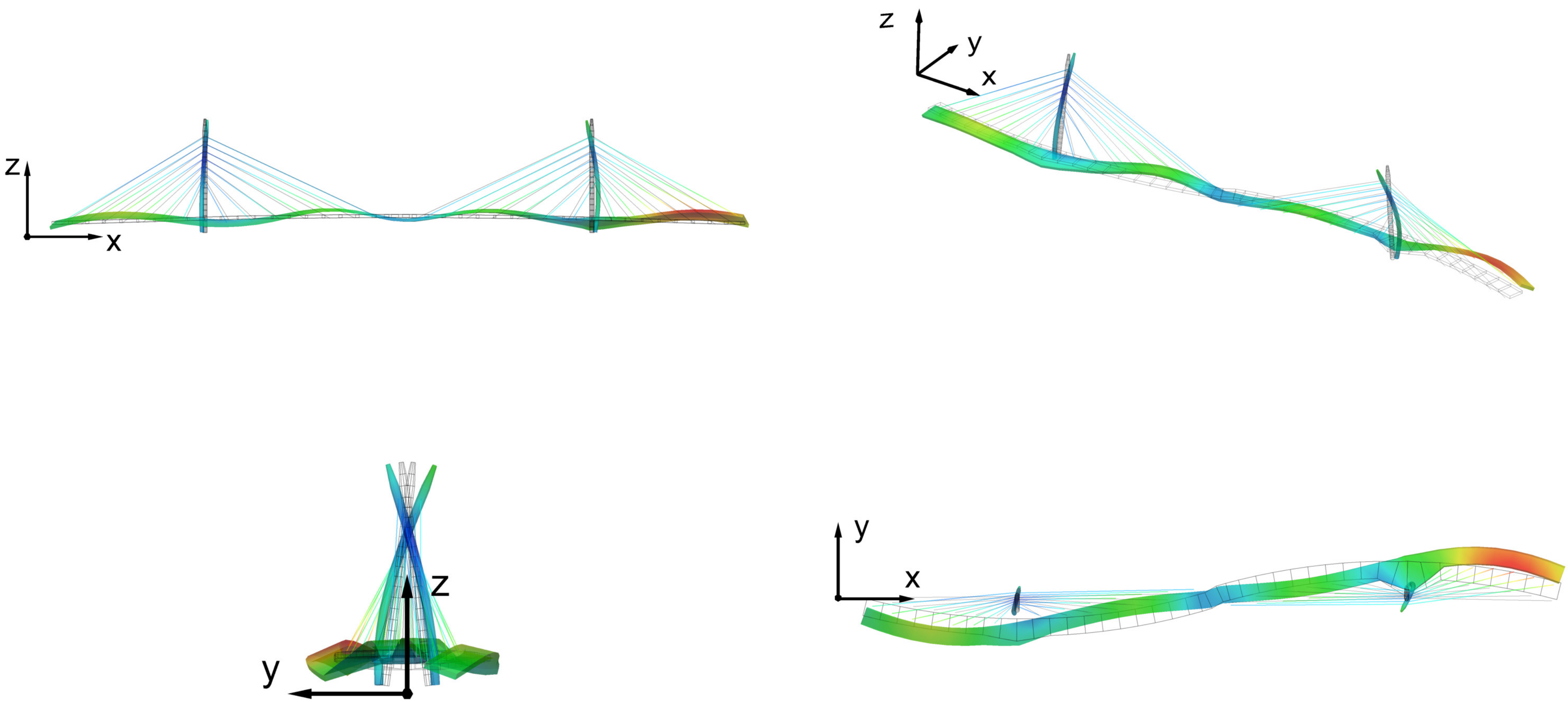
Dynamic Properties - McCallum Park Bridge
Mode 12, f = 1.732 Hz

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795

Appendix A1-12

Date: September 15, 2022



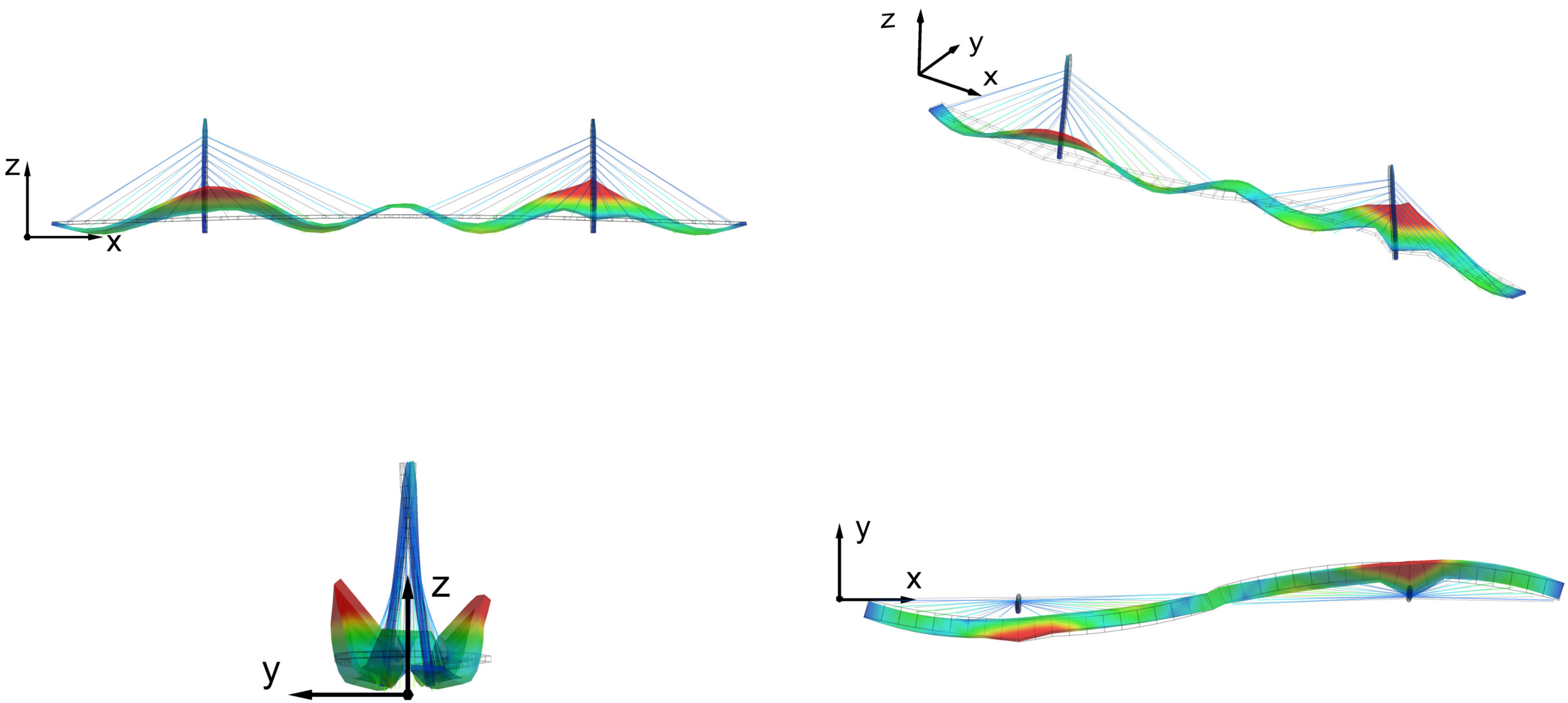
Dynamic Properties - McCallum Park Bridge
Mode 13, f = 1.876 Hz

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795

Appendix A1-13

Date: September 15, 2022



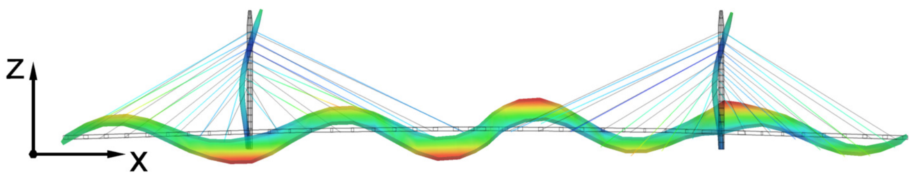
Dynamic Properties - McCallum Park Bridge
Mode 14, f = 2.070 Hz

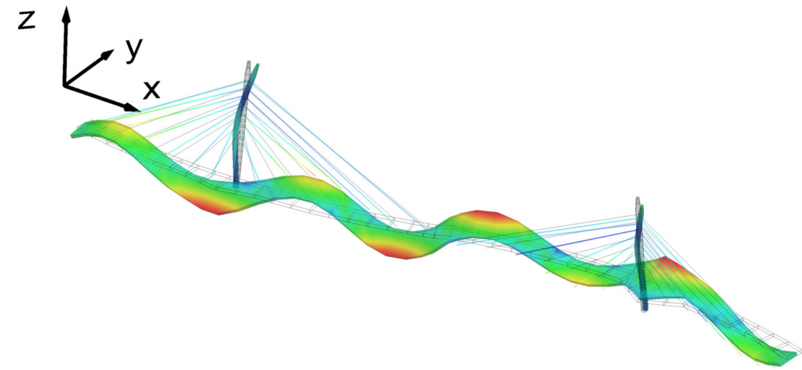
Causeway Pedestrian Bridges, Perth, Australia

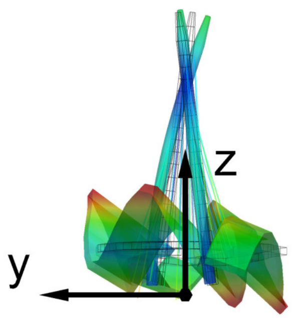
Project #2100795

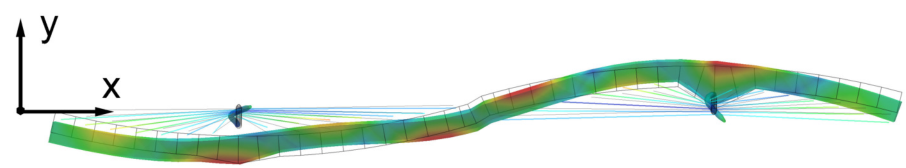
Appendix A1-14

Date: September 15, 2022









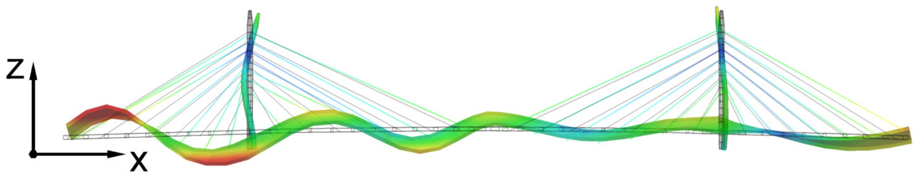
Dynamic Properties - McCallum Park Bridge
Mode 15, f = 2.257 Hz

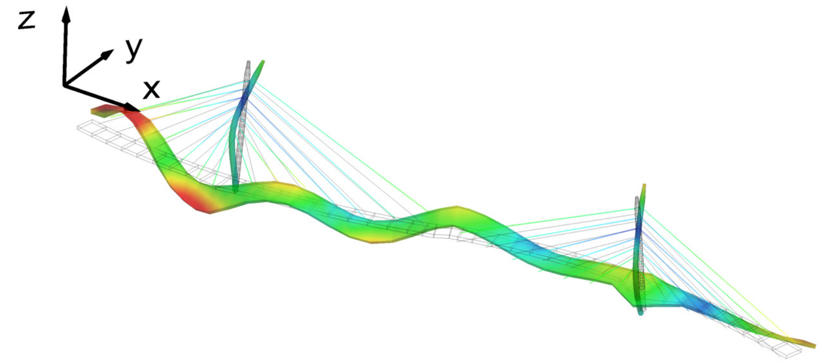
Causeway Pedestrian Bridges, Perth, Australia

