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SAMCO NEWS

Structural Assessment Monitoring Control Issue 17 / December 2005

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Final SAMCO Meeting 2006

Building of EMPA / Switzerland

The final SAMCO meeting will take place from March 30th to 31st 2006 on the premises of the Swiss Federal Laboratories for Materials Testing and Research (EMPA) at Dübendorf / Switzerland.

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The following sessions will be brought up in the course of the final meeting:

- a ½ day session on hardware development with presentations of different companies
- a session presenting the SAMCO history and achievements
- a session with presentations of partners and members
- a poster session for the access papers organized with 3 slide quick presentation and 1h for poster discussion
- a session on the strategic research agenda
- foundation of the European Association of Structural Assessment Monitoring and Control

The last ½ day will be reserved for a visit to the EMPA laboratory and for a panel discussion on the future of SAMCO and the perspectives of the field.

Standardisation Activities in SAMCO

Introduction

The standardization initiative embedded in SAMCO was involved into the international standardization activities of I-SAMCO. The following activities will be further developed within I-SAMCO and include international activities.

Guidelines for Structural Control

Structural control has gained more and more in importance because structures in aerospace, mechanical and civil engineering industries have become complex and sensitive to undesired vibration influences. The increasing number of publications confirms the interest of engineers and scientists on this topic.

The goal of this guideline is to give an overview and a state of the art, respectively. The guideline will present and summarize approaches and methods in the field of structural control. From this point of view, the guideline may be a helpful document and a source of ideas and references for end users. Using this guideline, an end user should be able to adapt and to combine possible ways of structural control devices in order to find a unique solution for suppressing undesired structural vibrations.

Standards of Germany, Japan, the United Kingdom, the United States as well as reports of international researcher organisations (e.g. federation du beton – fib; ISIS Canada) have been scrutinized. Only little material could be found. Nevertheless, structural control principles and their applications, different aspects of their testing, the derivation of equation systems etc. are described in many research publications, laboratory reports and books. The material was collected and systematized in a way that the information could be used for the guideline. Actual research results of EMPA Laboratory as well as those of SAMCO partners were considered.

Harmonisation, benchmarking and standardisation are only possible, if a critical mass of institutions and researches are standing behind the technology. The application in the market is widely depending on applicable standards, which can be drafted, supported or distributed.

Goal and Definitions

The guideline was developed by the Structural Engineering Research Laboratory of the Swiss Federal Laboratories for Materials Testing and Research (EMPA). The goal of this guideline is to give a state of the art or overview, respectively, of structural control. This guideline presents and summarizes the usual approaches and methods in the field of structural control. From this point of view, this guideline may be a helpful document and a source for ideas and references as well for engineers and scientists.

This guideline focuses on “Structural Control” of civil and large scale mechanical structures but not on macro or micro sized structures. Moreover, any pre-stressing of larger structures using piezo elements in order to produce the desired shape or pre-stress of the structure will not be treated within this document although such procedure is often called structural control. The reason is that such a procedure can also be seen as the original design of the structure. Hence, this guideline describes the common control hardware and control methods used for suppression of undesired structural vibrations that occur after the construction and erection, respectively, of the structure.

Structure of the Guideline

The guideline is divided in two main parts: the first chapter deals with control devices and control methods aiming to increase the damping of structures. This is the case when additional dampers/actuators are attached to vibrating structures and these dampers/actuators are feedback controlled by a control unit according to the actual vibration state. The subchapter damper devices include passive dampers, controllable dampers and actuators. For each of them the theoretical background, design issues, testing and validation procedures, implementations and applications (case studies) are explained. References to important publications are also included.

The second subchapter describes control algorithms, usually applied when controllable dampers or actuators are implemented for vibration control. First, the main control strategies such as feedback, feed forward and passive control are shortly introduced. Then, active damping with collocated pairs is described, followed by optimal control approaches. Finally, other common control approaches are summarized. In contrast, the second chapter gives an overview of vibration isolation systems. Here, the target is not increasing the damping of structures by external damping devices but isolating structures from disturbances. This chapter is divided in two parts. First, passive isolators are described, then, vibration isolation is presented.

