Restoration and structural health monitoring of Manitoba's Golden Boy

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Abstract: Although bridges were among the first civil engineering structures to use structural health monitoring (SHM) technologies, research is now expanding to explore other types of applications, including Manitoba's famous Golden Boy statue. Global research is identifying the value of using SHM technologies for civil engineering applications. Structural health monitoring uses a variety of sensors to gather information about the behaviour of a structure. The information creates a valuable knowledge base that can be analyzed to help identify potential structural risks, develop safer and more efficient new structures, and determine more effective ways to rehabilitate existing structures. This paper briefly describes the history of the Manitoba Legislative Building and the Golden Boy and also the use of SHM technologies to help preserve the Golden Boy statue, an icon of provincial heritage.

Key words: history, Golden Boy, statue, sculptors, architects, engineers, shaft, corrosion, sensors, monitoring.

Résumé : Bien que les ponts furent parmi les premières structures de génie civil à utiliser les techniques de surveillance de l'état des structures, la recherche s'étend maintenant à l'exploration d'autres types d'application, incluant la fameuse statue du Golden Boy, au Manitoba. La recherche globale identifie l'utilité d'utiliser les techniques de surveillance de l'état des structures pour les applications de génie civil. Les techniques de surveillance de l'état des structures utilisent une gamme de capteurs pour saisir des informations sur le comportement d'une structure. L'information crée une base de données précieuse qui peut être analysée et utilisée pour aider à identifier les risques structuraux potentiels, développer de nouvelles structures plus sécuritaires et plus efficaces et déterminer des manières plus efficaces de restaurer les structures existantes. Cet article décrit brièvement l'histoire du Palais législatif et du Golden Boy, ainsi que l'utilisation des techniques de surveillance de l'état des structures pour aider à conserver la statue du Golden Boy, une icône du patrimoine provincial.

Mots clés : histoire, Golden Boy, statue, sculpteurs, architectes, ingénieurs, tige, corrosion, capteurs, surveillance.

[Traduit par la Rédaction]

Introduction

Structural engineers, architects, and sculptors share a common characteristic — they all make three-dimensional (3-D) objects that can be regarded as works of art. When these artists work together, sharing expertise, they create magnificent works that not only inspire current generations but will also inspire generations to come. Bridges and buildings developed by architects and structural engineers are examples of 3-D art forms. The sculptors' statues that adorn these structures are also 3-D art forms.

The Manitoba Legislative Building, with its Golden Boy statue, is an example of artistic disciplines coming together to pay tribute to the past for the pleasure of future generations. In 2002, the Golden Boy underwent an extensive repair and renovation program, which included installing a combination of structural health monitoring (SHM) sensors. Science, art, and an appreciation for the value of preserving provincial heritage are ensuring that the legacy of the Golden Boy is preserved for future generations.

This paper begins with an overview of the history of the Manitoba Legislative Building and the Golden Boy statue and then proceeds to outline the SHM portion of the recent restoration project.

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Written discussion of this article is welcomed and will be received by the Editor until 30 April 2004.

Manitoba Legislative Building

At the turn of the 20th century, Manitoba looked forward to a future filled with tremendous growth and prosperity. Winnipeg came to be known as the Chicago of the north. Plans for a new Legislative Building were in the works, and Frank Worthington Simon, an architect from Liverpool, England, turned the vision into reality. Excavation work for the building began in 1913, but World War I delayed its completion until 1919.

Traditional Greek design principles had a major influence on Simon's classical building design. He took great care to pay homage to ancient cultures and civilizations. Referred to as the "preacher in stone", Simon incorporated the themes of social justice and law, courage, and discipline in the intricate and artistic details of the building. "Simon wanted the new building to 'make people around it more perceptive, more

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intelligent, and better balanced and altogether more civilized human beings'" (Gillies 2001).

Simon paid tribute to Egyptian civilization by including massive statues of the sphinx on the roof of the building. He captured Greek history with the prominent use of strong solid columns reminiscent of the Parthenon, that magnificent Greek tribute to the beauty of democracy, art, and science. The Golden Boy statue, inspired by Mercury of Roman mythology, was Simon's tribute to Roman civilization. The Manitoba Legislative Building with the Golden Boy perched on the top of its dome is shown in Fig. 1.

Inside the building, the central theme for the legislative chamber comes to life with striking artistic interpretations representing the origins of legislation. The essence of the artwork captures the spirit of famous lawmakers, philosophers, and leaders from the corridors of history. Massive bronze statues set in the wall represent Moses and Solon, two very famous lawmakers. Stone tablets mounted on the walls record the names of five great world legislators, Confucius of China, Lycurgus of Greece, King Alfred of England, Justinian of Rome, and Manu of India, creating a symbolic gathering of wisdom from the five corners of the globe (Department of Industry and Commerce 1956).