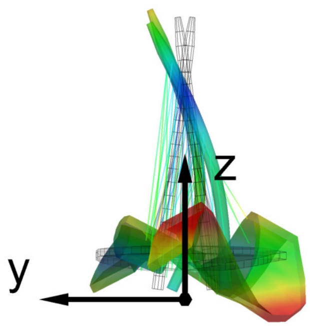
Project #2100795

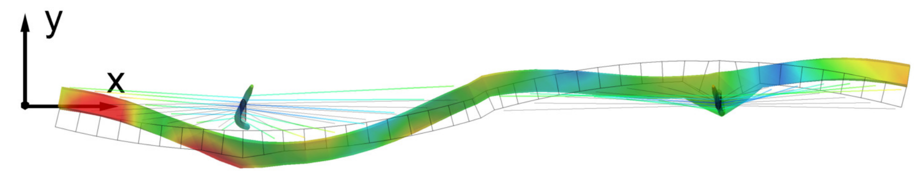
Appendix A1-15

Date: September 15, 2022

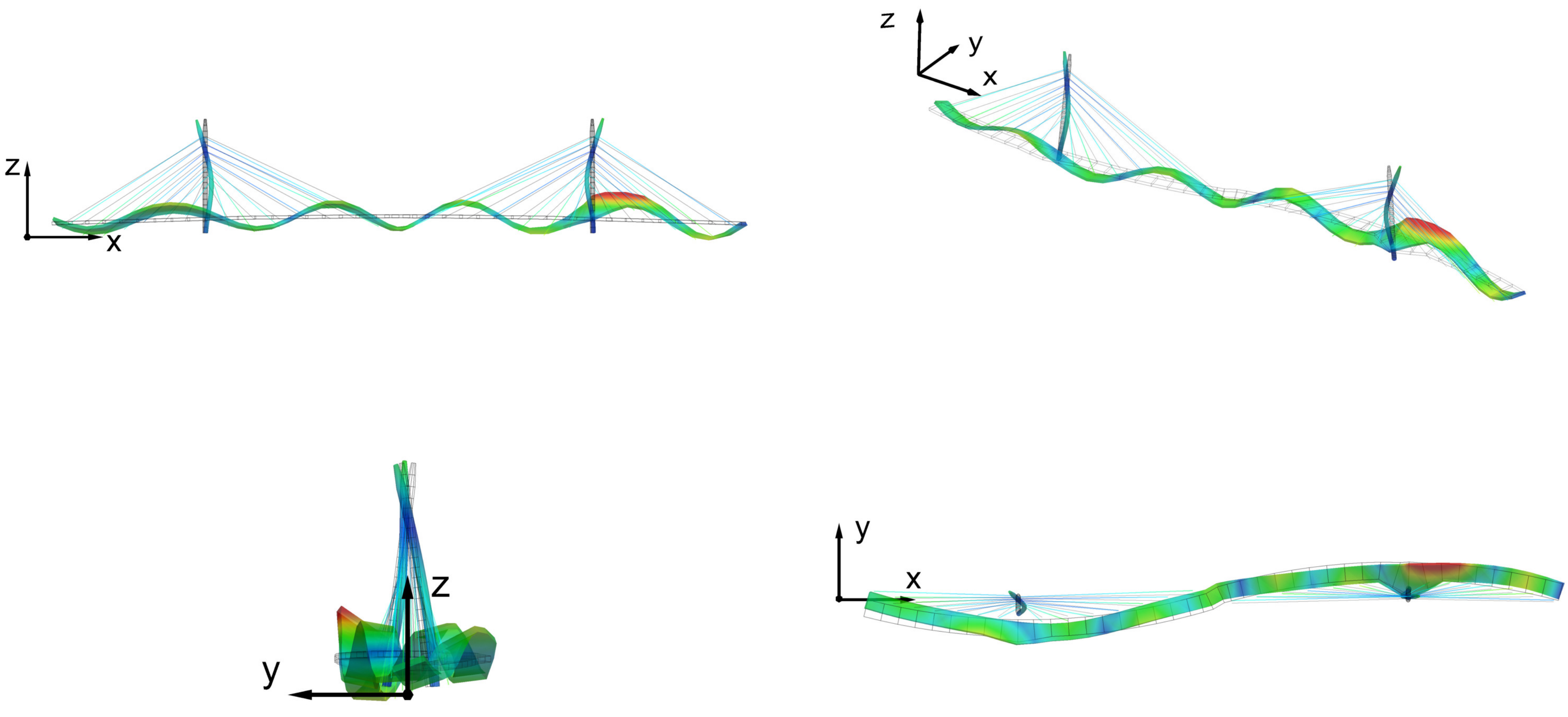








Dynamic Properties - McCallum Park Bridge Mode 16, f = 2.561 Hz Causeway Pedestrian Bridges, Perth, Australia — Project #2100795	Appendix A1-16 Date: September 15, 2022	RWDI



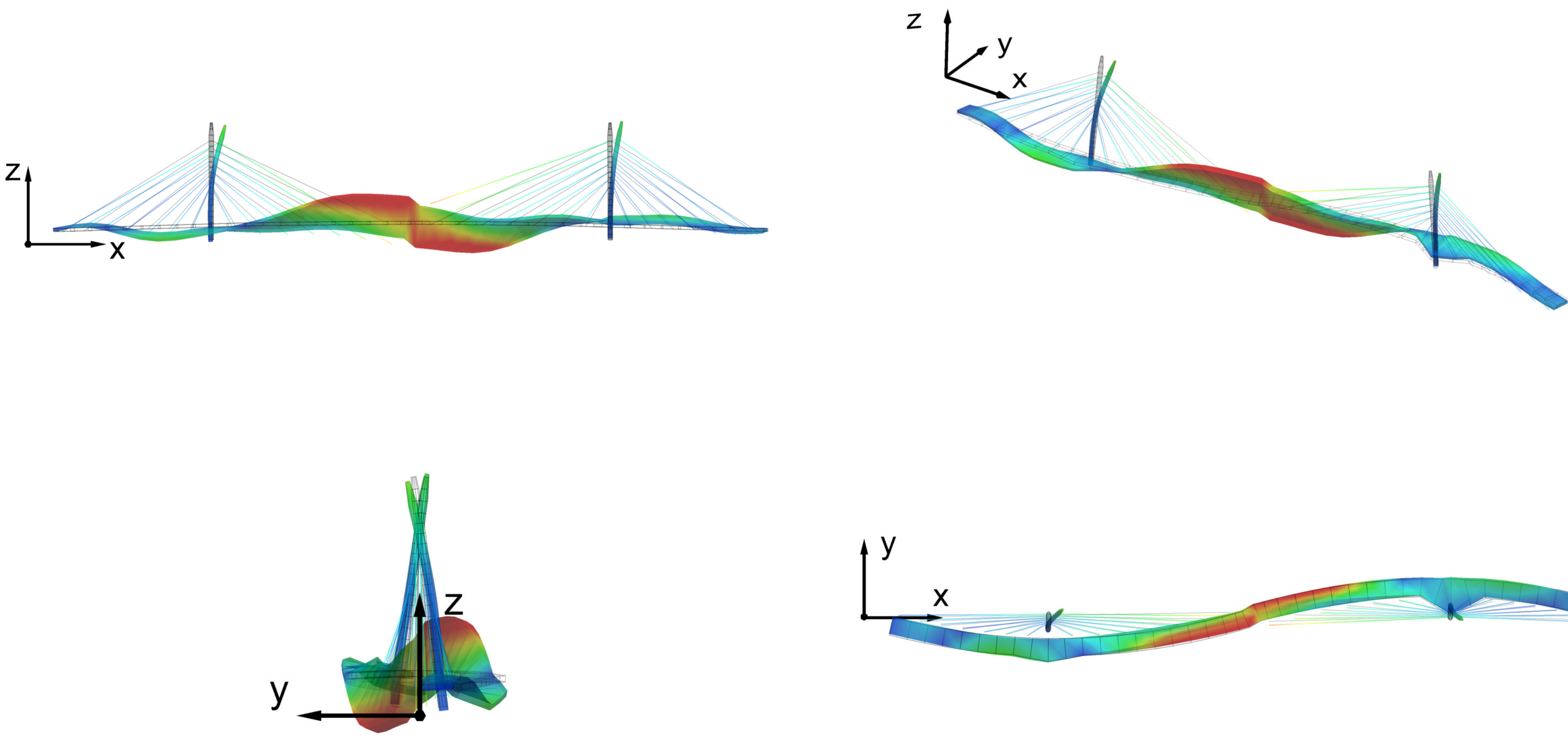
Dynamic Properties - McCallum Park Bridge
Mode 17, f = 2.671 Hz

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795

Appendix A1-17

Date: September 15, 2022



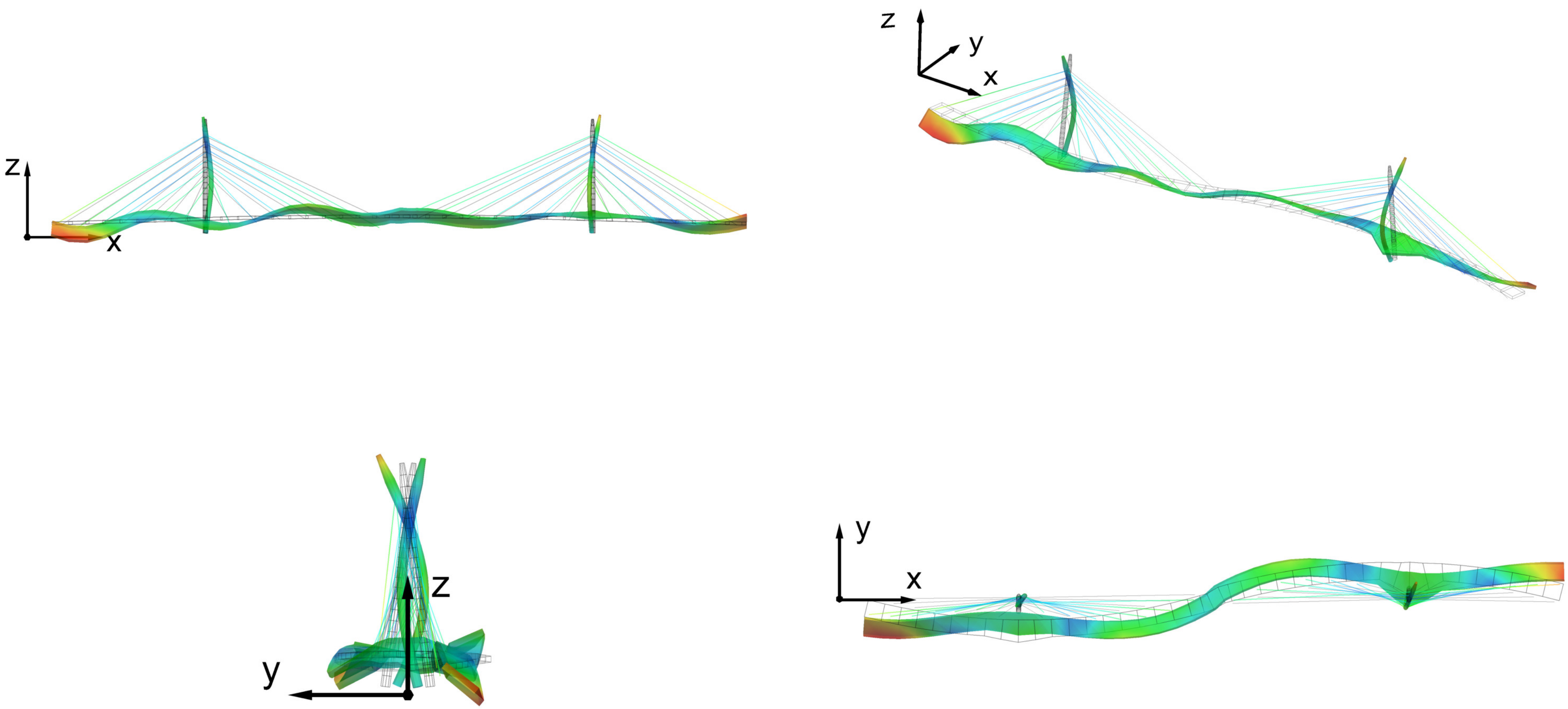
Dynamic Properties - McCallum Park Bridge
Mode 18, f = 2.960 Hz

