Interferometric Radar for the Measurement of Structural Deflection of Concrete Structures

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ABSTRACT
Owners are driven by safety requirements to monitor and predict the behaviour of their structures with increasing surety. Historically Engineers used deflection and strain measurement but more recently dynamic assessment of full-scale structures using vibration testing is being used to meet the owner's needs. Generally, this testing requires the installation of many transducers over the structure. The time and cost associated with installation limits the use of structural monitoring and therefore the safety of structures. Microwave interferometry, is a new technology that can monitor both deflection and vibration of many points on a structure. No contact is required during testing, and the system can be set up within 1km from the structure, and detects static and dynamic deflections of multiple points on the structure down to 0.01mm at up to 100Hz using its radar sensor.

This paper studies the use of the microwave interferometry in monitoring of structures for deflection under static and dynamic loading to ultimately monitor the overall health of the structure. A new move to investigate the deflection "signature" of new structures after construction to use as a base-line for future monitoring is also discussed. It includes a step by step description of the deployment of the sensor in the field and treatment of the resulting data. Case studies from Australia and around the world will be used to illustrate the information that stems from the system and will focus on comparing the technology to existing sensors to bench-mark the system.

KEYWORDS
Interferometric radar, deflection, vibration, testing

INTRODUCTION

Many different techniques are currently available for testing structures including measuring deflection for static and dynamic loading, ambient vibration testing and modal shape analysis. This testing is generally performed using a range of sensors including: total station, linear variation differential transformer (LVDT), accelerometers and piezoelectric sensors. Most of these sensors require contact to the structure for installation. Many also require considerable time to collect and analyse the data. When costing a project, the sensor cost must be added to the cost of installation, data collection, data analysis and ancillary costs such as traffic control in the case of bridges etc.

Currently load testing is seldom undertaken at any stage because of the high accumulated cost. So engineers are forced to make decisions without as-built structural performance data. This leads to higher reliability requirements throughout the structure's life than would be the case if such proof testing were undertaken. There is currently a conflict. Constructors are increasingly focusing on decreasing cost, programme length and limited resources, they are also becoming more risk adverse and seeking to improve their decision making ability.

Internationally the prevalence of structural failures is becoming an issue. Aging infrastructure means that the funds for inspection and repair of structures are being stretched thinly. The cost of inspection is a serious concern for agencies such as main roads departments. There is an extensive and growing list of failures noted every year from the well-publicised international case of the I-35W bridge (Levin 2007) collapse to the locally significant McLaren Vale tank collapse (Safework SA 2010). On the I35W in particular monitoring of the structure as suggested after several low ratings, stemming from corrosion and cracking issues may have prevented the collapse. Cost of investigation was definitely a factor in monitoring never being carried out.

With simpler systems for deflection measurement testing engineers could:

- Test the structure's actual reactions to load against the design predictions
- Test a structure at construction and again at regular intervals comparing the signature as time progresses to identify changes.

Microwave interferometry, is a new technology that can measure the static and dynamic deflection of structures. This data is readily used to calculate the velocity, acceleration and resonant frequencies by the software. The technique requires no contact whatsoever with the structure being monitored and can detect displacement of points on the structure with a resolution of 0.01mm and frequencies of 100 Hz (i.e. sampling frequency of 200Hz). A commercialised system called the IBIS-S designed specifically for structures was developed by the company IDS and University of Florence.

SYSTEM DESCRIPTION

The system consists of a sensor, power supply and control unit. The sensor has two horn antennas for transmission and reception of the radar signal; they are a typical super heterodyne design. The sensor generates a tune-able sine wave with central frequency of 16.75GHz and with a bandwidth of 300MHz. The Radar is classified as a Ku – band, according to the standard radar-frequency letter band nomenclature from IEEE Standard 521-1984 0. (Bernardini et al 2007)

The sensor is supported on a tripod with a fully rotatable head. This allows the sensor to be placed easily at many angles and hence in the required direction. Communication between the radar sensor and the control unit are achieved with the use a standard USB interface. The control system is a standard laptop running Windows XP as the operating system. The control system has dedicated data logging software to configure, store, process and view the data. The power supply is a commercially available motor cycle battery supplying 12V which can power the system for 6-8hrs in the field.