Simon hoped, by weaving historical symbolism throughout the building, he would create a magnificent tapestry that would inspire leaders of the province for years to come. "He was determined to give Manitobans, who had 'no mountains to lift up their hearts', a chance to raise their eyes skywards above flat prairie vistas" (Gillies 2001). Simon's goal was to create a building with great beauty, form, and function, and his design included the Golden Boy as its crowning glory.

Golden Boy

Frank Simon commissioned the Parisienne sculptor, Georges Gardet, to create his vision of the Golden Boy statue. Both Simon and Gardet had attended the Paris School of Art. They likely knew each other as students, and this led to their collaboration on the statuary projects for the Manitoba Legislative Building. Other statues that Gardet created for the building are shown in Figs. 2 and 3, including the great bison, which symbolize the true north and free spirit of Canada, and the Moses and Solon statues, which symbolize the religious and secular thinking involved in making the laws of Manitoba and Canada.

Heavily influenced by Greek design, Simon knew of the Greek god of science and eloquence, Hermes, who was also a messenger to the other gods. In Roman mythology, Hermes was known as Mercury. Mercury's image is reflected in Gardet's final presentation of the Golden Boy, which he officially named "Eternal Youth".

The evolution of Simon's vision of the Golden Boy is traced in Figs. 4 through 6. The statue of Mercury is shown in Fig. 4. A facsimilie of Simon's hand drawn vision of the Golden Boy, including both the height and weight of the statue, in which the statue has a torch in its raised hand and a sheaf of wheat in its other hand, is shown in Fig. 5. The finished statue of the Golden Boy is shown in Fig. 6.

The vision of the Golden Boy was conceived at the height of World War I, when Colonel John McCrae wrote his famous poem, *In Flanders Fields*. These hauntingly beautiful

Fig. 1. The Manitoba Legislative Building.

Fig. 2. Gardet created the great bison statues that guard the grand staircase.

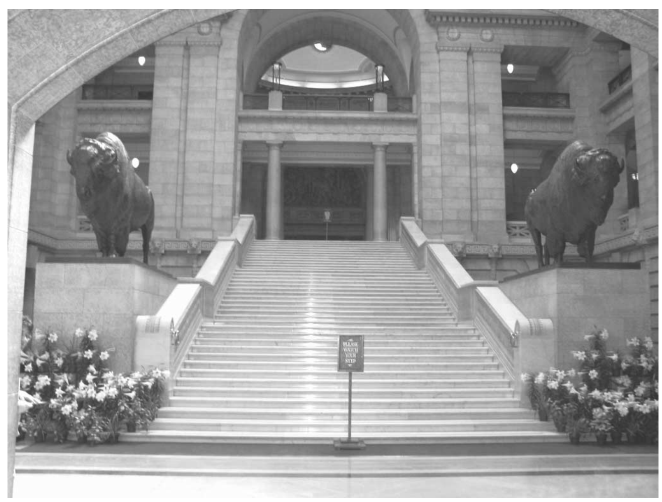

Fig. 3. Gardet also created the statues of Moses (left) and Solon (right).

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lines from the poem probably inspired Simon to put a raised torch in the Golden Boy's hand.

> To you from failing hands we throw
> The torch; be yours to hold it high [Granfield 1996]

The torch signifies the spirit of enterprise and the youthful enthusiasm of the province. The sheaf of golden grain represents hardworking Manitobans. The running stance of the Golden Boy shows that Manitoba is not going to stand still, but will continue to contribute to industry as history unfolds. The statue faces north, looking toward the province's vast treasure of natural resources (Government of Manitoba 2002).

The Golden Boy is a hollow sculpture made of bronze; he stands 4 m (13.2 ft) tall from his toes to the tip of his torch. He weighs between 1550 and 1600 kg (just over 3600 lb), and the top of his torch is 77 m (255 ft) above ground, the equivalent of a 24-storey building (Government of Manitoba 2002).

Cast in 1918 at the Barbidienne Foundry in France, the Golden Boy survived the war unharmed, despite the fact that the foundry was destroyed by bombs. Just as the Golden Boy was leaving France for Canada, the ship he was travelling in was called into active duty for troop transport. Safely stored in the hull of the ship, the Golden Boy made several trips back and forth across the Atlantic Ocean before eventually arriving in Halifax harbour at the end of the war. He travelled from Halifax to Winnipeg by rail and was perched on the dome of the Legislative Building on 21 November 1919.

Simon was concerned about the stability of the statue at the top of the Legislative Building. He asked Gardet to cast the statue monolithically with the shaft that was to fix the statue to the building. Because of World War I there was a shortage of steel in France and the monolithic casting was not possible. Instead, a steel shaft was purchased in Chicago, inserted in the left leg of the Golden Boy, and plugged at the heel.

Similar to other statues in the building project, the Golden Boy was originally cast in bronze. By 1940 he was sporting a new coat of gold paint and in 1951 he was gilded with gold leaf. Probably around this time, his name changed from "Eternal Youth" to Golden Boy. The last major alteration to the Golden Boy included an electrical connection and light fixture mounted on top of his cast torch. This had a detrimental effect on the health of the statue.