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795

Appendix A1-18

Date: September 15, 2022



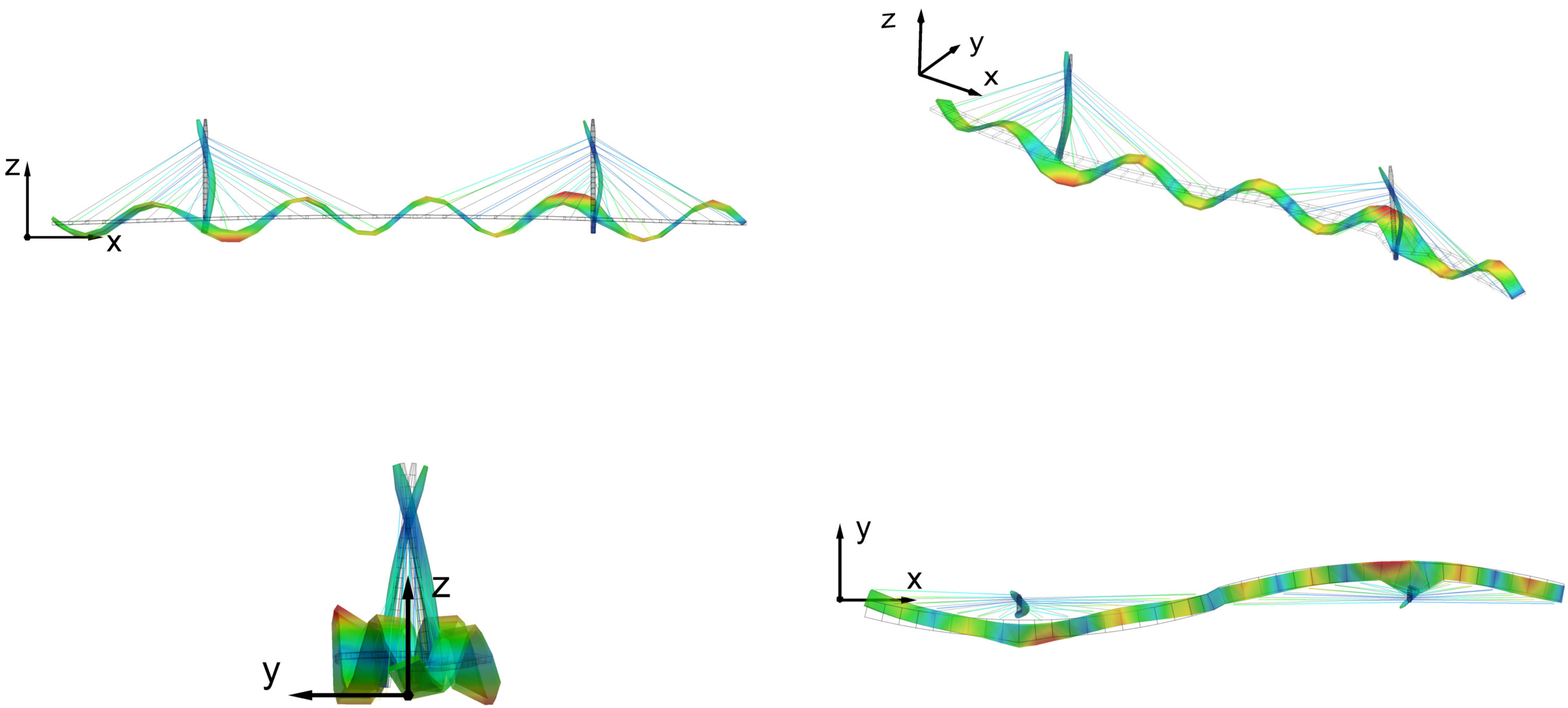
Dynamic Properties - McCallum Park Bridge
Mode 19, f = 3.069 Hz

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795

Appendix A1-19

Date: September 15, 2022



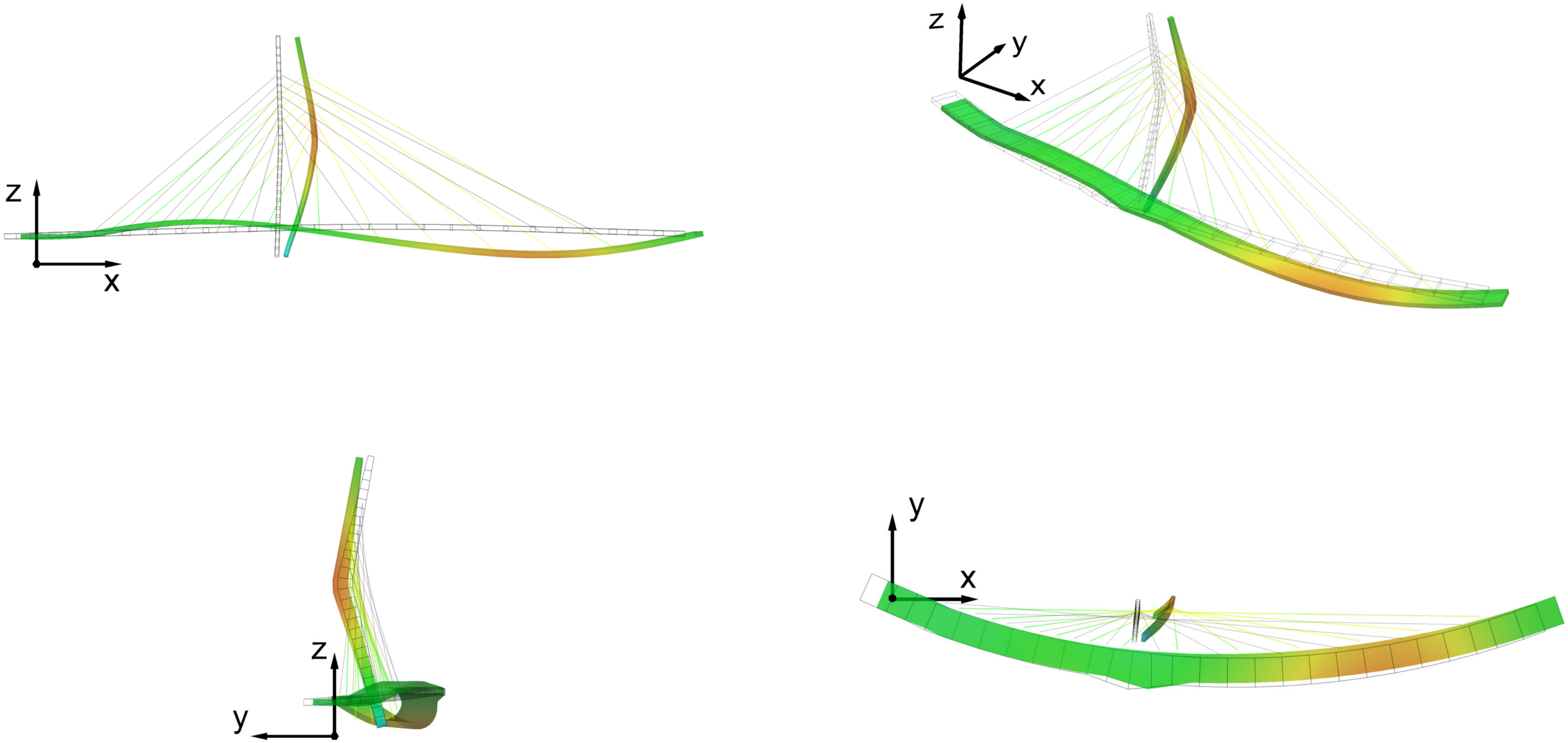
Dynamic Properties - McCallum Park Bridge
Mode 20, f = 3.245 Hz