Unlike Ground Penetrating Radar, the intensity of the returned signal is not only due to the material composition (i.e. dielectric constant). A more important factor is the geometry of the target. Shapes that focus the reflected radio waves give a stronger reflection than the surrounding area and work well as targets, for example the right-angle created by a beam placed flush beneath a bridge deck will reflect better than the flat surface of the soffit. Targets can also be installed onto the structure where a particular point on the structure needs to be analysed and there is no natural feature to act as the target. While engineers are often able to use existing features as the measurement point on existing structures for new structures targets can be incorporated as part of the design (Figure 1).

BASIC MEASUREMENT PRINCIPLE

This Interferometric Radar system makes use of two techniques, stepped frequency continuous wave and differential Interferometric.

The Stepped-Frequency Continuous Wave (SF-CW) technique (Taylor 2001)

This technique differs from Impulse Radar which is commonly used in Ground Penetrating Radar systems. The principle is that the radar steps through a range of frequencies from the bottom of the band width to the top of the bandwidth. The sensor cycles through the bandwidth at up to 200 times per second (i.e. 200Hz). The data is analysed in the frequency domain rather than time domain allowing not only the real but the imaginary component of the signal to be analysed. Essentially this means that the phase and amplitude data can be retrieved by Inverse Discrete Fourier Transform (IDFT). An amplitude range profile of the radio echoes is constructed for 0.5m bins from the calculated IDFT. This is basically a one dimensional map of the most intense reflectors within the view of the sensor.

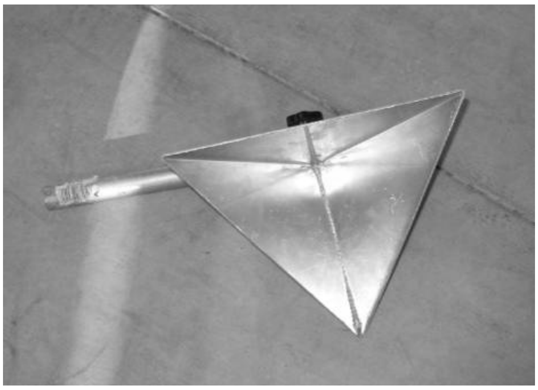

Figure 1: Suitable permanent target (Bernardini et al 2007)

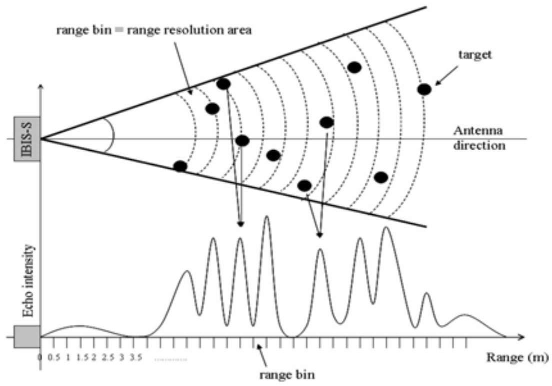

Figure 2: Targets within the same range bins cannot be distinguished (Bernardini et al 2007)

Figure 2 demonstrates the concept. Targets reflect the radio waves within the range of the antenna, the range and intensity of the reflection is illustrated in the lower graph, where peaks in the radiogram are apparent for each of the targets. Due to the IDFT calculation targets within the same range bin appears as the same peak. The sampling frequency controls maximum frequency measurable by the system. The Nyquist frequency or maximum detectable frequency is approximately half the sampling frequency. The frequency that can be sampled is controlled by the distance from the structure as the radio waves must travel further to the structure and the sensor must wait longer for receipt of the returned signal. Practically this means a range of 1km can only be sampled at 20Hz, whilst a small structure may be sampled at 200Hz. The sampling rate does not have any effect on the accuracy as this is determined by the wavelength of the radio waves.

The Differential Interferometric Technique (Henderson & Lewis 1998)

Once the measurement data has been assigned to range bins and the peaks selected for the targets of most interest, the deflection of the targets is measured using differential interferometry. Basically the phase of the returned radio waves from each target is measured during every consecutive sample. Where the phase of the returned signal changes we can calculate the physical displacement of the target by using the formula:

$$d_p \propto \frac{\lambda}{4\pi}\Delta\varphi$$

Where dp is the radial displacement, λ is the wave length, and φ the phase change. Because a range of frequencies, and hence wave lengths are used, even where the deflection is greater than wavelength in one frequency (i.e. indiscernible by phase data alone) a sample from another frequency will indicate this. Figure 3 illustrates the overall concept graphically.

