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VISION-BASED, MULTI-EPOCH DEFORMATION MONITORING OF THE ATRIUM OF FEDERATION SQUARE

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Abstract

One of the significant architectural features in Melbourne's new Federation Square building complex is the 16m high North Atrium. This is made up of galvanised structural frames in a triangular geometry, developed into a folded 3D structure that is glazed on the outside. The Atrium was designed using a cantilever system that allows the final 14m section to be suspended in free space. This paper describes the multi-epoch deformation monitoring of the North Atrium, which was conducted to ascertain the structural movement during and after construction, associated with both the de-propping and glazing processes. Automated digital close-range photogrammetry was utilised at each of the measurement epochs to provide comprehensive, high-accuracy 3D deformation data within a very short time span of only a few tens of minutes for 70 or so principal monitoring points. The vision metrology surveys yielded deflection vectors which enabled both an independent verification of a second-order elastic analysis of the structure and a subsequent refinement of the structural model. Particular characteristics of the North Atrium structure are described, the requirements for monitoring are reviewed, the design and conduct of the photogrammetric measurement operation are outlined, and the results of the subsequent deformation analysis are presented.

1. Introduction

The Federation Square was conceived in 1996 as a celebration of Australia's Centenary of Federation. It is as big as a city block and houses about a dozen buildings, different yet linked and coherent. As indicated in Fig. 1, Federation Square forms a landmark, civic focal point for the city of Melbourne and comprises art galleries, entertainment facilities and other attractions. One of the prominent architectural structures in Federation Square is the Atrium, which is an open, galleria-like public space comprising two distinct elements. One of these, the North Atrium, forms a covered forecourt and is made up of galvanised structural frames in a triangular geometry, developed into a folded 3D structure glazed on the outside. The framework structure, which evolved from the triangular geometry of the façades, was designed with a cantilever system that allows the final 14m section to be suspended in free space, as indicated in Fig. 2.

Due to the geometric complexity of the North Atrium structure, and its lack of redundancy, compounded by the importance of preventing any possible interaction between the superstructure and the intricate façade skin, an accurate structural analysis was essential with particular emphasis on evaluating the deformation characteristics in the cantilever section of the North atrium where significant overall deflections were expected both in the de-propping process during construction, and in the glazing. As an independent deformation monitoring system, automated digital close-range photogrammetry was to be employed during the construction process to determine structural deflections, which could then be compared with the deflections anticipated from theoretical predictions.

Figure 1. Federation Square complex, Melbourne.

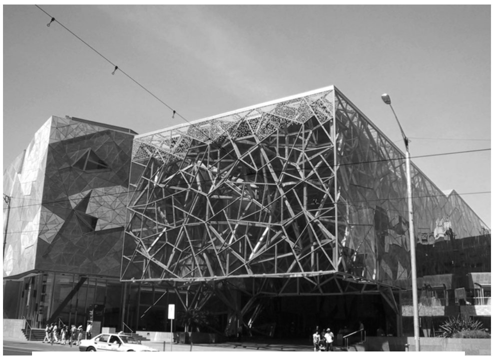


Figure 2. North Atrium showing 14m cantilevered section.

2. North Atrium Structure

The superstructure frame for the North Atrium is fabricated from 200mm square hollow sections and comprises two skins of in-plane frames separated by an average gap of approximately 1.5m, as can be seen in Fig. 3. The frames consist of 4- to 5-sided irregular polygons connected by in-plane diagonals based on a “pinwheel” configuration allowing a sense of randomness whilst preserving geometrical definition which is essential for the attachment of an economical glazed façade system. The two skins are connected by out-of-plane diagonals to provide the necessary lateral stability to resist wind loads. The roof structure consists of a series of 2.0m deep trusses which have the dual function of supporting the roof and facilitating walkways and catwalks required for maintenance work and servicing of light and sound systems for organised entertainment. The roof structure over the cantilever section is far more complex with a “pinwheel” structural system similar to that adopted for the walls.