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795

Appendix A1-20

Date: September 15, 2022



Dynamic Properties - Point Fraser Bridge

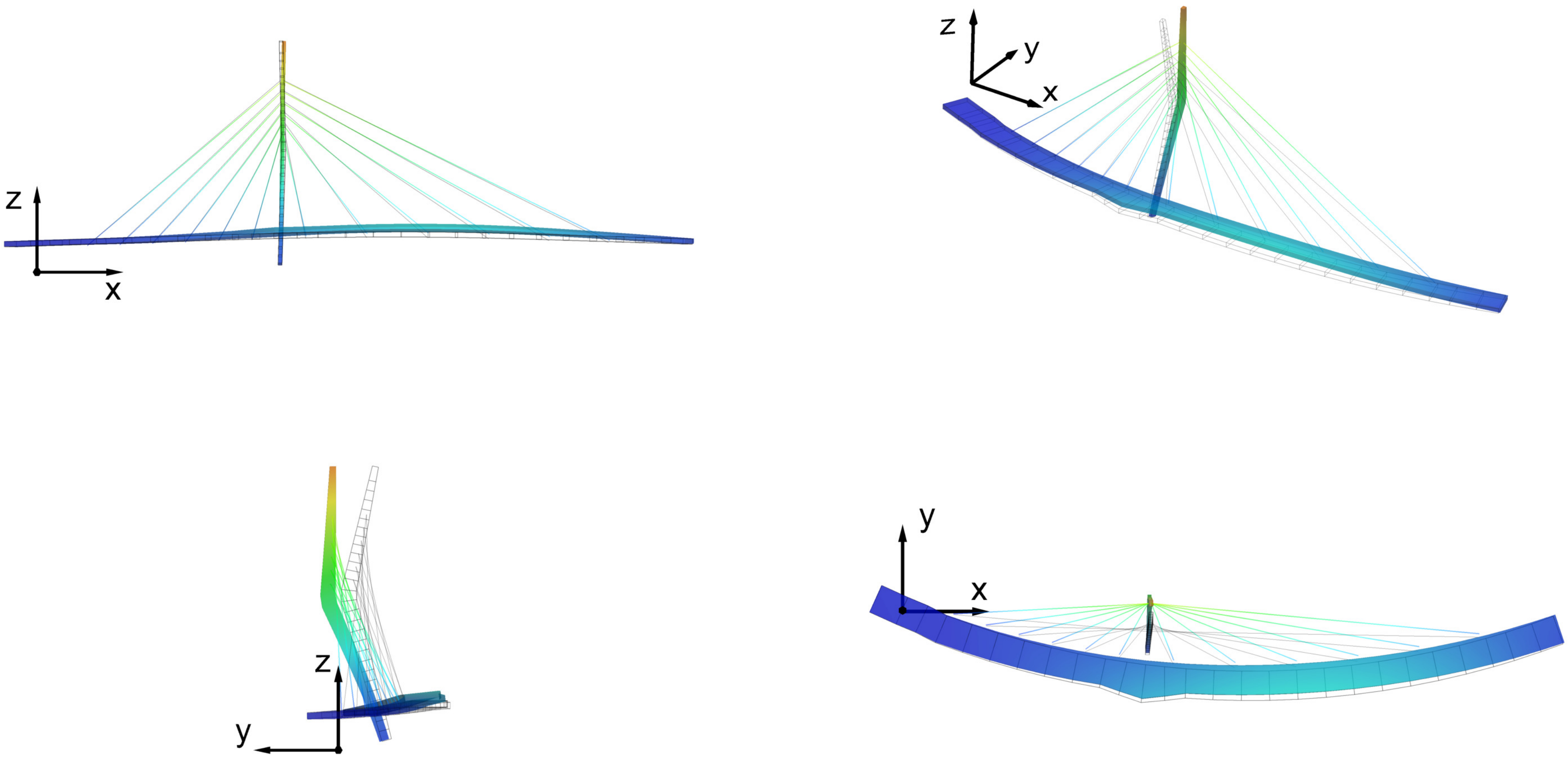
Mode 1, f = 0.552 Hz

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795

Appendix A2-1

Date: September 15, 2022



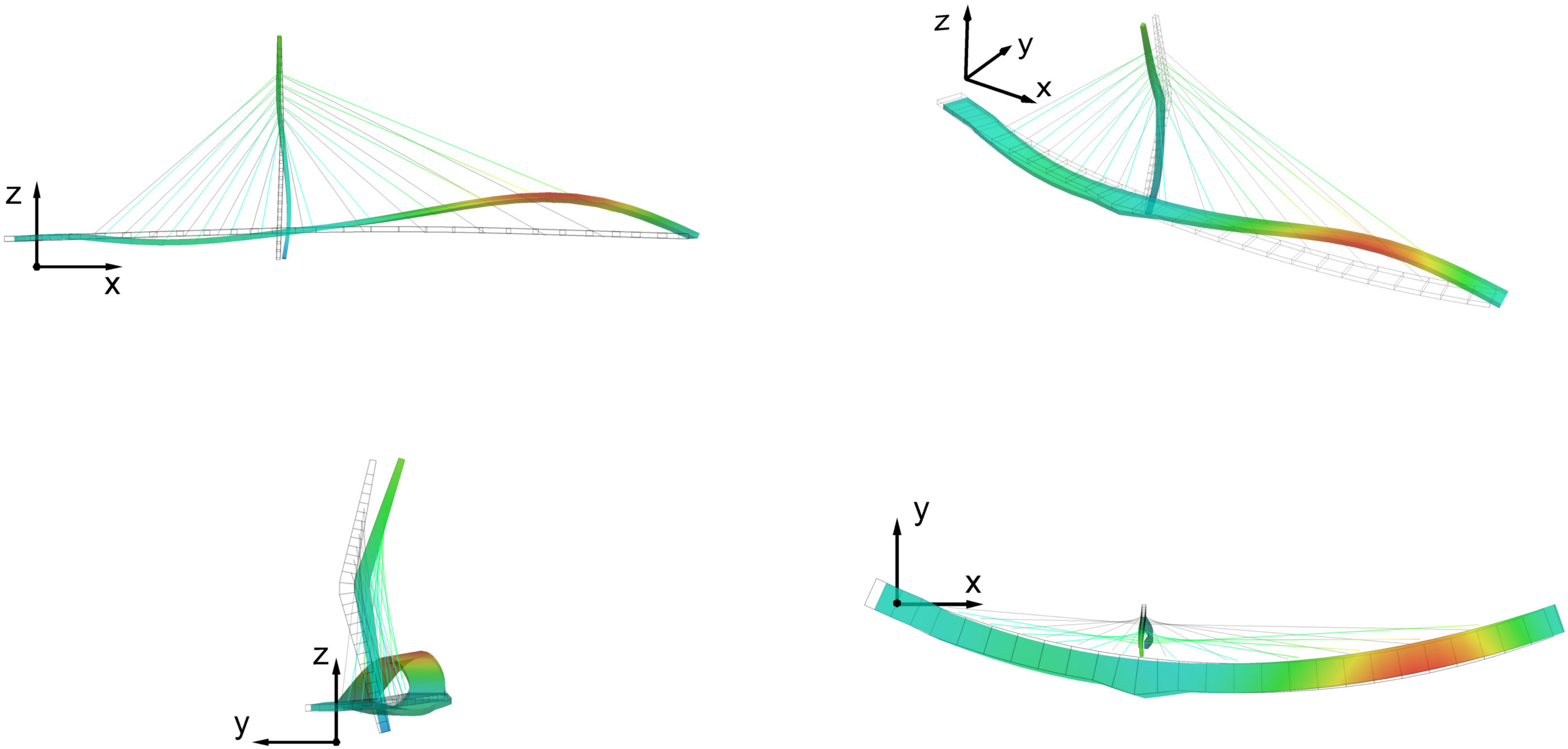
Dynamic Properties - Point Fraser Bridge
Mode 2, f = 0.618 Hz

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795

Appendix A2-2

Date: September 15, 2022



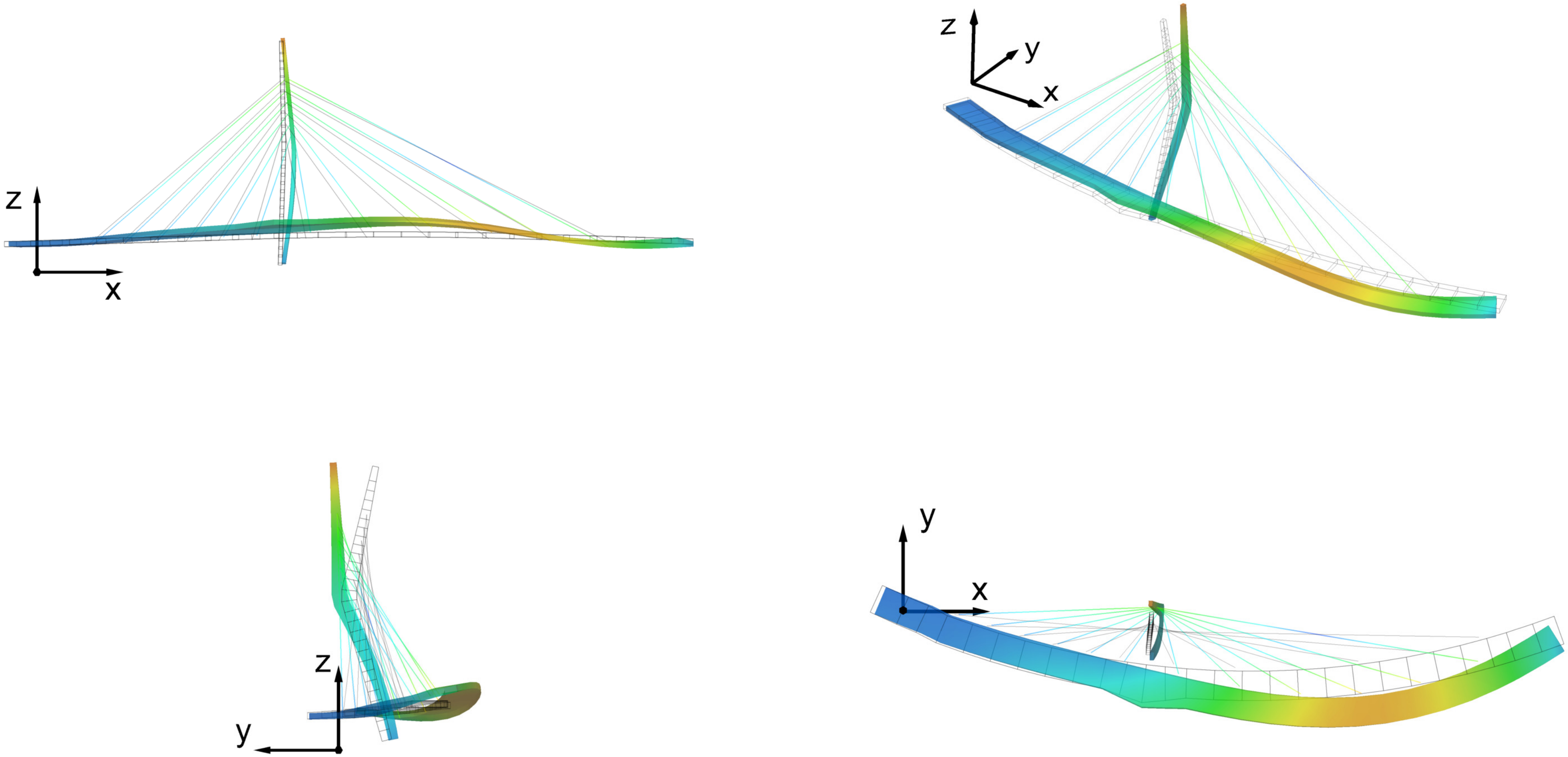
Dynamic Properties - Point Fraser Bridge
Mode 3, f = 0.693 Hz

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795

Appendix A2-3

Date: September 15, 2022



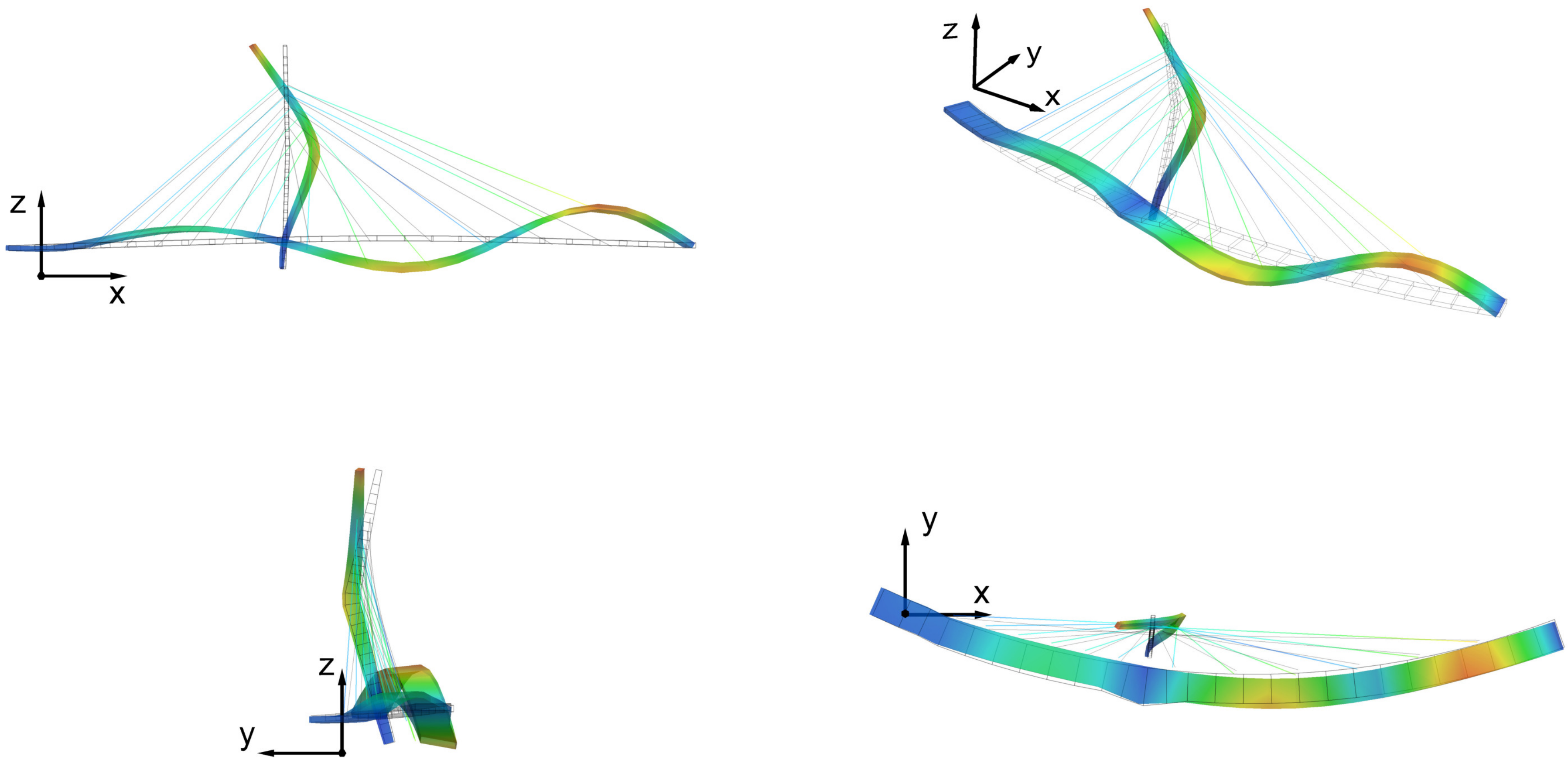
Dynamic Properties - Point Fraser Bridge
Mode 4, f = 1.053 Hz