On 31 December 1966, the Golden Boy's electric torch lit up for the first time, marking the beginning of Canada's centennial year of celebrations. The holes drilled to accommodate the wiring permitted the intrusion of precipitation and moisture into the Golden Boy, eventually contributing to severe corrosion at the base of the support shaft.

Restoration and repair project

During the last few years, the Manitoba Legislative Building underwent a major restoration program. As a part of the overall project, the Golden Boy was to be regilded with 24 karat gold leaf. A close inspection of the statue revealed severe corrosion at the base of the steel shaft that attached the statue to the dome. Originally 127 mm (5 in.), the diameter of the shaft now measured about 114.3 mm (4.5 in.). The corrosion created a serious safety risk, adding structural repair to the aesthetic restoration of the statue (Redston 2002). Figures 7 and 8 show the corroding shaft. ISIS Canada researchers concurred with the project's consulting engineers, Dillon Consulting, that the supporting steel shaft of the Golden Boy should be replaced.

Fig. 4. Mercury, from Roman mythology.

Familiar with ISIS technologies, government officials suggested to Dillon Consulting that the Golden Boy might be a candidate for structural health monitoring. Under the leadership of Dr. Aftab Mufti, ISIS Canada researchers confirmed that SHM would be an effective way to help ensure the future health of the Golden Boy.

Prior to the implementation of SHM, however, the structural safety issues of the statue had to be addressed. It appeared too risky to repair the Golden Boy while he was still on top of the dome. The potential threat of fire from repair activity combined with the instability of the shaft presented serious safety concerns.

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Fig. 5. Simon's sketch for Gardet.

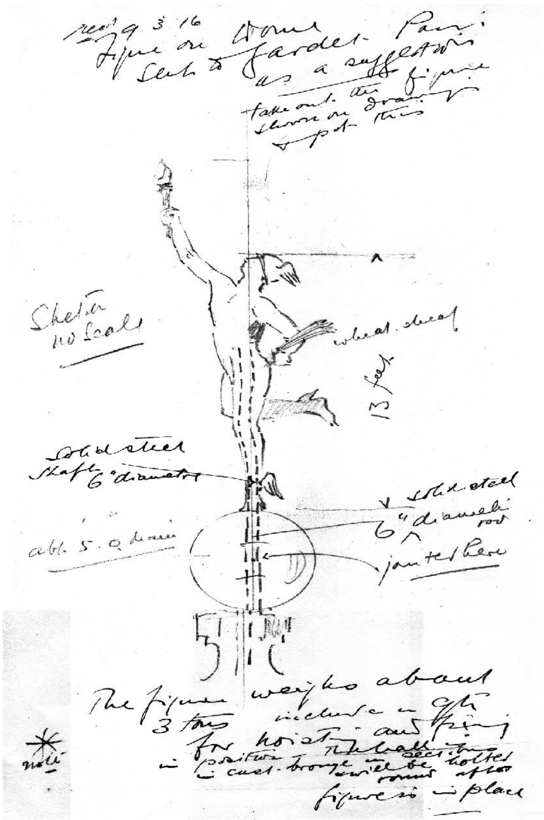


Fig. 6. The finished statue, the Golden Boy.

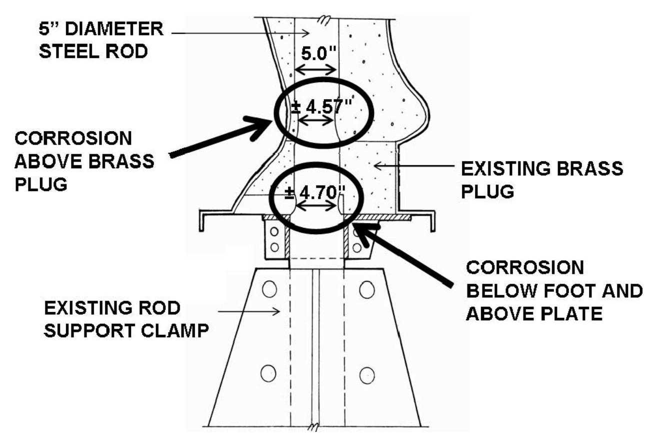
Confirming the actual structural safety issues was the next phase in the restoration of the Golden Boy. For the finite element analysis, Dillon Consulting and coworkers fixed reflective tape at strategic locations on the Golden Boy and recorded coordinate data from the reflective points on the tape. Figure 9 shows the reflective tape on the statue.

The coordinate data were used to develop two types of numerical models for the Golden Boy, one simplified and the other complex. An accurate scale model for wind tunnel testing was developed from the complex model. Figure 10 illustrates the complex numerical model, and Fig. 11 shows the physical 1/20th small-scale model that was used in the wind tunnel testing at The University of Western Ontario. Wind tunnel tests (Kopp and Surry 2001) were also conducted on a precisely 1/100th scaled-down model of the Legislative Building (Fig. 12).

