Summary

Time is of the essence during the data acquisition phase of a forensic structural investigation; the preservation of post-failure site conditions may be limited and access to the site may be restricted. The acquisition of accurate and timely information from the field is a vital component of every forensic structural investigation and often occurs during limited time frames. Laser scanners and vibration sensors are becoming ubiquitous on construction sites. Collection and processing of laser scan data, correlated with vibration and other sensors, can be effective for assessing the condition of an existing building or for collecting forensic information after a failure or collapse. The automatic collection of data creates new challenges: how to effectively sift through the wealth of information provided by the scanning and sensing devices. A good engineer in the field can accurately describe a structure with only hundreds of measurements. A laser scanner on the other hand takes thousands of points of information. Case studies of forensic investigations that have used laser scan technology and vibration sensors will be presented along with ideas for how to enrich our forensic tools with the growing wealth of available devices.

Keywords: 3D Laser Scanner; Scans; Software for point cloud data; Vibrations Sensors.

1. Introduction

Forensic investigations are fundamentally different from new design or peer reviews because engineers have access to the actual physical structure. The more as-built information engineers gather the more comprehensive and accurate the conclusions of their investigation and any prescribed repairs can be. Vibration sensors can confirm the global behaviour of the structure or assembly, while laser scanners capture the geometric details of a structure and record any superficial damage.

Vibration monitors capture the dynamic behaviour of an object. For a building scale structure the first fundamental modes and the damping are most clearly captured. The mass of a structure is usually confirmed through the shop drawing and construction administration phases. While the material is a large component of the cost of the structure, the stiffness is estimated from models that usually include little more than the bare steel, concrete frame or shear walls. The partition walls, cladding and other finishes can have an appreciable impact on the actual stiffness of a building [3]. For forensic investigations, the dynamic behaviour of the structure provides an overview of how the structure has changed before and after an event; a significant shift in a structure’s frequency or even damping can be cause for alarm [1],[5].

Laser scanning is a method for accurately capturing the dimensions and position of any object. It provides an accurate record of the as-built conditions of a structure or assembly. Portable laser scanners in particular are becoming powerful forensic tools. The laser scan data enables the engineer to capture the site and chronicle any damage or deformation precisely. This allows the
investigator to differentiate between damage caused before the scan and damage caused by repair, recovery, or other clean-up activities that occur after the scan has taken place. The laser scan can be processed into a three dimensional representation of the structure allowing investigators to safely revisit a scanned scene virtually from the computer. Additional measurements can be taken and details that were not evident at the first and often only site visit can be discovered. Also, since the laser scan produces digital data, the information can be easily shared and manipulated.

The ability to quickly capture and access detailed data and accurate digital reproductions aids our property loss consulting and forensic investigation teams in assessing and analyzing structures of all types. Combining the laser scan information and the vibration information allows for the construction of extremely accurate as-built models. The connections and components that contribute to the stiffness are captured in the laser scan, and the resulting shift in frequency compared with the bare structure is verified with the vibration sensors.

2. Laser Scan and Point Cloud Technology

A laser scanner systematically records the distance from the laser scanner to the surfaces around it. The collection of point measurements is called a point cloud. Using post-processing software these points can be used to extrapolate general geometries and reconstruct even complex three dimensional structures and assemblies. Multiple scans from various sides of a structure can be combined into a single point cloud. Edges and surfaces can be reconstructed using specialized software.

There are two basic parts in the scanning process. The first is the field work where the scanner captures the data at the location of the structure. The scanner needs to be positioned strategically to capture as many sides of the structure as possible. Environmental conditions and the light also affect the quality of the scan. Scanner placement is further complicated by site logistics. In order to capture a large site and obtain a three dimensional output, multiple scans are required. Artificial targets, such as check board markers (flat targets) or reference spheres, are placed in strategic locations. The markers provide fixed points that can be used to weave together multiple scans into a single comprehensive point cloud and are fundamental for the second component of the laser scanning process, the post processing.

The combined point cloud can be further processed to produce a more useful deliverable. The combined point cloud files tend to be very large and a bit unwieldy, and navigating an unprocessed point cloud requires experience and patience. Noise resulting from varying sampling densities can be reduced and registration errors can be removed during post-processing of the point cloud. Walk-through and fly-through scenes that allow the investigator to pan, zoom, and rotate views can be created. Typical deliverables include two dimensional plans and elevations and three dimensional panoramic images with geometric information embedded. Processing the point cloud into a full three dimensional building information model is possible, but requires significant post-processing and specialty software.

2.1 Laser Scan Applications

The laser scan technology may be used for a variety of applications in the civil engineering and architectural industry. It can be a powerful tool in collapse investigations and structural damage assessments, it can enable the creation of interactive databases, and be used in heritage data collection.