Guidelines for Monitoring and Assessment

To remove the major obstacle in the application of the already existing methods guidelines shall be drafted to form a basis for a public order of such services. This is the demand which the EU Commission has placed at the SAMCO network with the expectation that the guidelines will be the base for an inter-national code to be worked out.

There isn't a comprehensive international standard yet which describes the use of methods and procedures of SHM (Structural health Monitoring) according to comparable results. The following explains the concept and the contents of that guideline for monitoring and assessment of engineering structures which is developed at BAM currently and brought into the international standardization process (CEN or ISO) for the processing until March 2006.

Structural assessment is an essential part of the management of structural networks and the development of strategies and procedures for achieving an optimum balance between cost and safety as well as cost and serviceability is becoming a major objective for authorities, operating buildings, bridges, tunnels, dams and industrial structures.

The determination of the conditional state of structures is in most cases still based on visual inspections and described by subjective indices. Beside those traditional methods permanent monitoring will be more and more applied in future for observation of the structural state.

The required technique is by now available and the adopted procedures are state of the art in a wide range. Nevertheless it needs to be pointed out, that these tasks require a multidisciplinary cooperation between the specialists of civil-, electrical- and computer engineering. To obtain comparable results from monitoring for further use as input values of the assessment process, a standardised concept for monitoring is necessary. Such a standardised concept is supposed to be developed with the monitoring guideline.

Structures are then typically assessed by the same idealized models and procedures as used for their design. These traditional methods have been indicated as the most critical technical barrier to effective infrastructure management. Maintenance needs should be based on quantitative values like objective safety and serviceability rather than on the qualitative values of the visible condition state of the structure. There is a wide range of assessment procedures with different sophistication developed worldwide. Especially in recent years, based on the progress in sensor and computer technology, the stochastic character of structural state influencing values can be considered in the assessment process. The wide range of possible assessment procedures need to be described and structured in dependence to the assessment objective. This is supposed to be done in a guideline for structural assessment with the major ambition to give an outline of possible methods to allow the practicing engineering community to pick up the method, adequate for the assigned task.

Certification

Concerning recommendations and codes arsenal research Ges.m.b.H, an Austrian research centre, has contributed in SAMCO to the establishment of codes and guidelines in the field of monitoring and assessment of civil engineering structures. Main subject area of arsenals contribution is devoted to certification. A first draft of the certification program was submitted to the coordinator under the title “Draft Procedure for Certification” beginning 2004.

The stock of civil engineering structures like buildings, bridges, tunnels and many others was increasing all over the world during the last century. Users and owners of such structures, have experienced, that their constructions are reaching a critical age, where rehabilitation and retrofit works become essential. This critical age in average starts after 30 years of service. Owners and maintenance authorities are therefore in a difficult position because public safety is a must and the financial and economic consequence of a structural failure is considerable.

Therefore alternative methods and approaches are required in order to manage the huge stock of aging structures in a proper way. So far, the commonly applied concept of maintenance is based upon a periodic inspection of structures, where usually the simple visual inspection is the first step. Due to the fact, that more objective methods are required to assess structural condition, there is a demand need for new technologies in the field of civil engineering.

Several technologies have been developed and applied during the last decade, the commonly used approaches are shown in this current practice report. Key point in extending the lifetime of structures as well as keeping structural safety to a reasonable limit is to determine the current structural condition by a proper investigation program. Main prerequisite of investigations concerning the structural condition is, that the applied technologies do not have an impact to the structural integrity itself. In addition no negative consequences either to the users of such technologies as well as the environment should occur. Non destructive testing (NDT) of materials and structures plays a significant role for new constructions, development of products and for the implementation in maintenance strategies. Thus, the importance of NDT technologies is still increasing.

The “Current Practice Report on Structural Assessment” mainly represents non destructive testing technologies and has been written to contribute to SAMCO project WP 3. Main aim is to provide fundamental knowledge of these techniques in civil engineering. The report is submitted together with this draft contribution for certification.

The currently applied technologies comprise a wide field of different approaches and methods. It was tried to give an overview about the principle, the physics as well as the practical application of the described testing methods. It should be further noticed, that this review could not be a comprehensive survey of all existing technologies, but rather a snapshot of the essential and applied technologies for structural assessment in the civil engineering practice.