Results from analytical calculations (Mufti and Tadros 2001) indicated that the shaft supporting the statue was being subjected to 91% of its ultimate capacity. Results from the wind tunnel testing (Kopp and Surry 2001) were similar, indicating that under expected wind velocities, the shaft would be stressed to 93% of its ultimate capacity. A comparison of the results is shown in Table 1.

It should be noted that the shaft is a simple structural element. It is a cantilever fixed at the base. The shaft has bending, axial, and torsional loads. Under these loading conditions, the combined stresses could be calculated as shown in Appendix A. Calculations are based on the formulas listed in the CHBDC (CSA 2000) and Timoshenko and MacCullough (1961).

Fig. 7. Corroding support shaft.



Testing of the simplified and complex models confirmed the Golden Boy was at risk of being blown off the top of the Legislative Building. It was predicted that a 100-year wind storm could fail the shaft, causing the Golden Boy to topple. The tests also confirmed earlier apprehension about the safety of the Golden Boy during restoration. It was decided

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Fig. 8. Close up of corroding shaft.

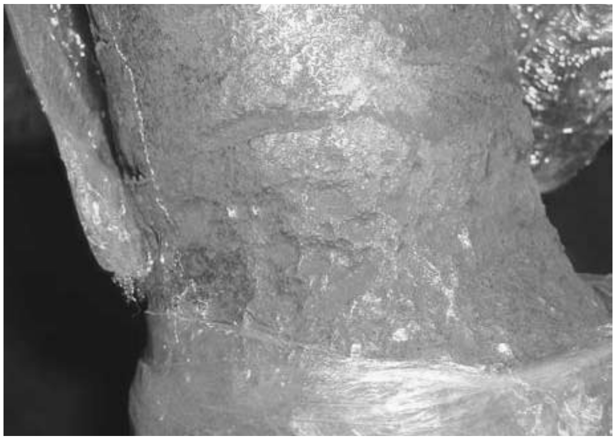

Fig. 9. Reflective tape on Golden Boy.

Fig. 10. Complex model developed from reflective tape coordinates.

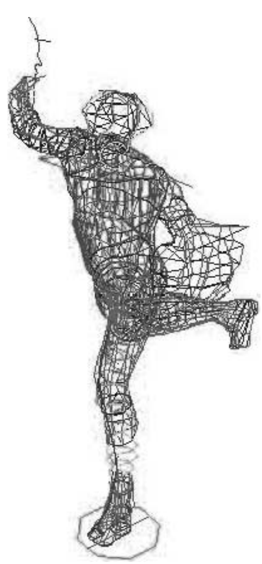

Fig. 11. Scale model of Golden Boy used for wind tunnel testing.

to remove the statue from the top of the dome and restore the Golden Boy on the ground.

The Golden Boy came down to the ground in February 2002. He enjoyed a full police escort to the Manitoba Museum, where over 140 000 Manitobans came to visit him before he was moved to a secure workshop at Pritchard Machine for the repair process.

Structural health monitoring system

The Golden Boy was taken apart in five original sections, thoroughly cleaned, and given a new, high strength, stainless steel shaft. After cleaning, but before he was pinned back together, four types of SHM gauges were installed: accelerometers, electric resistance strain gauges, fibre optic strain gauges, and thermocouples. Figure 13 shows the locations of the sensors.

Two accelerometers at the top of the shaft inside the statue record the movement of the statue in response to wind and various weather systems. The motion is measured in frequencies or beats. Frequencies outside the normal expected range will signal the need for investigation.

To provide a redundant sensing system, a combination of glued electrical resistance strain gauges and Bragg grating fibre optic sensors were installed on the support shaft near the heel of the Golden Boy. These gauges monitor the strains in the shaft due to wind on the Golden Boy. The principles and end use of the fibre optic sensors are described in *Guidelines for Structural Health Monitoring* (Mufti 2001).

Thermocouples, located in close proximity to the gauges at the base of the support shaft, record temperatures. Measuring temperature is important because it affects the strains

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Fig. 12. Scale model of Legislative building used for wind tunnel testing.