Construction of the North Atrium was to be a complex operation, which called for a comprehensive prior understanding of how the structure would deform over time. In addition to determining the structural performance at the final permanent state, continuous evaluation of deflections, both absolute and differential, during the construction phase was of paramount importance. This allowed the designers to develop acceptable façade connection details to facilitate the predicted movements. Staged second-order elastic analysis to predict such movements was carried out for this assessment, concurrently with the construction program. The critical construction activities included the de-propping of the cantilever section and the installation of the glazing which dominates the contribution towards the overall dead load. Illustrated in Fig. 4 is the structural deflection predicted from finite element analysis, with the maximum deflections at any node point in the cantilevered section being of the order of 50mm.

Figure 3. Two skins of in-plane frames.

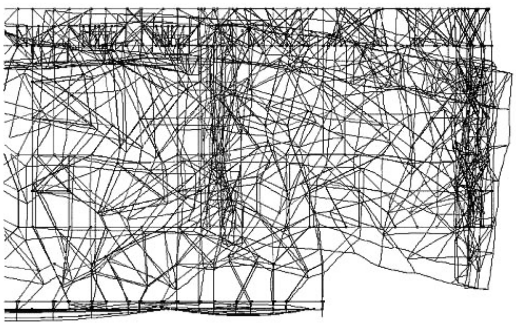


Figure 4. Deflected shape due to dead load in cantilever section (not to scale).

3. Deformation Measurement Requirements

In view of the complexity of the Atrium structure and the specific requirement for accuracy in determining deflections of the structure, an independent monitoring program was sought to validate the theoretical predictions and to provide some “peace of mind” feedback for the owners. Specifically, a 6-epoch monitoring program was required, where at each epoch the 3D coordinates of 71 structural node points could be determined to 0.3mm accuracy within a common reference coordinate system. This would then allow both absolute and differential node point deflections to computed to the required accuracy of 0.5mm. The six monitoring epochs, during and after construction, were to be: an initial condition before de-propping, three during de-propping, one during the glazing process, and a final post-construction condition. To date, only the first five measurements have been conducted and the paper will concentrate on these.

The deformation monitoring was to take place during what was a very busy and involved construction process, with minimal disruption to production being an absolute imperative for the adopted monitoring technique. Indeed, the measurement technology needed to be very fast, automated, economical, reliable, highly accurate (proportional accuracy of close to 1:100,000) and largely unaffected by the cluttered construction environment. Automated digital close-range photogrammetry, or vision metrology, is a technology displaying these attributes and it could be argued that for the North Atrium monitoring project it was the only practical measurement method available.

4. Photogrammetric Surveys

An off-line vision metrology approach was adopted for the photogrammetric measurements, with the V-STARS system from Geodetic Services, Inc. being utilised (GSI, 2003). This system comprised essentially just an INCA 4.2 (4 megapixel) digital camera and a notebook PC, which rendered it quite suitable for data processing and analysis to be conducted on site, immediately following acquisition of the images. The object features of interest, the 71 node points were signalised with 2cm retroreflective targets, and 97 coded targets were employed to effect automatic point labelling and to provide network tie points, as shown in Fig. 5.

Although the photogrammetric approach could accommodate most of the constraints imposed by the construction site, one difficulty was visibility. Node points on both the inner and outer frames were to be monitored, which gave rise to some targets being visually obstructed from desired camera station positions. The approach adopted to overcome this problem was simply to add more camera stations. Thus, the nominal 32-station network usually produced between 100 and 140 images. Photography was captured from a telescopic boom, with the operator occupying usually three to five different viewing positions at a nominal location in order to minimise visual obstructions. It should be recalled that the added effort of recording a network with 100, 120 or even 150 images is measured in minutes, both at image acquistion and within the final photogrammetric orientation and triangulation, which is fully automatic. The recording of the images at each epoch typically took about 25 minutes whereas the photogrammetric bundle adjustment and subsequent computation of deflection vectors needed only 5 minutes.

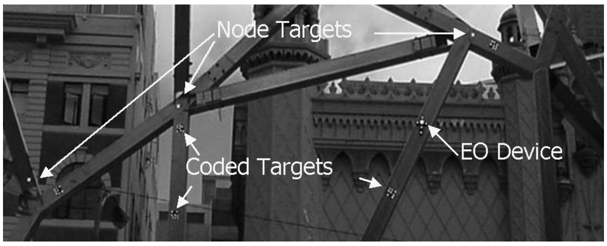


Figure 5. Section of frame showing node point targets, coded targets and an exterior orientation (EO) device.