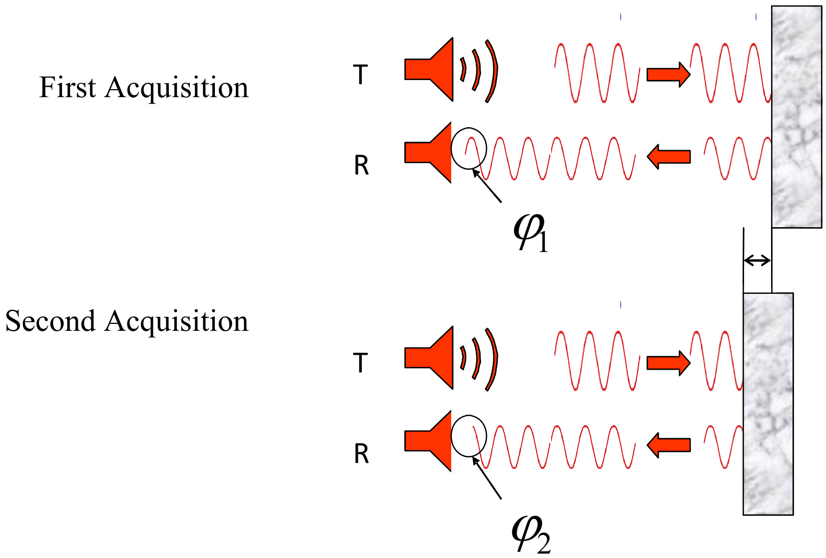

Figure 3: Data collection process in the Interferometric process (Lee 2010)

At this stage in the process the displacement being measured is the radial displacement (i.e. along the line direct from the sensor to the target). In order to calculate the vertical or horizontal deflection, the geometry of the test set up needs to be taken into account. In the example shown in Figure 4 the vertical component of the deflection of the bridge is calculated as: d_p= d sin (α). Where the structure is vertical, the same calculation would give the horizontal component.

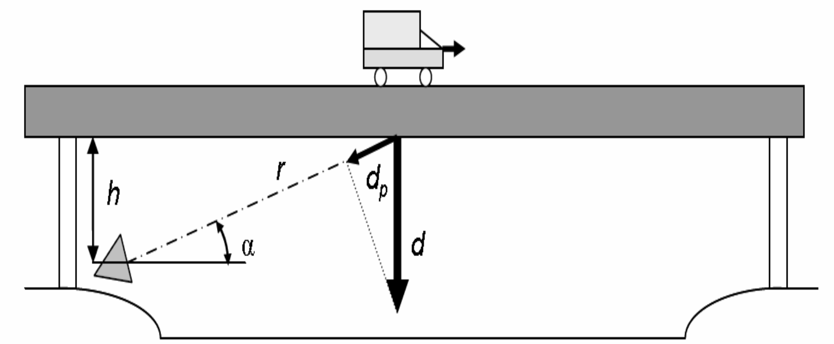

Figure 4: Example of Resolving Measured Movement as a Deflection (Lee 2010)

In order to calculate only one component of movement (i.e. vertical or horizontal) care must be taken in the alignment of the system. Where the vertical component is required for a bridge beam or deck the alignment must be directly down the length of the structure, in most cases this would be accessed from beneath the structure. To measure the horizontal component, the alignment would be from the side at the level of the bridge of the deck or edge beams. Where 3 dimensional movements are required to be measured, the current acquisition system allows for up to three sensors to be synchronised wirelessly and placed at points near the structure advantageous for measurement of each component. This allows torsional movements to be monitored.

TYPES OF STRUCTURES

Interferometric Radar lends itself to many types of structures and test type as shown in Table 1.