In general, the technology has some limitations which need to be considered before performing a scan. Scans performed in the outside environment are generally less successful during a snow or rain event or when the temperatures are too high or too low. Even if the device is protected or is waterproof, the scans will have the noise generated by the rain drops or the snow flakes. Also, the reflectance of the snow can result in overexposed pictures. The reflection of the laser beam does not behave as expected when scanning of an interior with mirror or black elements; a potential decrease of the information of the data collected is likely and false data can be recorded. The scanner is not equipped with a flash. In order to collect data in colour the ambient light needs to be sufficient. Even without sufficient light however, the scanner is capable to collect data in grey point cloud form.
Depending on the unit, lasers scanners can scan vertical surfaces within a certain height and up to a certain horizontal distance. Horizontal and vertical measurements become inaccurate when the distance is greater than the one indicated in the device specifications. This limitation can generally be overcome taking multiple scans using reference targets. Also, the device needs to be stable and level within prescribed tolerances.

2.1.1 Collapse Investigations

In the case of a structural collapse, the scanner gives the opportunity to record the exact failure scene before the site clean-up. (Fig. 1). The point cloud and the photos taken by the scanner enable the user to navigate the scene remotely at a later time. The scans of a collapsed structure show the location of the structure’s elements relative to each other. The point cloud is a powerful cache of information that can help verify the assumptions used in the collapse analyses (e.g. take additional measurements, verify supports, and contact conditions, etc.). Moreover, the collapsed geometry, fractured surfaces and deformed shapes reconstructed from the point cloud can be compared to the results obtained from the analysis model and can thus serve to validate the analysis and its conclusions.

2.1.2 Structural Damage Assessment

Scans of a damaged structure collect accurate point cloud information of damaged elements. Large structures with complex geometry can be scanned, and the actual damaged condition can be assessed. Because the accuracy of the point cloud data is high, measurements and mark ups can be taken from it. This cloud can be exported for further processing in different programs. The point cloud in this specific case has been exported and manipulated into AutoCAD (see Fig. 2). AutoCAD was used to measure the displacement due to the damage. With the use of the animation it was possible to simulate the open and close configuration of the bridge and assess the interference between the two leaves.

2.1.3 Data Collection and Interactive Databases

Collecting data using the laser scan technology of an existing building or structure with no damage allows comparison of the data with a future variation. One of the challenges of this type of application is the site’s size and nested spaces which need to be scanned. The locations of the targets play an important role in the registration process. After collecting all the needed individual scan-data sets the multiple scans are merged into a single point cloud. Figure 3 shows multiple scans of a mechanical room registered together. A complete set of scans of mechanical rooms enables the owner to capture and store the status of the rooms, in particular the equipment and
structure, at a datum time and subsequently navigate the site. Additional information can be linked into the point cloud and create a complete database (i.e: equipment tags, maintenance schedule, etc). The data collected from the laser scanner is also thoroughly photographed. A single room can be selected and used to look closely at a particular area of the scanned site. The data can be shared with other parties using “WebShare” options offered by different software. This feature allows the information to be stored in a single location and at the same time can be shared with customers and partners.

2.1.4 Heritage Data Collection

Ideal for quickly capturing highly accurate and detailed as-built conditions of historical structures and buildings (Fig. 4), the laser scan constructs 360-degree point clouds of scanned surfaces to create 3D models used in building restoration or historic preservation plans. The data collected can be archived and used as reference for later studies. The point cloud can be manipulated and detailed elevations and plans can be produced. Heritage structures are usually very detailed and complex, the laser scan application reduces considerably the data’s collection time. Also, this application can help the user to build 3D finite element models of the as built condition to evaluate the structural capacity and integrity.

3. Vibration monitoring devices and technology

Vibration sensors allow for the measurement of the dynamic response of a structure to various excitations, but some understanding of the sensors’ limitations and output are required to correctly select and use them. Different technologies are used to within accelerometers, such as piezoelectric ceramics or micro-electrical mechanical (MEMS) devices, but the end result is the same: a voltage output in proportion to the accelerations. Typically accelerometers have a limited frequency range which they can reliably measure. Most have a minimum frequency, but some, such as MEMS accelerometers, do not. Structural vibrations are usually low frequency, which places them outside the range of many accelerometers intended for use in industrial or aerospace applications. Table 1 below gives a few common building vibration sources and the frequency and magnitude of vibrations typically associated with them. The natural period of multi-story buildings are typically between 0.1Hz and 1 Hz. Selection of an accelerometer should account for the sensitivity of the sensor compared to expected acceleration range in addition to the frequency.

The correct placement of the sensors is important to capture the dynamic response of the structure. There must be enough points of measurement to capture the modal shapes needed and the extent of the vibration issue. The type of excitation under investigation must be considered.

Once the accelerometers have been set up and powered, the signal from them must be properly conditioned and processed. Signal amplification or low noise wiring may be necessary to eliminate any noise from the signal, although some accelerometers have this built into them. A data acquisition (DAQ) system must be set up to record the incoming signal at sample rate high enough to capture the essential frequencies and to record a sample length long enough to adequately capture
the structural response. From here filters can be applied to eliminate unnecessary high or low band frequencies, and application of windows can mitigate the problems of signal aliasing in finite sample sets.