In order to provide a time-invariant reference system, six targets were established as stable 'datum' points. These were positioned on lower sections of the Atrium framework, though not upon absolutely stable structure since this was not feasible. Some small movement of the datum points was thus anticipated, though the magnitude of their deflections was predicted to be of limited consequence for the determination of accurate overall structural deformation.

Within the five photogrammetric surveys conducted to date, an accuracy of 0.15mm (RMS, 1-sigma) or better has been achieved in node point positioning. Coordinate determination has been via self-calibrating bundle adjustments comprising about 170 object points (nodes and coded targets) and 90-140 images, with image scales generally being in the range of 1:500 to 1:1000. The combination of retro-reflective targeting and precise image centroiding yielded an image coordinate measurement accuracy of 1/40th of a pixel (approx. 0.2μm). Accurate absolute scale was not a requirement for the deformation monitoring, but redundant scale information was nevertheless used as it provided a further external accuracy check. At the first measurement epoch, two 2.5m-long precise invar scalebars were included in the network, with the discrepency in the measured lengths of these known distances being only 0.05mm. An insight into the vision metrology measurement process can be gained via Figs. 6 and 7, which show the telescopic boom platform used for photography along with a sample image.

5. Determination of Structural Deformation

The primary aim of measuring node point deflections arising from the de-propping and installation of the glazing was to compare the actual versus predicted deformation of the North Atrium structure and thus both validate the results of a 2nd order finite element frame analysis and allow a refinement, if necessary, of the structural model. As a first step in this process, all five photogrammetric networks required transformation into the chosen reference system, which was represented by the six datum points at Epoch 1, the initial 'propped' condition. Straightforward 7-parameter similarity transformation was used to bring all 3D coordinates into the common datum, after which node point deflections where computed from coordinate differences. Shown in Fig. 8 are plots of the resulting point deflections, which reached a magnitude of 22mm, somewhat less than predicted.

Noteworthy in Fig. 8 is that the 6 datum points did not in fact remain stable throughout the monitoring period, and it is apparent that as the structure was de-propped the increased loading upon the lower frames induced small lateral, outward movements of 5mm or less at the maximum loading (Epoch 5). It was fortunate that these movements where horizontal as they then had little effect on the computed values of the node displacements on the frames of the cantilevered section, which were close to orthogonal to the displacements of the datum points.

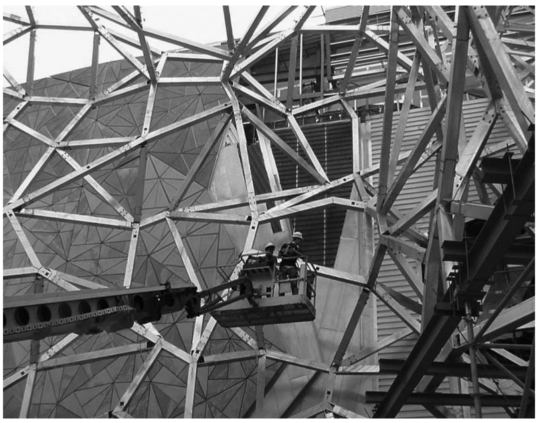
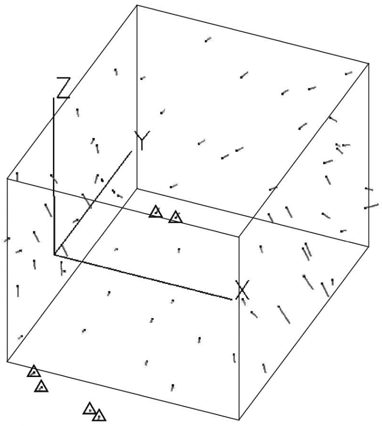
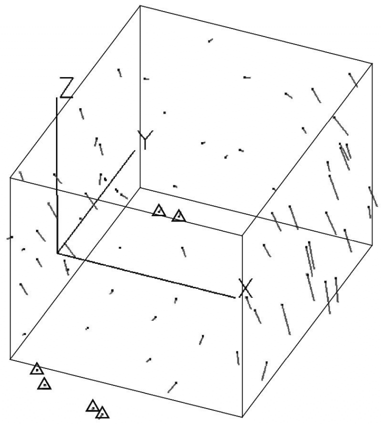


Figure 6. Recording of images.