Table 1: Applications of Interferometric Radar on Structures

Suitable Structures	Methods of Application
Bridges *Measurement of deflections under dynamic and static traffic loads to verify structure and element structural condition during construction, on completion of construction and during service.* *Monitoring instantaneous deflections to identify change in loading with time.*	Static Load Testing *Defections measured as load (e.g. kentledge, water or vehicles) is applied.*
Buildings *Static load tests without the need for reaction frames on suspended slabs.* *Assessment of natural frequency from wind load vibration tests.*	Dynamic deflection measurement *Deflections measured during normal operations as structure subject to dynamic wind or traffic loads.*
Pavements *Stiffness testing of sub-base and subsequently cast slab for slabs on grade to check thickness and compaction*	Assessing the natural frequency of structures *Deflections due to wind load.*
Towers (Radio, Power Transmission etc) *Measurement of multipoint deflections under wind loads to assess lattice performance*.	Modal Analysis for vibration *Model the various modes of vibration for a structure above the first harmonic.*
Cable Stays *Vibration analysis to give cable tensile stress.*	Determination of frequency/tension of cables *Vibration under to wind loads (e.g. cables).*
Silos *Dynamic and static load tests by measuring hoop and vertical deflections during loading and unloading.*	Calibration of finite element models *Static and dynamic tests compared to FE result, particularly to test the boundary conditions assumed during modeling.*
Tunnels *Measurement of long term deflections within the tunnel during construction and service life.* *Monitoring of movements of critical structures above the tunnel.*	Determine baseline/signature deflection and frequencies for structures *To be used for network level investigation of bridges and structures, repeating the measurements over time and finding distress by finding changes to the behaviour of structures.*
Mines *Real time monitoring and alarming of slopes to give warning of potential slips.* *Dynamic analysis of major structures e.g. un-loaders and crushers.*	Measure the effectiveness of strengthening *Take deflection readings before and after construction to monitor outcomes for projects and match modeling.*

CASE STUDIES

The system has been used on a number of different structures in Australia and overseas. Case studies discussed below just scratch the surface of what can be done with the system. There are of course limitations to the method, it is not a panacea, but the examples show that it is an important structural assessment tool that has the capacity to increase the proof testing undertaken thereby increasing reliability or enabling cost saving measures while maintaining the reliability.

Soul Building (Gold Coast, QLD)

The Soul Building is a new high-rise structure currently being constructed in Surfers Paradise QLD. The structure has three interconnected towers reaching a height of 249.4m with a total of 77 floors and is located directly adjacent to the beach and hence is not protected from any weather approaching from the East.

Excitation of the structure was measured from the West side of the structure. The source of the excitation was the lifting and lowering of weights on three roof top cranes. Various positions and combinations for the cranes were used for the experiment. The sensor was placed 106.8m (measured using a total station) from the base of the structure, with a tilt angle of 55°. Data was collected in 10 minute files so as to keep the data manageable. A sampling frequency of 94Hz was used.

Figure 5 shows a small amount of the data collected during the experiment. It is the projected displacement for a target (underside of a balcony) at a height of 136.5 m up the tower. The displacement has a cyclical nature, indicating that the structure was swaying under ambient condition. A period of excitation can be seen from 490-500 seconds, where the amplitude of the displacement triples to approximately 5 mm horizontally forwards and backwards in relation to the sensor.

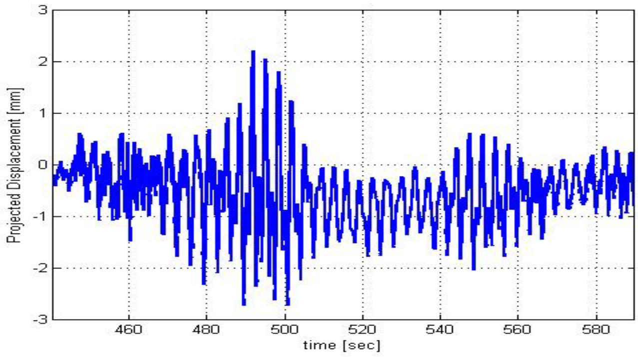

Figure 5: Time domain data collected during testing of the Soul Building

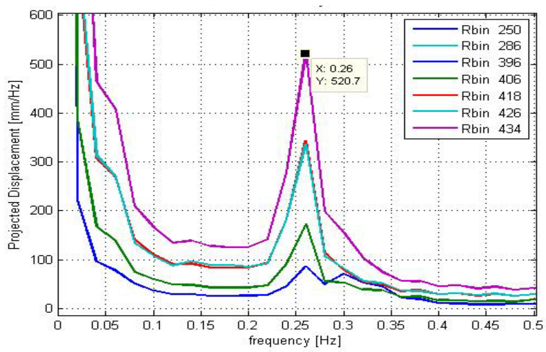

Figure 6: Soul Building frequency domain Data showing the structure natural frequency

The data was also analysed in the frequency domain to pick the harmonics of the structure. The cyclic nature of the data in Figure 5, clearly indicates that at least one harmonic should be apparent. Figure 6 shows the frequency data for a number of positions on the structure. All seven displayed indicate a peak in the frequency data at 0.26Hz which is close to the natural frequency which was determined during design of the building.