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795

Appendix A2-4

Date: September 15, 2022



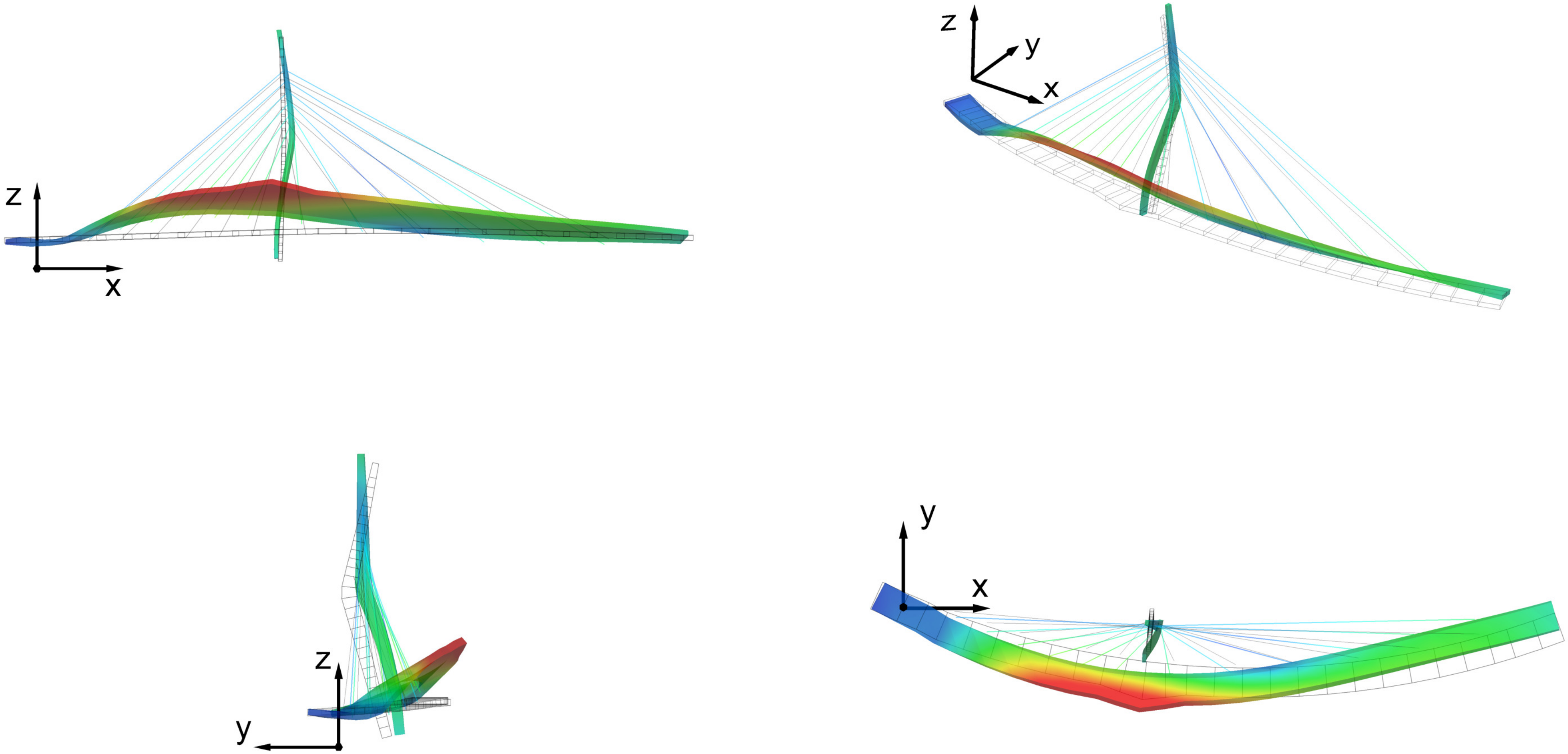
Dynamic Properties - Point Fraser Bridge
Mode 5, f = 1.375 Hz

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795

Appendix A2-5

Date: September 15, 2022



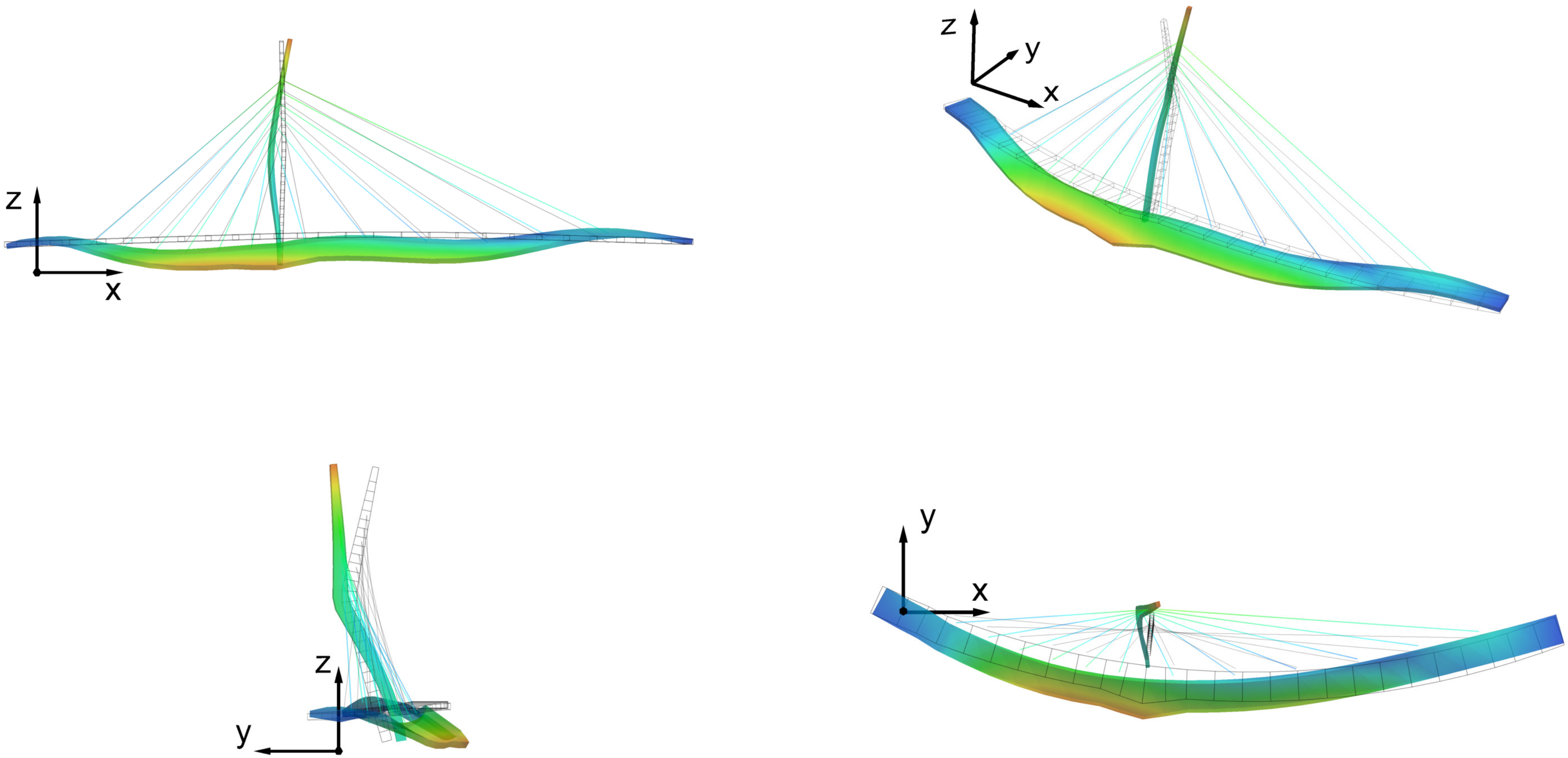
Dynamic Properties - Point Fraser Bridge
Mode 6, f = 1.694 Hz

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795

Appendix A2-6

Date: September 15, 2022



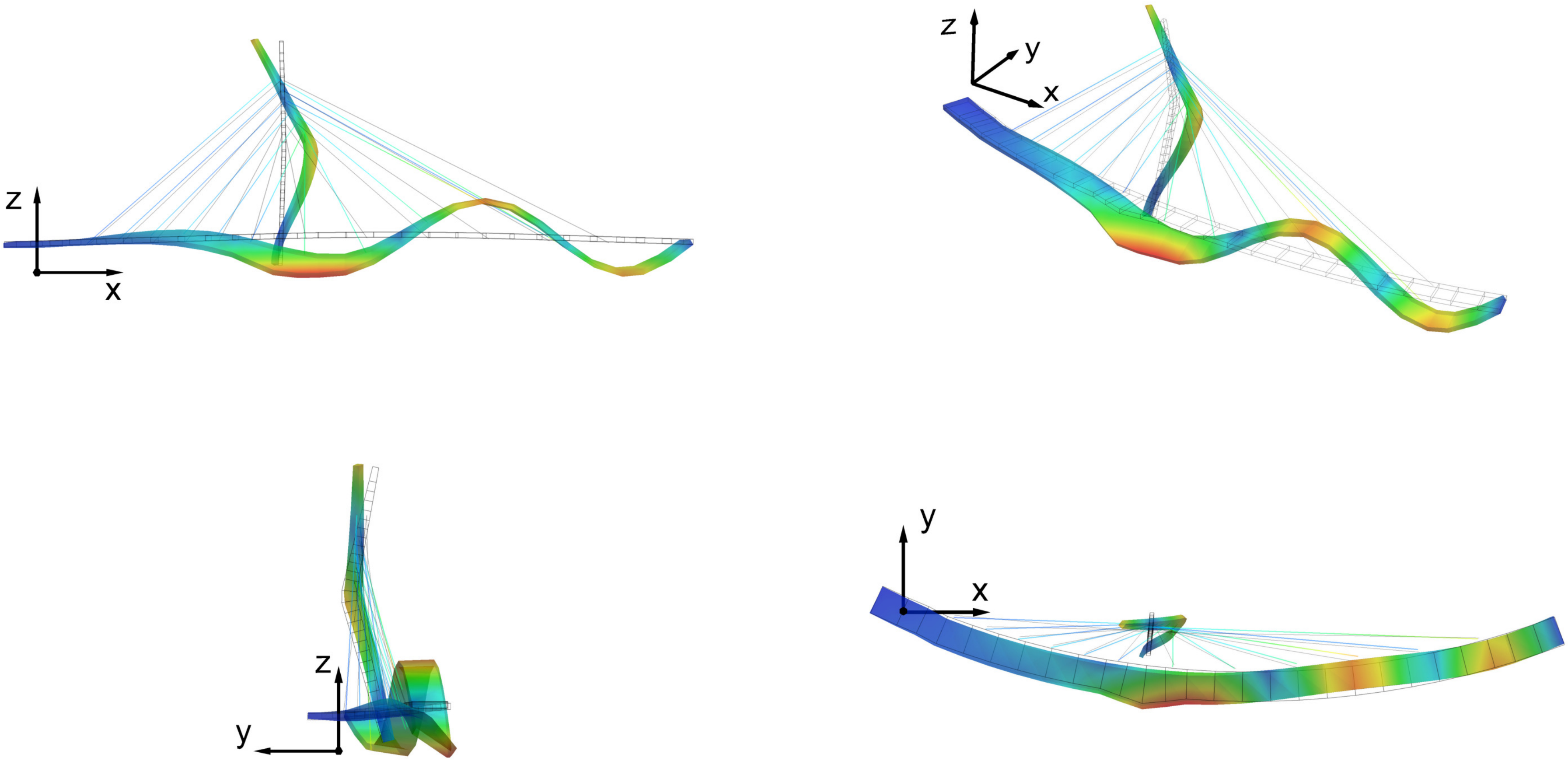
Dynamic Properties - Point Fraser Bridge
Mode 7, f = 1.932 Hz