As technology improves, the usefulness of vibration measurement and monitoring improves and expands. Accelerometers are increasingly compact and less expensive. Applications have been developed to take advantage of nearly ubiquitous accelerometers and gyroscopes built into smart phones and allow for nearly instant and easy measurements and frequency analysis. Figure 5 shows the type of data collection possible from two apps created for the iPhone. Improvements in wireless technology allow for the monitoring and transmitting of data where conditions or layout would make wiring impossible or impractical and allow for more flexibility in how sensors are deployed. Improved and expanded wireless and cell services allows for the possibility of remote monitoring in more places. Incorporated in larger databases vibration recordings can further inform on the overall performance and condition of the structure.

3.1.1 Applications of vibration monitoring

Within the field of Structural Forensics vibrations sensors can aid in damage assessment, verification of analysis models and theories, and as condition monitoring post event. In case of catastrophic or total collapse accelerometers may be unable to provide much insight into the causes of failure after the fact but can be deployed to monitor the site and surrounding structures for excessive or problematic vibrations during the recovery phase. Construction projects commonly implement a vibration sensor in a similar way to ensure surrounding structures and properties do not experience excessive vibrations. In cases of partial failure where the structure remains and there are questions as to the extent of damage and repair and rehabilitation of a structure, recording and measuring the vibration signature of the structure can provide important verification of analysis models and calculations.

3.1.2 Use in understanding vibration issues in existing buildings

Increasingly slender lighter structures are being favoured for architectural reasons or materials savings leading to an increase in problematic vibrations. Frequently the issues are not related to safety or strength but to user comfort, but excessive vibrations can also lead to fatigue and damage to the structure. Non-structural changes, such as a change in interior partitions or layout, change in use of structure, or change in mechanical pieces, can create an issue where there was not one before. The frequency content of the problematic vibrations can help pinpoint the source: whether it is footfall excitation, mechanical, train or road traffic, or even natural forces such as wind. Making use of the accelerometer built into most smart phones can permit quick measurement and assessment of the vibrations for smaller scale issues such as uncomfortable floor vibrations. For more transient vibrations, a monitoring and data acquisition system can be installed.

Table 1: Typical range of structural response for various sources [2]

<table>
<thead>
<tr>
<th>Vibration source</th>
<th>Frequency range (Hz)</th>
<th>Acceleration range (%g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic</td>
<td>1 to 80</td>
<td>0.2 to 10</td>
</tr>
<tr>
<td>Machinery - inside</td>
<td>1 to 1000</td>
<td>0.2 to 10</td>
</tr>
<tr>
<td>Human activities</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-impact</td>
<td>0.1 to 100</td>
<td>0.2 to 50</td>
</tr>
<tr>
<td>-direct</td>
<td>0.1 to 12</td>
<td>0.2 to 2</td>
</tr>
<tr>
<td>Earthquakes</td>
<td>0.1 to 30</td>
<td>0.2 to 200</td>
</tr>
<tr>
<td>Wind</td>
<td>0.1 to 10</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5: Vibration measurements as recorded by an iPhone. The left most image shows the output of an FFT analysis of a vibration set. The centre and right images show vibration recordings in progress.
and set to record when a threshold of acceleration is reached, allowing the investigator to “catch” the vibration as it happens. Vibration monitoring provides verification of any analysis of the structure, which can give more confidence to any proposed repairs of retrofits.

3.1.3 Structural vibration monitoring

As with laser scanning, if vibration monitoring is deployed prior to a failure event, it could help to determine whether a structure has been significantly damaged after an extreme loading event. Non-trivial damage will change the stiffness and damping of the structure. Knowing how the dynamic properties have changes after a major event or a failure gives more information to the analysis team to understand what happen and to analyse possible repairs scenarios. Progress is being made toward the implementation of real time monitoring which allows building managers to check on the overall health of their building or would give state and local officials more information in determining when to repair or close bridges prior to failure [4].

4. Conclusions

Vibration monitors and laser scanners are becoming ubiquitous in the built environment. Vibration monitors are in every phone and laptop, and table top and hand held laser scanners are similarly sold to consumers. While both technologies can support forensic structural investigations, neither supersedes the traditional forensic investigation. In order to collect the data efficiently it is important to understand the limits of the laser scanning process. A large quantity of data can be collected in a few site visits. The data can be processed in the office and details which were not obvious at first sight can be found during a subsequent assessment. Cost effectiveness of laser scanning may be obtained by limiting site visits and time spent in the field. At the same time, it is important to remember that all the data collected needs to be manipulated in the post processing where often capabilities of both software and hardware are limited. Vibration monitors similarly excel at capturing average or global information about a structure, but the behaviour of the structure under investigation must be sufficiently understood to ensure the correct sensors, number of data points and placement are used to obtain useful data. Nevertheless, the combination of laser scans and vibration monitors help confirm structural behaviour and analyses. At a minimum, the additional information will help investigators explain and support their conclusions.

5. References