Adda River Bridge (Italy)

The case study investigates a bridge which crosses the Adda River between the towns of Capriate and Trezzo in Italy (about 50km far from Milan). A schematic drawing of the bridge is shown in Figure 7. The bridge was constructed from concrete in the 1950’s, has a total length of 113.3m. The central span which was investigated is 62.5m long and consists of two variable-depth balanced cantilevers (21.80m long each), connected by one simply supported drop-in girder (18.9m long). The monitoring exercise aimed to analyse the Modal and dynamic behaviour of the bridge and compare the Interferometry data against Accelerometer data.

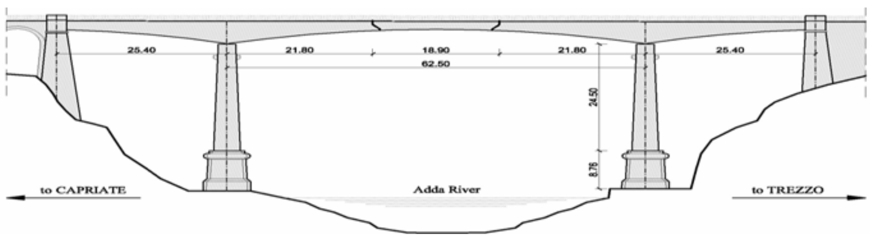

Figure 7: Schematic of the Adda River Bridge, showing the central span in question (Bernardini et al 2007)

In order to directly compare the accelerometer data to the Interferometry data, 32 accelerometers (model WR 731A) were installed along the either side of the bridge's central span. Passive targets, to be monitored by the Interferometer, were placed adjacent to these accelerometers at six positions. Figure 8 indicates the position of the sensors and the passive targets; it also shows an image of the target/sensor installation. It should be noted that the targets are only required where specific points on the structure need to be measured.

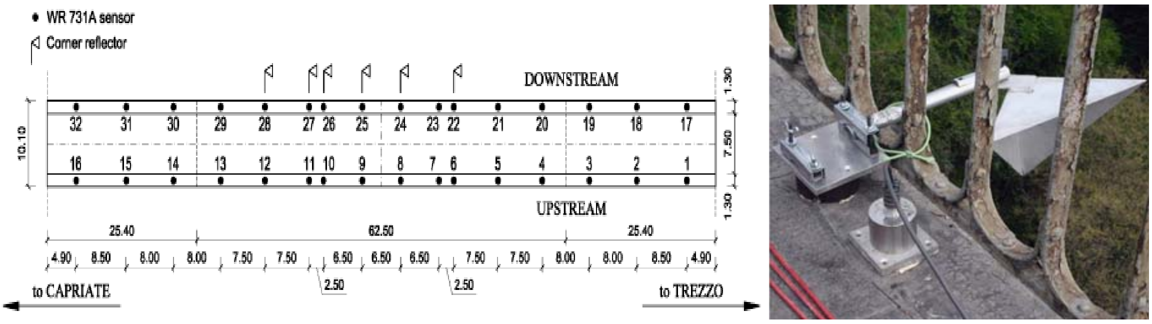

Figure 8: Location of accelerometers and passive targets on the central span (left), image of accelerometer and target installation (right) (Bernardini et al 2007)

The Interferometer system was placed near the basement of the Trezzo-side pier, at a distance of 4.60m from the axis of the pylon. A series of ambient vibration tests were carried out using both sensors simultaneously. Approximately 10 minutes of data was collected in each data set with a sampling frequency of 100Hz used for the Interferometry data. Figure 9 demonstrates the returned radar signal from the structure. There were a number of good reflections from the bridge, including the passive targets that had been installed. The correct targets were confirmed using the distance from the sensor to the target as a reference.