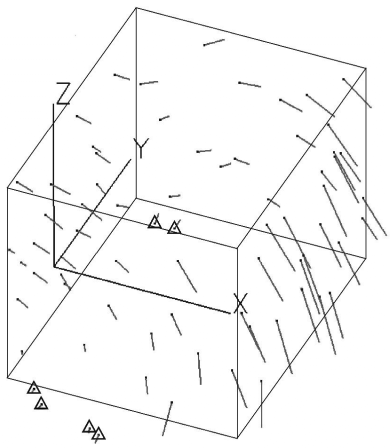
Figure 7. Sample image from vision metrology network.



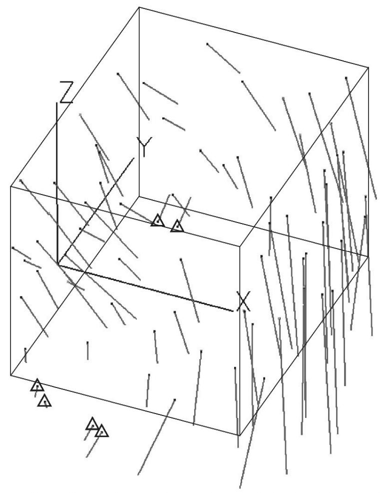
(a) Epoch 2 versus Epoch 1



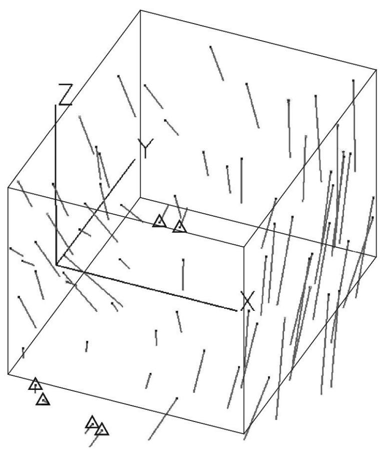
(b) Epoch 3 versus Epoch 1



(c) Epoch 4 versus Epoch 1



(d) Epoch 5 versus Epoch 1



(e) Epoch 5 versus Epoch 4

Fig. 8. Computed node point displacements between measuring epochs; (a)-(c) effect of depropping, (d) de-propping and glazing (total dead load), and (e) glazing load alone.

As can be seen from Fig. 8, significant deformation accompanied the de-propping of the cantilevered section of the North Atrium structure. The maximum node point deflection at the first de-propping (Fig. 8a) was 2.5mm, with the corresponding deflections for the second (Fig. 8b) and third (Fig. 8c) de-propping being 5.3mm and 8.5mm, respectively. With the significant load accompanying the installation of the exterior glazing, the deflections sharply increased, especially vertical displacements on the glazed north and west walls where a maximum deflection of 22mm from initial condition occurred (Fig. 8d). Of this overall 20mm vertical settling, approximately 14mm could be attributed to the weight of the glazing (Fig. 8e). In general, the behaviour of the structure was in good agreement with theoretical predictions based on the Atrium’s design, even though a number of the nodes had deflections that were less than predicted.

6. Concluding Remarks

Although vision metrology has been adopted widely in the large-scale manufacturing sector as a flexible, economical and highly-accurate 3D tool for deformation measurement (eg Ganci & Handley, 1998; Fraser, 1999), the technology has not attracted broader usage within the building and construction industries, though applications to the monitoring of large engineering structures have been reported (eg Kersten & Maas, 1995; Fraser, 1995; Fraser & Brizzi, 2002). The successful conduct of the multi-epoch deformation monitoring of the the complex North Atrium structure has highlighted the applicanbility of photogrammetry and the benefits of this technology for building construction. Without the vision metrology surveys performed, the engineering team would have needed to rely solely on complex CAD models of the overhanging atrium section for subsequent analysis. Instead, the photogrammetric measurements yielded comprehensive deformation data to independently assess the structural models and to subsequently refine these models.

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