Structural assessment and in particular non-destructive-testing is an active and ongoing field of research, which is mainly triggered by the strong requirement from the industry to support subjective visual inspection methods by objective testing and non-destructive evaluation tools. These approaches are mainly based upon physical measurements of structural response or material properties followed by interpretation of the recorded data. Technologies can be classified in two main groups which are looking to the global and local behaviour of structures. Whereas local methods always focus on a part of the structure, global methods employ a response characteristic of the structure to determine the condition and reliability of the whole construction.

Local NDT methods shown in this state of the art report are based on acoustics, eddy currents, hardness testing, magnetic fields, and radiography for example. A successful global approach to assess the structural condition is based upon measurement of the vibration characteristics or the structural deformation during loading. In this context it should be noted, that vibration-based damage detection relies upon the fact, that a local stiffness change caused by a damage, leads to a change in the global dynamic response of the structure.

The main advantage of global methods is, that measurements taken in a few locations of the structure only, are sufficient to assess the condition of the whole construction. Main target of global methods in the first step is, to limit prospective damage areas to local zones in order to apply local NDT methods quantify the extent of damage. A successful maintenance and investigation program therefore should employ both – global and local – methods over lifetime of any structure. Usually there are four levels of damage identification which have to be treated:

- Level 1 – Damage Detection:
  Is the structure damaged or not?
- Level 2 – Damage Localization:
  Where is the damaged area located?
- Level 3 – Damage Quantification:
  What is the extent of damage?
- Level 4 – Prediction:
  What is the remaining service life of the structure?

The main groups of non destructive testing approaches can be summarised as follows, a more detailed list concerning techniques which have been used successfully for monitoring civil engineering constructions is prepared in the report already mentioned:

- Mechanical and Optical
- Penetrating Radiation
- Electromagnetic and Electronic
- Acoustic and Ultrasonic
- Chemical Techniques
- Thermal Techniques
- Signal-Image Analysis

Structural Health Monitoring today - Results from collected case stories

A major input for pre-standardisation is the knowledge about current practice and methodologies. Therefore an extensive set of case stories about the present application of Structural Health Monitoring was compiled by BAM.

The following data was requested:

- kind of structure
- monitoring objective
- monitoring technique
- kind of sensors
- data and analysis
- monitoring results

The interpretation of the results from case studies was done on the basis of the structure, the monitoring system and sensors and the data and analysis.

NEES-IT Technology

NEES-Grid

The Network for Earthquake Engineering Simulation (NEES) currently integrates the major US laboratories on the NEES-Grid, making it possible for researchers to collaborate remotely on experiments, computational modelling, and education.

The NEES-Grid tutorial workshop for all the EU Partners (follow up of the I-SAMCO Harmonization Workshop of September 27th to 28th 2004) was organised at the JRC-Ispra on May 23rd to 24th 2005.

The objective of the seminar was to provide potential European Partners with the necessary background to evaluate the NEES initiative and consider the possibility to assume the NEES-IT technology as the basis for harmonization of data and experimental results. The technology includes also items of interest for the realization of distributed (virtual) laboratories, which are under development also in Europe and at JRC in particular.

The main topics of the Seminar have been:

- Training of System Administrators for the NEES-Grid technology
- Training to the Users showing how to use NEES-Grid for conducting research projects
- Training to the Developers showing how earthquake engineering and IT specialists world-wide can add new features and capabilities to the NEES-Grid software

DRAFT Collaboration Agreement on IT Networking Technologies

Through the SAMCO Network, JRC accumulated specific competences in IT networking technologies and Databases. Due to the common interest of collaboration, a DRAFT Collaboration Agreement for a bilateral NEES-Org and JRC collaboration has been prepared and is ready for signature.

This initiative is the basis for a wider EU-NEES collaboration on IT technologies for the networking of laboratories in the world and for the harmonization of data and results of experimental tests. This standardization is the basic element for the communication and the possibility to take advantage Europe of tests results obtained in USA and vice versa.

Since a similar collaboration has bees signed between NEES-Org and NIED (Japan), there is the possibility to enlarge the collaboration and diffuse the standardization of the experimental results.