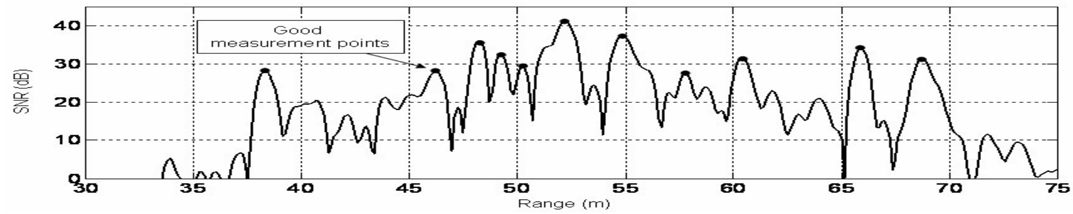

Figure 9: Intensity of the returned radar signal (Bernardini et al 2007)

Figure 10 indicates velocity/time data for both the accelerometer and the Interferometer over a period of 200s. All of the major and indeed minor excitation noted during the period corresponds between the two data sets. The major sources of excitation during the experiment were ambient movement from wind gusts and passing traffic over the bridge.

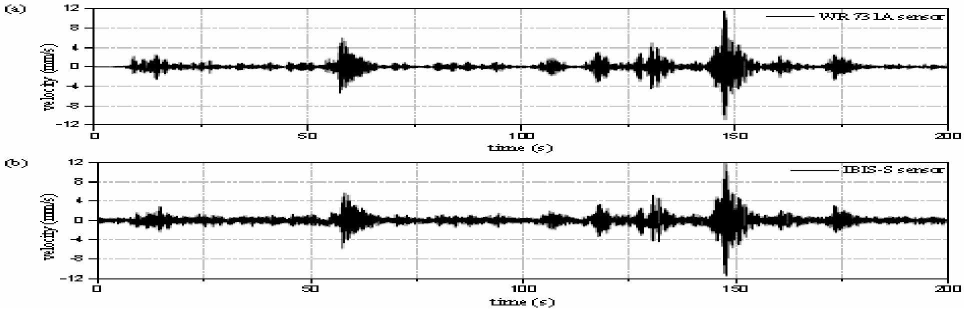

Figure 10: 200s of Velocity/Time data for both sensors (Bernardini et al 2007)

The resonant frequencies and mode shapes, identified from the radar signals, were also compared to the corresponding modal parameters estimated from the accelerometer's data. The identified natural frequencies turned out to be almost equal to the values obtained from operational modal analysis of the ambient acceleration (with the frequency discrepancy being less than 0.90%, see Figure 11).

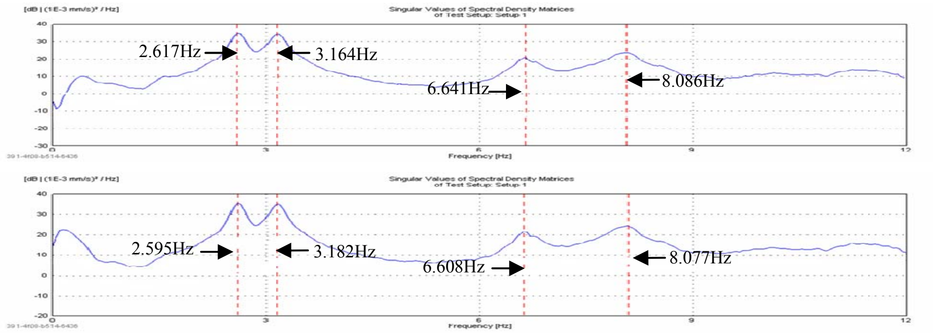

Figure 11: Frequency data measured using the accelerometers (top) and Interferometer (bottom) (Bernardini et al 2007)

CONCLUSIONS

Interferometric radar is a new device for measurement of structural deformations to a high degree of accuracy provided suitable target can be identified and site geometry is suitable to the test method. The method is expected to have a wide range of applications and it is anticipated that it will facilitate greater proof load testing of structures.

For new structure it is foreseen that targets will be fixed as part of construction and the structure will be measured during construction and on completion to verify construction is in accord with design. Subsequent measurements during the structures life will be checked against the initial signature to show changes in condition.

For existing structures it is expected that the method will be used to measure deflections and vibrations in real time to give an indication of structural capacity and applied loads.

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