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795

Appendix A2-7

Date: September 15, 2022



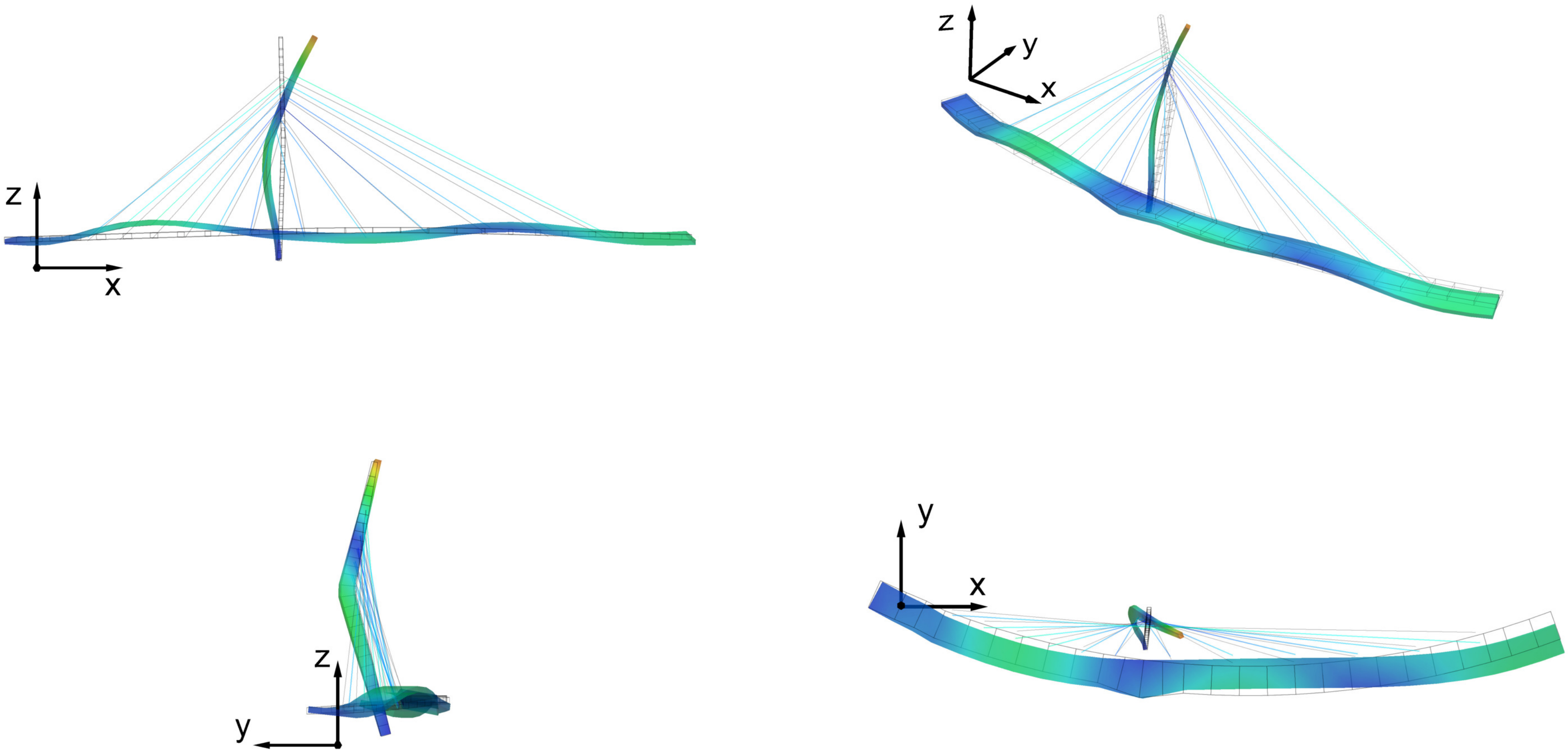
Dynamic Properties - Point Fraser Bridge
Mode 8, f = 2.304 Hz

Appendix A2-8

Date: September 15, 2022

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795



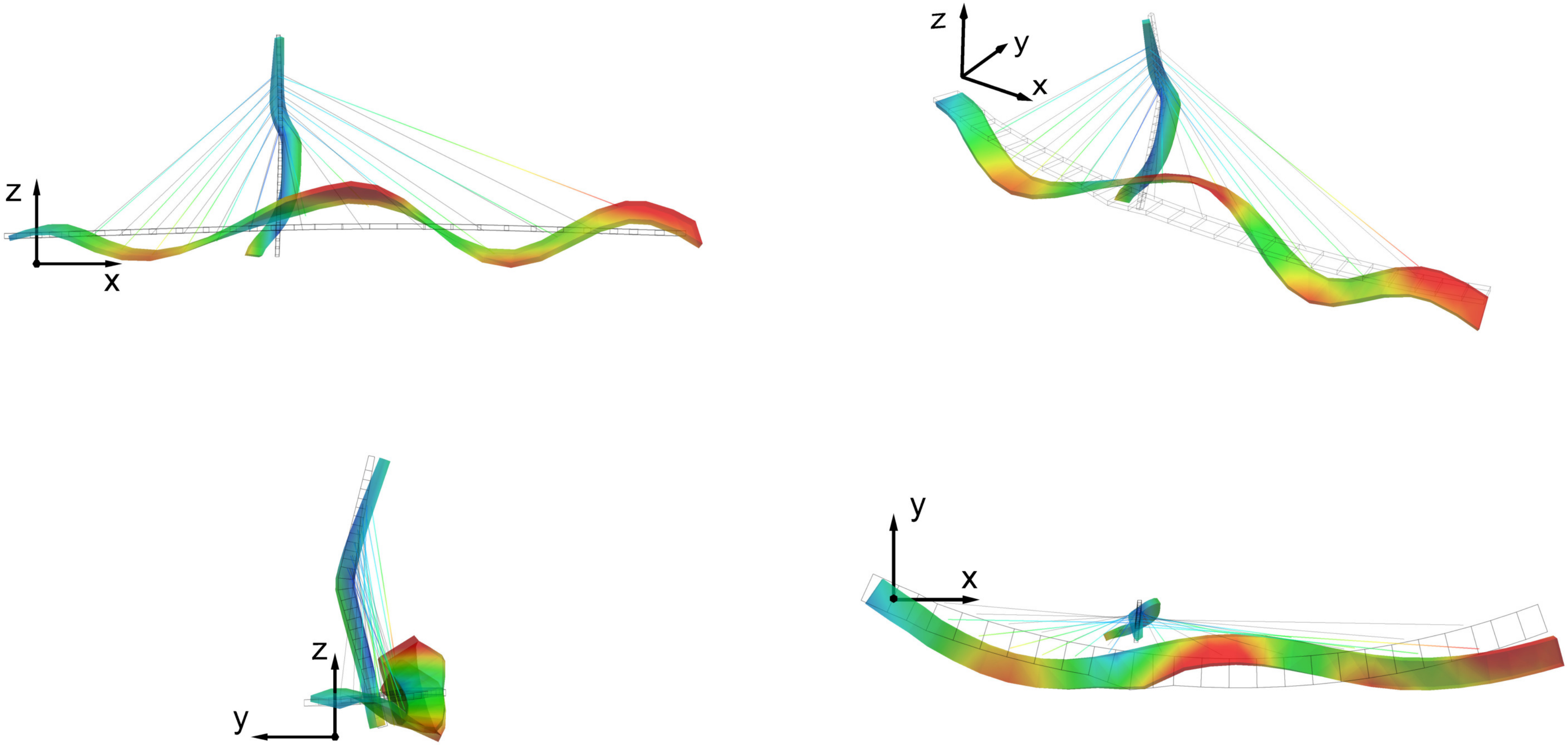
Dynamic Properties - Point Fraser Bridge
Mode 9, f = 2.548 Hz

Appendix A2-9

Date: September 15, 2022

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795



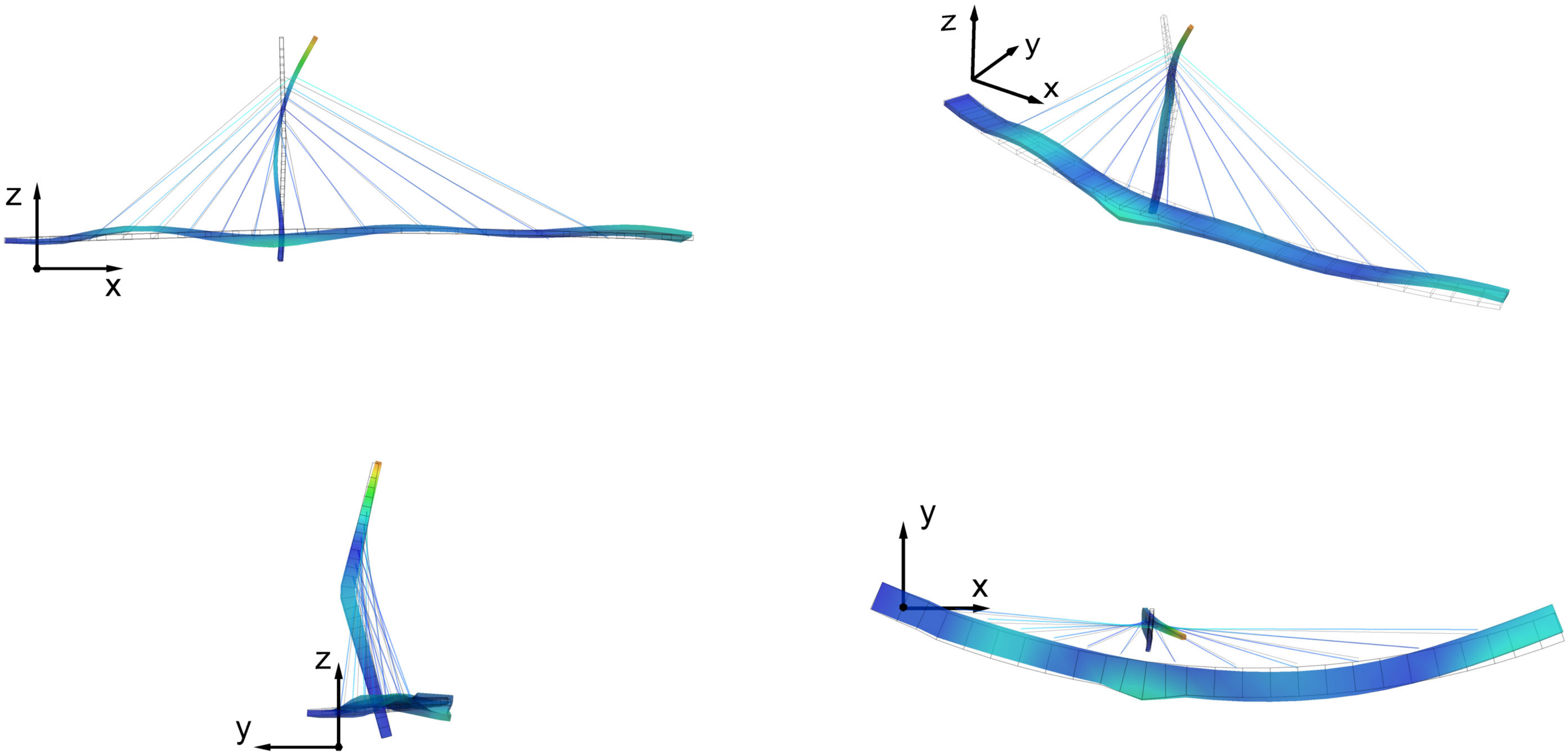
Dynamic Properties - Point Fraser Bridge
Mode 10, f = 2.636 Hz