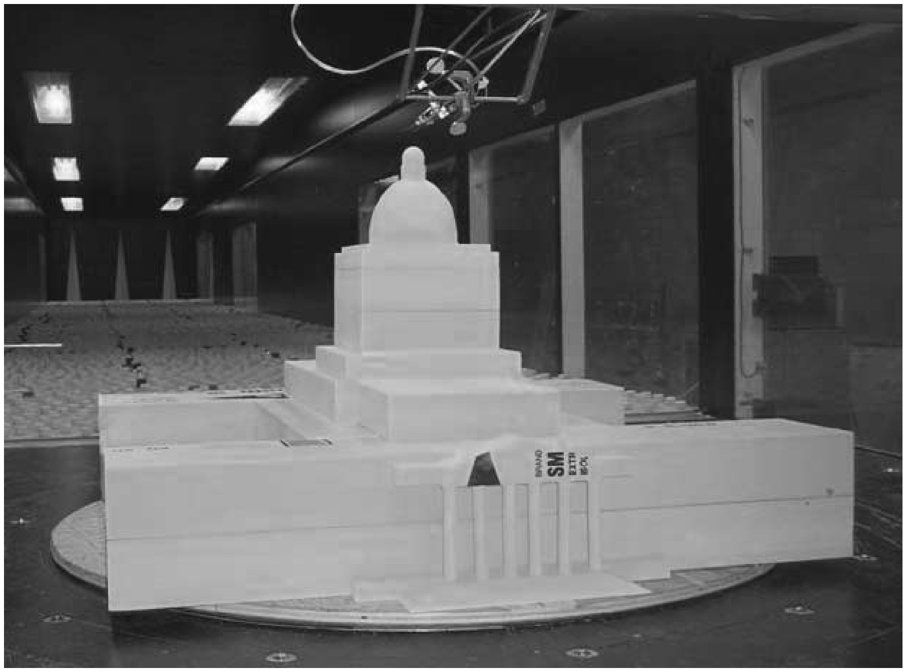

Fig. 13. Instrumentation design for Golden Boy project.

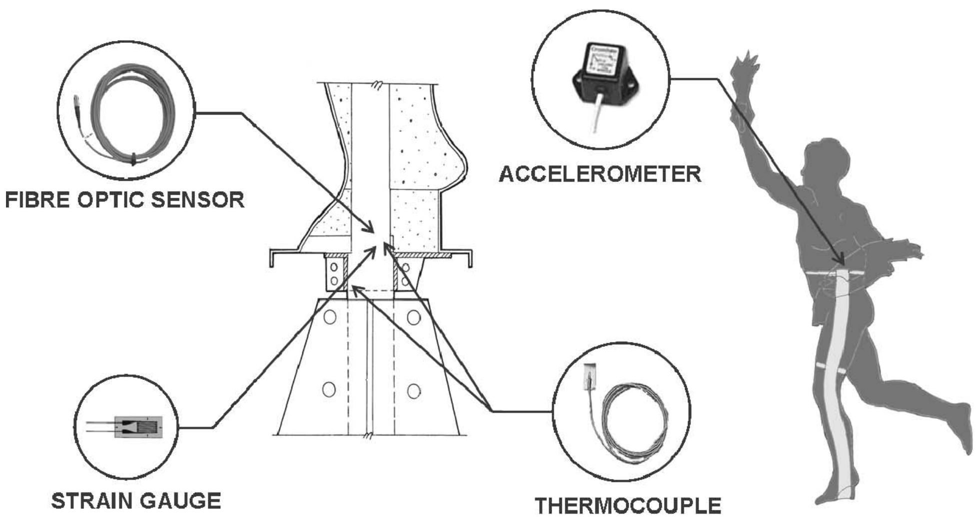

Table 1. Comparison of theoretical and wind tunnel testing analysis of wind effects on the support shaft of the Golden Boy — diameter due to corrosion = 116 mm.

Analysis	Maximum stress (MPa)	Yield stress (MPa)	Yield (%)
Theoretical	249	275	91
Wind tunnel test	255	275	93

of the supporting shaft, which, in turn, can affect the integrity of the shaft.

With the SHM system installed and renovations preventing any future instrusion of moisture into the statue, the Golden Boy was then moved on to the final stage in the refurbishment process. He was re-crated and transported to the Forks Market in central Winnipeg, where he received a new coat of 24 karat gold leaf. The Golden Boy was then returned to his home atop the Manitoba Legislative Building.

The SHM sensors are currently wired to a data logger that is connected to a resident computer in the Legislative Building. Real-time access to the sensing data is available on a continuous basis through an Internet hook-up. During the initial stages of the monitoring program the Golden Boy live-data screen page is being hosted on the ISIS Canada Web site (www.isiscanada.com), as shown in Fig. 14. However, according to long-range plans, the Manitoba Department of Government Services will eventually take over responsibility for maintaining the Golden Boy web site.

Comparing health monitoring principles

The principles of SHM for the Golden Boy are analogous to the principles that guide personal health monitoring. Med-

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Fig. 14. Screen shot of live data showing amplitude of accelerations with respect to time.