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795

Appendix A2-10

Date: September 15, 2022



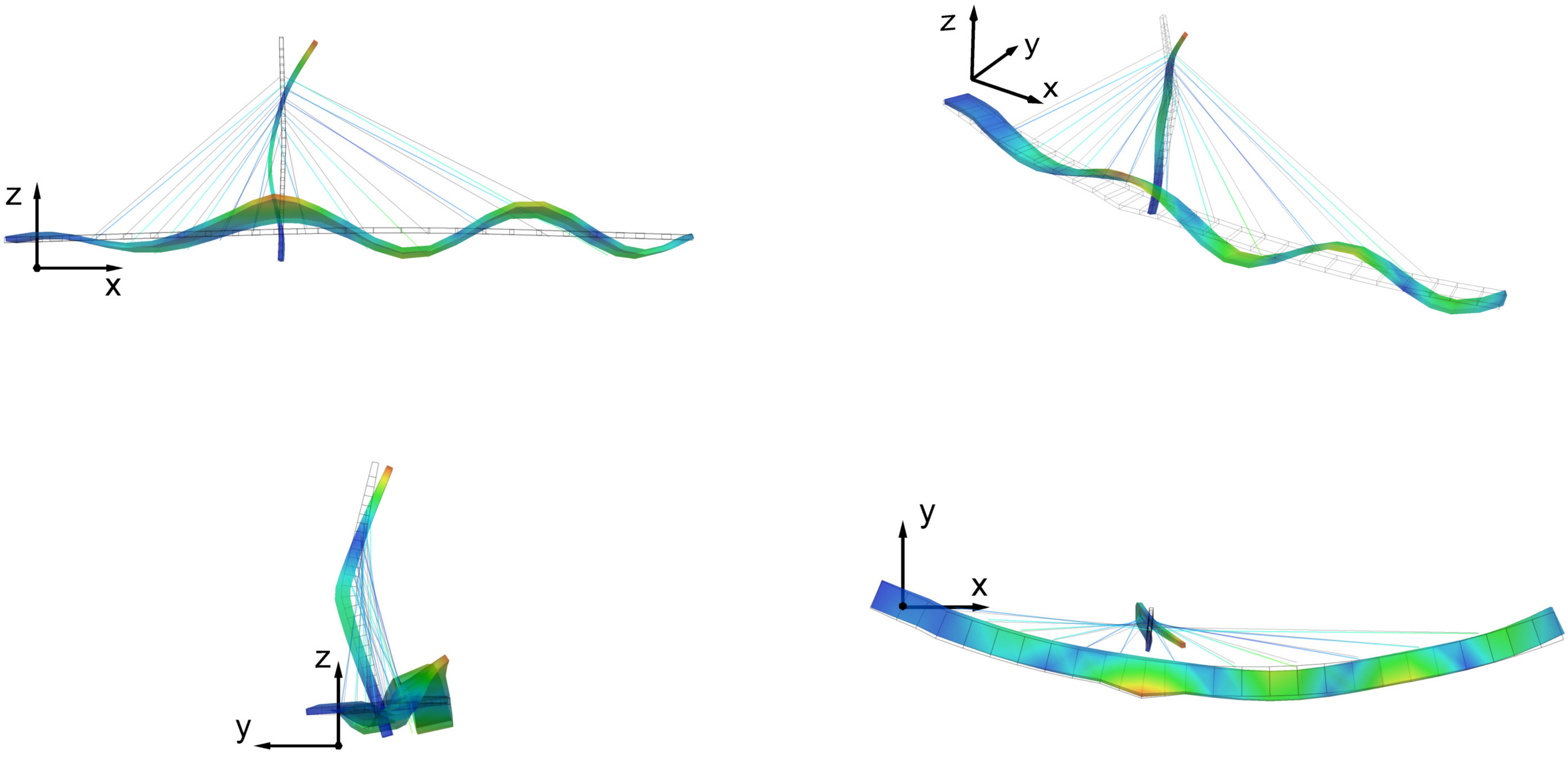
Dynamic Properties - Point Fraser Bridge
Mode 11, f = 3.102 Hz

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795

Appendix A2-11

Date: September 15, 2022



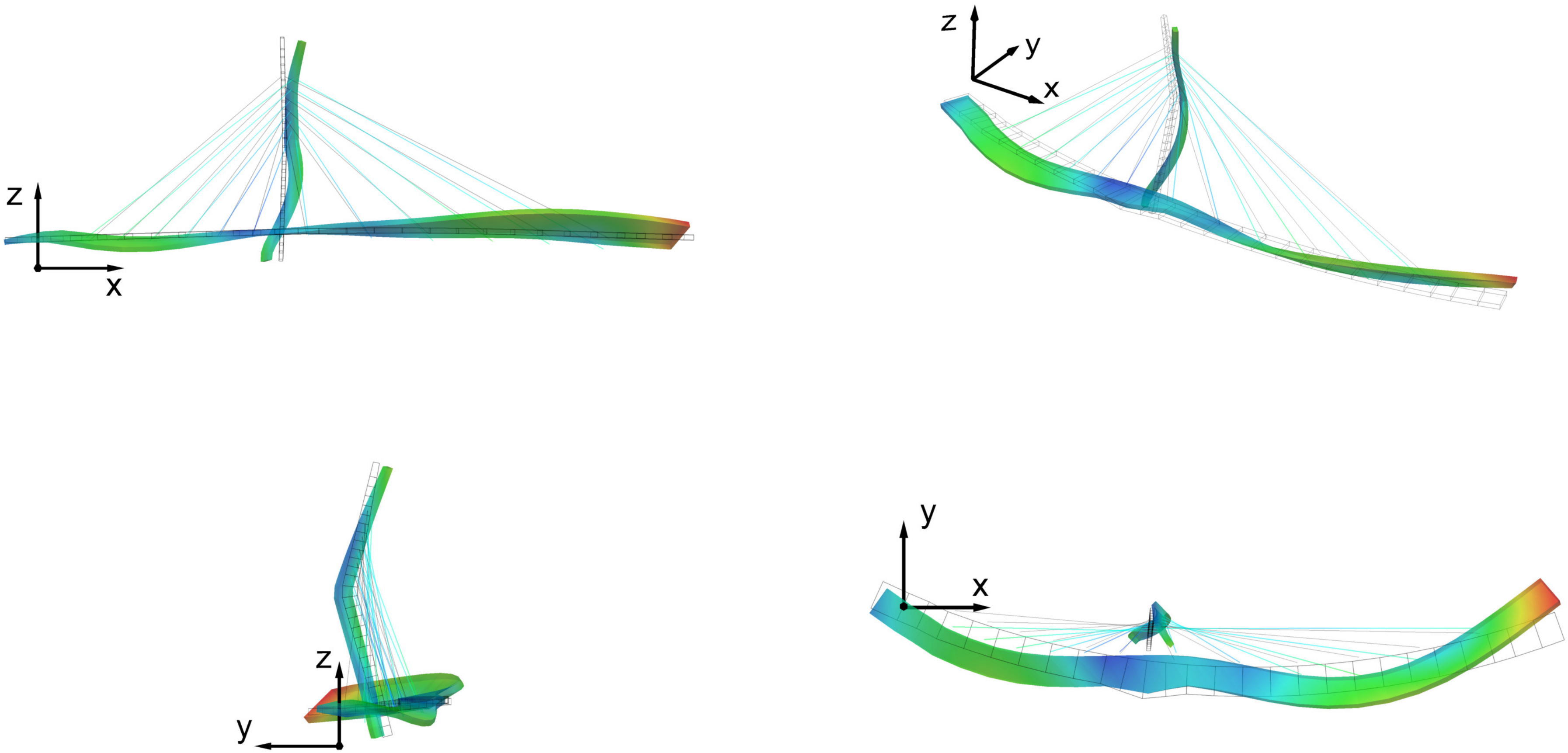
Dynamic Properties - Point Fraser Bridge
Mode 12, f = 3.280 Hz

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795

Appendix A2-12

Date: September 15, 2022



Dynamic Properties - Point Fraser Bridge

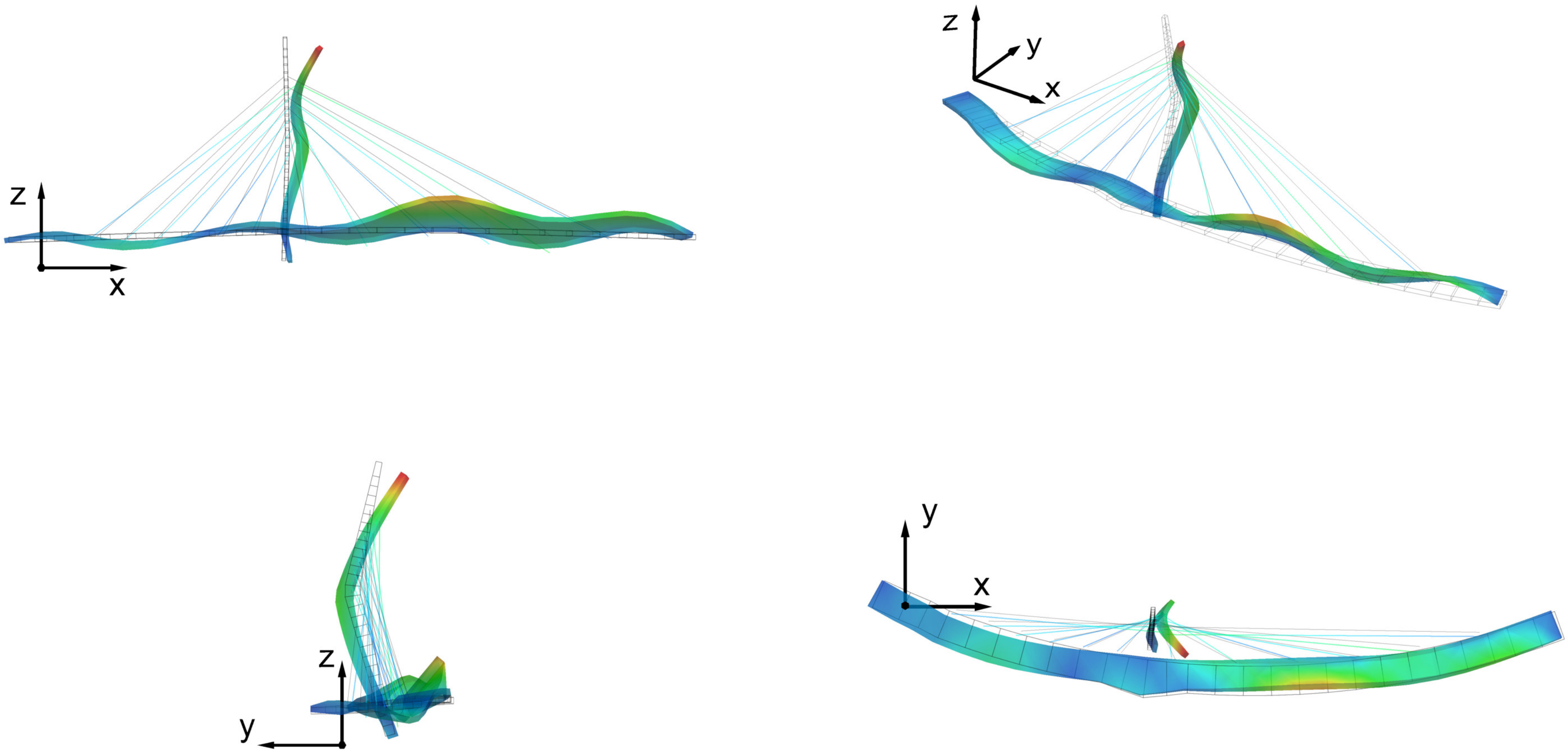
Mode 13, f = 3.595 Hz

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795

Appendix A2-13

Date: September 15, 2022



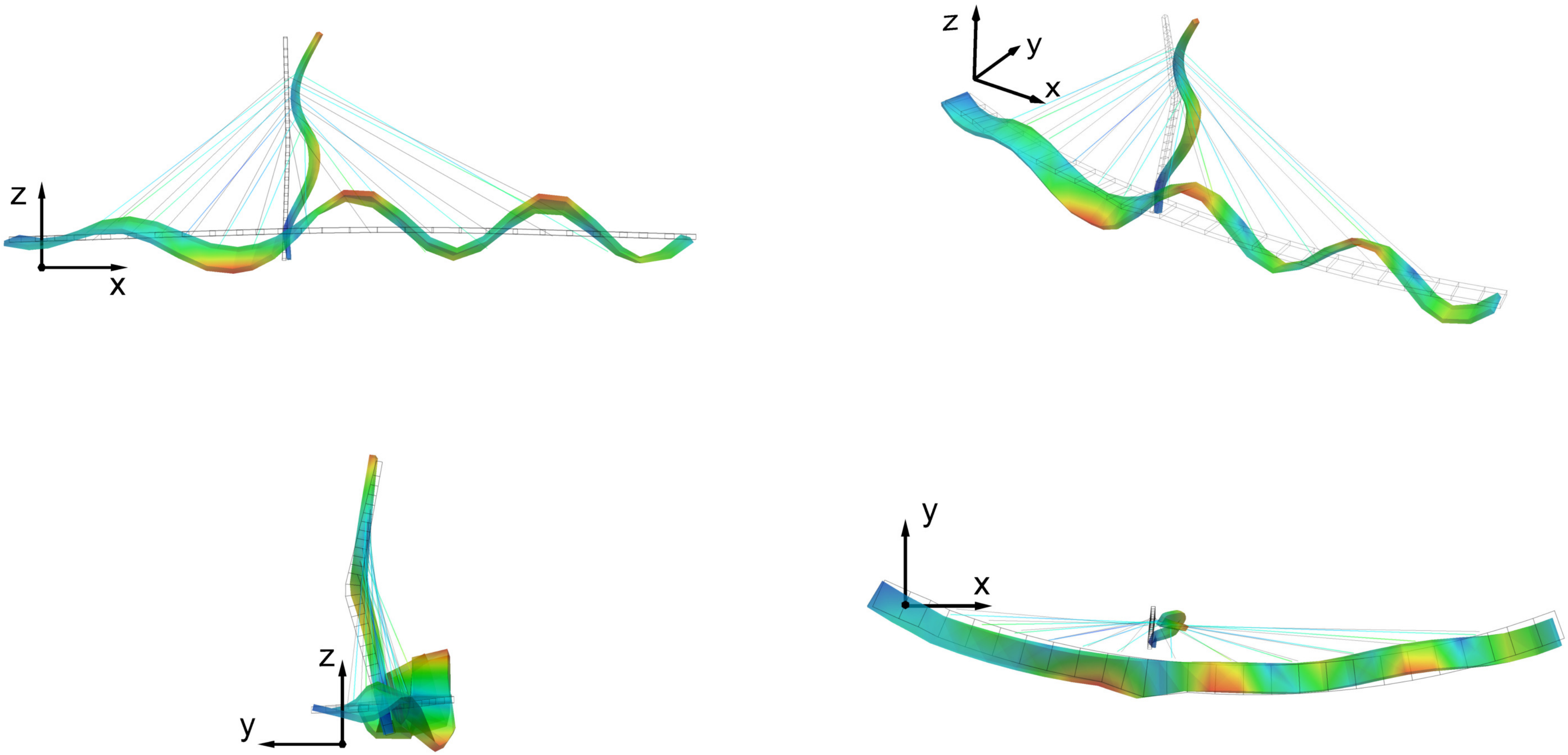
Dynamic Properties - Point Fraser Bridge
Mode 14, f = 4.063 Hz

Appendix A2-14

Date: September 15, 2022

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795



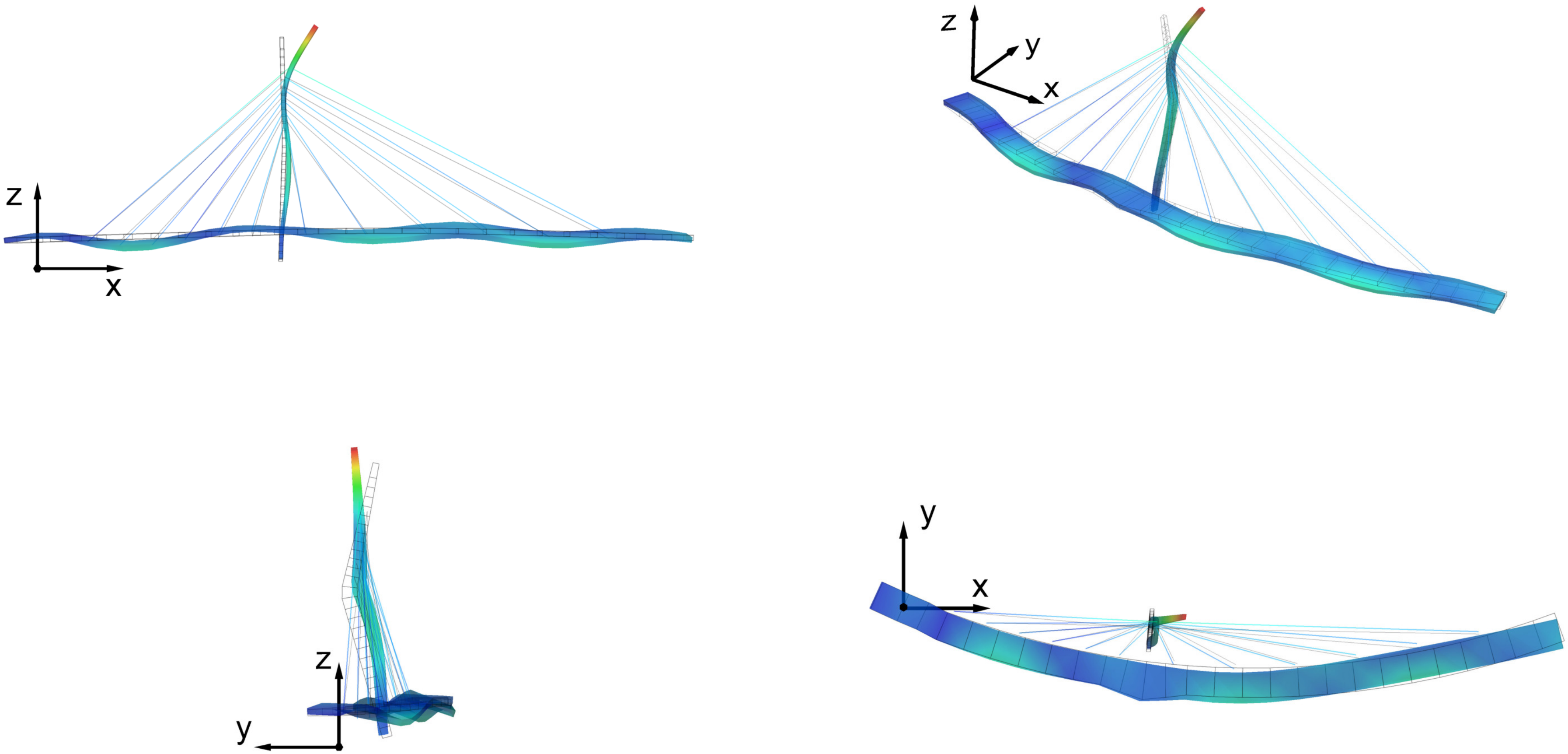
Dynamic Properties - Point Fraser Bridge
Mode 15, f = 4.377 Hz

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795

Appendix A2-15

Date: September 15, 2022



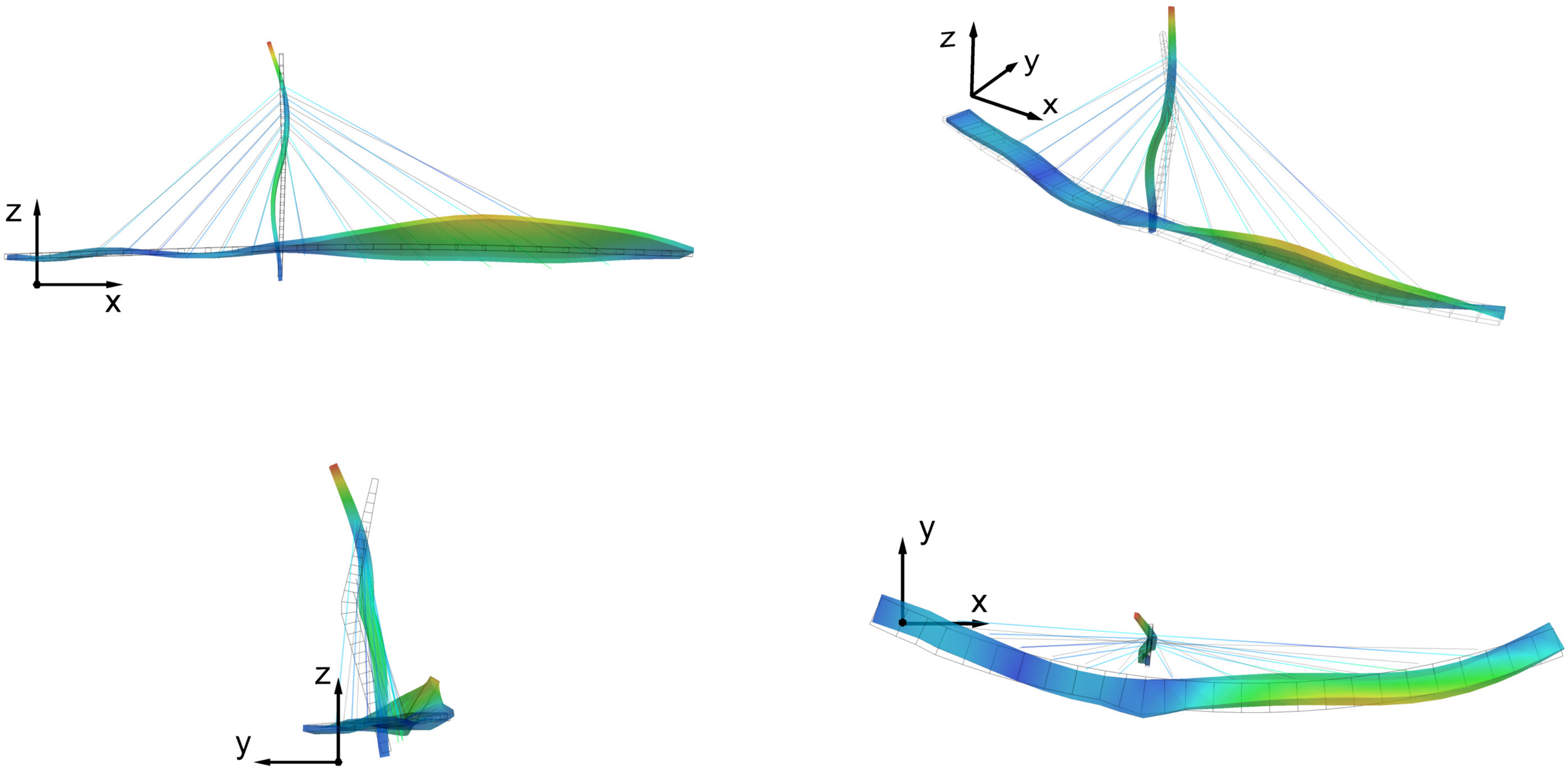
Dynamic Properties - Point Fraser Bridge
Mode 16, f = 4.552 Hz

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795

Appendix A2-16

Date: September 15, 2022



Dynamic Properties - Point Fraser Bridge
Mode 17, f = 5.177 Hz

Appendix A2-17

Date: September 15, 2022

Causeway Pedestrian Bridges, Perth, Australia

Project #2100795