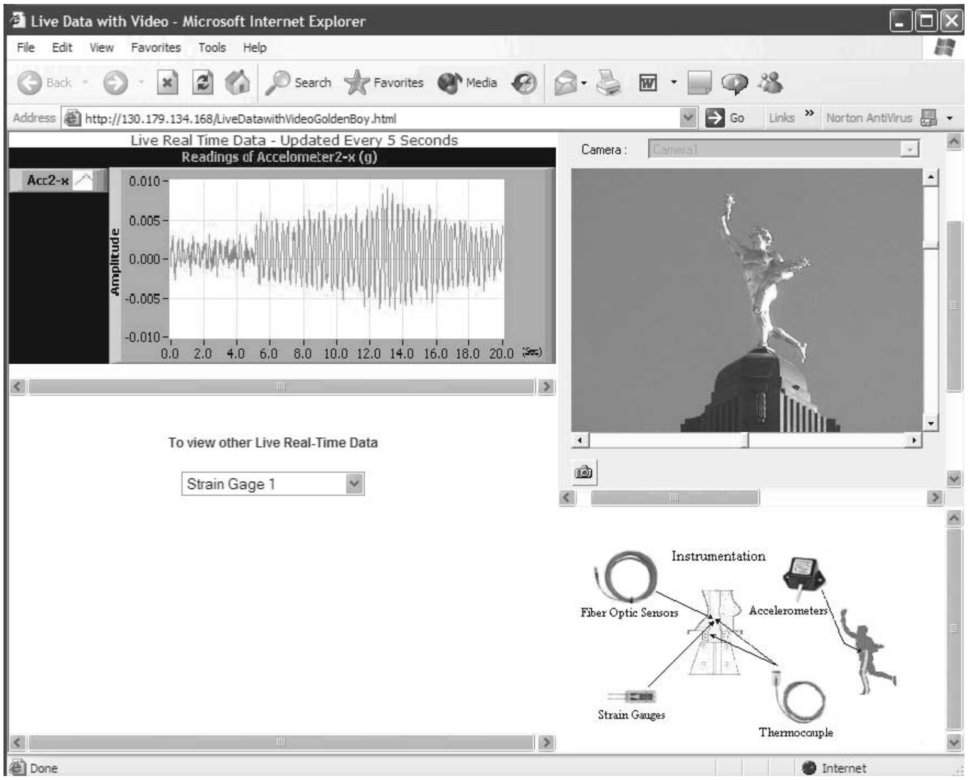
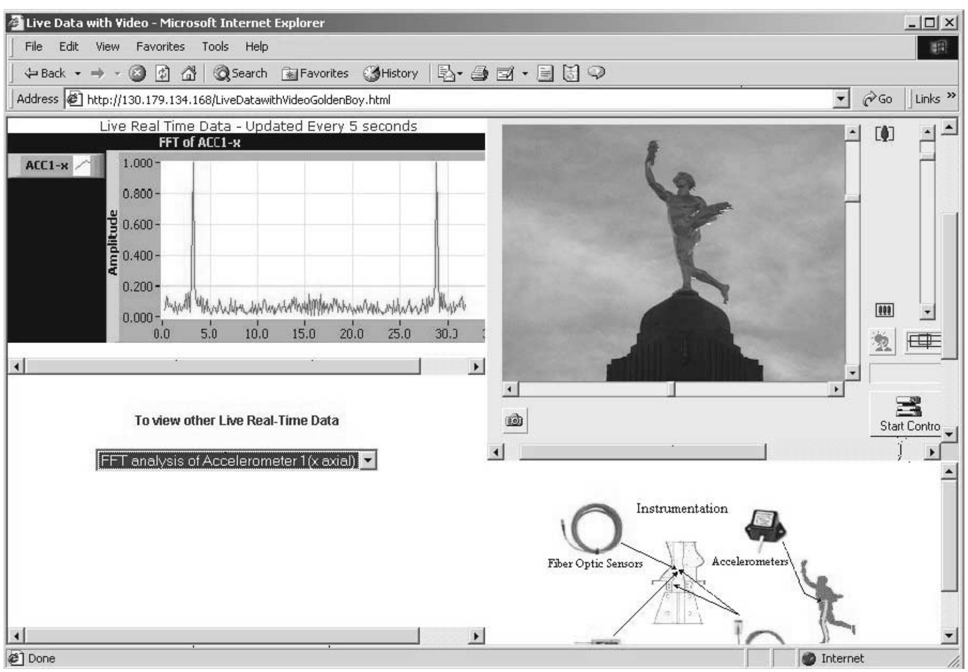


Fig. 15. Screen shot of Golden Boy live data showing natural frequencies.



ical doctors use stethoscopes and blood pressure gauges to obtain readings that measure heartbeat and blood pressure, both strong indicators of physical health. Readings outside the normal expected range indicate a physical health issue. For SHM, we use an accelerometer to record natural frequencies (beats) of the shaft. If the frequency or beats remain unchanged, the Golden Boy is deemed healthy. The normal frequency or beat for the Golden Boy is 3 Hz, as shown in Fig. 15. The strain gauges on the shaft measure the forces acting at the base of the statue.

As noted before, the shaft is a simple structural element. It is a cantilever fixed at the base. The shaft could be mod-

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eled as a simple one degree of freedom system. The fundamental frequency of this simplified system is calculated in Appendix B to be 2.48 Hz. Calculations are based on the formulas listed in the CHBDC (CSA 2000) and Timoshenko and MacCullough (1961).

Conclusions

Access to continuous readings from state-of-the-art SHM diagnostic tools is the first step in moving the care of the Golden Boy from a high-cost, acute care method of maintenance towards a more cost efficient, preventive health care model. While data are being collected, work on the implementation of decision-making software is also progressing.

There are three main benefits of incorporating SHM technologies into the Golden Boy restoration project.

- Analysis of the SHM data will contribute to the development of cost efficient maintenance procedures that will save taxpayer dollars over time.
- Early access to information about the physical and structural state of the statue will help identify potential risks.
- Knowledge gained from analyzing the SHM results can be used to create safer and better designs for similar structures.

Queen Elizabeth II rededicated the famous Manitoba icon during her Golden Jubilee visit to Winnipeg in October 2002. The Golden Boy is now illuminated at night by floodlights as he looks out over the province, continuing to symbolize a rich and prosperous future. The science of SHM technology will help ensure that the legacy of the Golden Boy will keep shining for future generations.

Acknowledgements

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Appendix A. Golden Boy stress analysis

Table A1. Golden Boy – calculation of wind speeds.

Wind frequency from CHBDC code (CSA 2000)	p	q (kPa)	P (kPa)	V (m/s)	V (km/h)	V (mph)
1/10	0.10	0.35	1.71	23.3	83.9	52.1
1/30	0.03	0.42	2.05	25.5	91.8	57.0
1/100	0.01	0.49	2.39	27.5	99.0	61.5
1/500	0.002	0.59	2.58	30.1	108.4	67.4
1/1000	0.001	0.63	3.07	31.2	112.3	69.8
Wind tunnel test						
1/30	—	—		25.4	91.4	56.8
1/100	—	—				

Note: Basic wind speed: V (m/s) = $\sqrt{q/0.00064645}$ where q = pressure in kilopascals (V (km/h) = V (m/s) × 3.6 km/h). Unfactored M_{base}.

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Table A2. Wind load factor, α_w.

Bias factor, δ_ω	1	Sensitive factor, κ	0.89
Coefficient of variation for wind load, V_w	0.29	Wind load factor, α_w	1.99
Reliability index, β_T	3.50		

Fig. A1. Golden Boy stress analysis, trial 1 (Mufti and Tadros 2001).

GOLDEN BOY STRESS ANALYSIS

Trial 1 - Using A. Mufti & G. Tadros Data

Projected area (from SHA) 3.04 m^2

Design Wind Load (100 yr storm) 2.39 kPa

Horizontal Wind Load = 3.04 x 2.39

= 7.27 kN

DL = 3.0 tons ... assumed

= 27.0 kN

Armature Shaft Data

steel Fy = 275 MPa

dia at support = 116.08 mm

$I = \pi d^4 / 64 =$ 8.91E+6 mm^4

$J = \pi d^4 / 32 =$ 17.82E+6 mm^4

$A = \pi d^2 / 4 =$ 10.00E+3 mm^2

Mr = 0.9 (I / c) Fy = 38.0 kN.m

	Unfactored Load	Load Factor	Factored Load	Moment arm (m)	Mf at base kN.m
Wind Load	7.27	1.65	12	2.400	28.80
DL	27.0	1.25	33.75	0.150	5.06
					33.86 kN.m

Torque = 12 x 0.15 = 1.8 kN.m

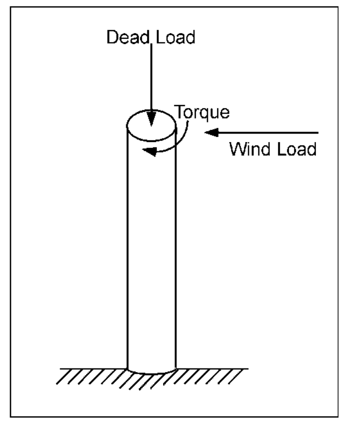
Design Loads:

Moment Mf = 33.86 kN.m

Axial Load Pf = 33.75 kN

Shear Vf = 12 kN

Torque Tf = 1.8 kN.m



Stresses:

Bending stress fb = M c / (ϕs I) = 33.86 x 10^6 x 58.04 / (0.9 x 8.91x10^6)

= 245.07 MPa

Axial Stress: fa = Pf / ϕs A = 33.75 x 10^3 / 0.9 x 10000

= 3.75 MPa

Shear Stress: fv = 4 / 3 Vf / ϕs A = 4 / 3 x 12 x 10^3 / 0.9 x 10000

= 1.78 MPa

Torsional Shear Stress τ = T c / ϕs J = 1.8 x 10^6 x 58.04 / 0.9 x 17.82 x 10^6

= 6.51 MPa

Maximum principal stress from Mohr's Circle:

OB = 245.07 + 3.75

= 248.82

AB = OB / 2 = 124.41

BC = 6.51

$\therefore$ σ max = 124.41 + sqrt (124.41^2 +6.51^2)

= **248.99** MPa vs Fy = 275 MPa

91% of yield

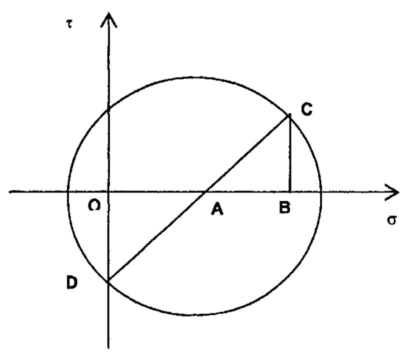


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Fig. A2. Golden Boy stress analysis, trial 2.

GOLDEN BOY STRESS ANALYSIS

Trial 2 - Using Wind Tunnel Test Results for Worst Wind Direction

From Wind Tunnel Report (Summary and Main Findings):

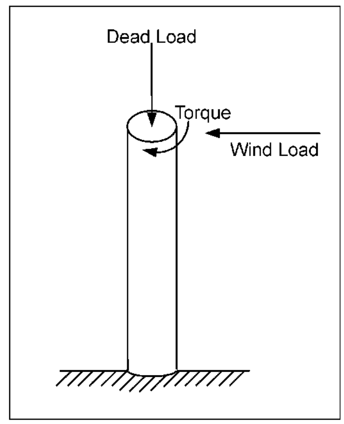
Moment at base = 16.9 kN.m
Horizontal Wind Load (shear) = 6.2 kN
∴ momt arm (loc of CG) = 16.9 / 6.2
= 2.726 m vs 2.750 assumed ... quite close
DL = 3.0 tons ... assumed as before
= 27.0 kN

Armature Shaft Data

steel Fy = 275 MPa
dia at support = 116.08 mm
$I = \pi d^4 / 64 =$ 8.91E+6 mm^4
$J = \pi d^4 / 32 =$ 17.82E+6 mm^4
$A = \pi d^2 / 4 =$ 10.00E+3 mm^2
Mr = 0.9 (I / c) Fy = 38.0 kN.m

	Unfactored Load	Load Factor	Factored Load	Moment arm (m)	Mf at base kN.m
Wind Load	6.2	1.99	12.34	2.400	29.62
DL	27.0	1.25	33.75	0.150	5.06
					34.68 kN.m

Torque = 12.34 x 0.15 = 1.85 kN.m



Design Loads:
Moment Mf = 34.68 kN.m
Axial Load Pf = 33.75 kN
Shear Vf = 12.34 kN
Torque Tf = 1.85 kN.m

Stresses:

Bending stress fb = M c / (ϕs I) = 34.68 x 10^6 x 58.04 / (0.9 x 8.91x10^6)
= 251.01 MPa

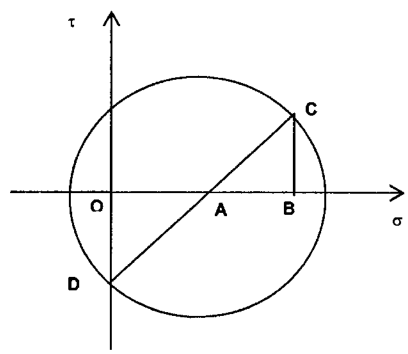
Axial Stress: fa = Pf / ϕs A = 33.75 x 10^3 / 0.9 x 10000
= 3.75 MPa

Shear Stress: fv = 4 / 3 Vf / ϕs A = 4 / 3 x 12.34 x 10^3 / 0.9 x 10000
= 1.83 MPa

Torsional Shear Stress τ = T c / ϕs J = 1.85 x 10^6 x 58.04 / 0.9 x 17.82 x 10^6
= 6.69 MPa

Maximum principal stress from Mohr's Circle:

OB = 251.01 + 3.75
= 254.76
AB = OB / 2 = 127.38
BC = 6.69
∴ σ max = 127.38 + sqrt (127.38^2 +6.69^2)
= **254.94** MPa vs Fy = 275 MPa
93% of yield



Appendix B. Calculation of natural frequency of Golden Boy

Table B1. Calculate natural frequency.

	Given data	Units	Calculations	Units
Length of bar	2 750	mm		mm
Diameter of bar	127	mm		mm
E	200 000	MPa		MPa
m_1	1.52	Tons	14 911.2	N
m_2	0	kg/m^3	0	N
g	9 810	mm/s^2		
$I = \pi d^4/64$			12 769 820	mm^4
$K = 3EI_{xx}/L^3$			368.4	N/mm
$M = (m_1 + m_2)/g$			1.520	N
Natural frequency $f = 1/2\pi\sqrt{K/M}$			2.48	Hz

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