Results from Initiatives outside the EU

The major initiative in the field of structural assessment, monitoring and control concerning pre-standardisation can be found in the NEES (John Brown Network on Earthquake Engineering) project, support by the US NSF (National Science Foundation).

The network is interested in the harmonization of data and methods and is willing to cooperate with European partners.

Data Exchange by NEESit

The major task of NEESit is to support the scientists at their test facilities by a suitable IT infrastructure. This infrastructure was launched in October 2004. An introduction on the priorities and services of NEESit was given at the NEESgrid Workshop.

Currently there is an interim data repository, a user support centre, a FTP server, a web server, an e-mail list management, etc.

The software architecture of NEESit includes on principle three domains of software:

- In San Diego there is the central data repository and the **NEEScentral.**
- At the equipment sites there is the software **NEESpop** that is the interface between NEEScentral and other software applications, flexTPS, which is the tool for tele presence, and NEESdaq for data acquisition on the test sites.
- **Remote clients** can connect via internet to the NEESpop for tele presence and data visualization. Remote control to the facilities in the equipment sites can be provided, so that a test can be run remotely form outside the laboratory. The tools implemented on this stage are the RDV, the real-time-data-viewer, that is used for visualization of data during tele presence session, the NTCP for Matlab, which is the NEES transfer protocol and finally the PNNL electronic notebook.

NEEScentral is a web based interface to the data repository with an authentication model. NEES members are able to upload and download data to the server. By an authorization model the data can be made public or accessible to a restricted user group. Currently it contains all NEES projects and also some non NEES projects. It could be seen that this platform is quite similar to the SAMCO database with regard to its conception.

The NEEScentral provides a web-interface to the interim metadata model. There is a certain folder / file hierarchy for the upload and storage of the data. This structure is very generic and high-level, because it is made to fit all the disciplines in earthquake engineering from experiments on shake tables to the tsunami wave basin. In future it should reflect the local storages of the labs, so that an easy migration of the data from the local sites to the central repository is possible. It is planned that in future the equipments sites will use this repository as backup for their data.

The mentioned high-level file hierarchy of the Meta data model consists of a project folder at top-level; the next level consists of experiments carried out in this project, then trails within the experiments and finally data acquired in the experiments. All of these levels can contain documents, analyses, and other general information. As already mentioned this is a very ruff structure that needs to be more detailed in future in order to be used as standard.

NEESpop is installed at the testing facilities sites and gives access to the tele presence tools, collaboration tools, local data tools and simulation tools by a web interface. Besides NEESpop flexTPS should be installed, providing a web interface for the tele presence software tools at the testing facilities and allowing remote control of the facilities in real time. NEESdaq for the data acquisition software Labview should also be installed.

A demonstration was given on flexTPS and RDV at which a connection to the San Diego lab was created and a small shaking table was started up and remotely controlled. With the RDV client the data could be viewed in real time. I was stressed that the software is not able to handle a huge number of channels.

In NEESpop there is another collaboration tool called CHEF. It was stressed that CHEF is not robust enough and will probably be taken out of NEESit architecture. CHEF is an internet portal that provides project workspaces (upload / download of data, e-mail distribution lists, chat rooms, e-mail archive and group calendars).

News from Profession & Practice

System Identification and Damage Detection using Wavelet Analysis: **Applications in Frame Structures**

Abstract

A novel wavelet analysis is presented in this paper in order to locate damage sources in civil structures.

The presence and location of damage are detected by solely analyzing the acceleration time history responses obtained from the structure of interest. Two structures running in various operational environments are investigated: FE – model of a three storey shear-resisting frame excited by band-limited white noise ground acceleration and a prestressed reinforced concrete test beam under impact loading conditions. The presented technique requires the availability of measured data from a previous "reference" or "undamaged" structural state. Using the Haar mother wavelet a first level fast wavelet decomposition of both the reference and actual acceleration measurements is applied, where the approximation and detail coefficients are obtained.

Subsequently reconstruction of the actual structural response is performed by combination of the "reference" approximation coefficients and the "actual" detail coefficients. Then, the error, which is the difference between the "reconstructed" signal and the actual acceleration measurement, is defined as the damage-sensitive parameter.

The basic idea is that the detail coefficients carry the whole information of discontinuities in the structural time history response at the damaged sites. Therefore, the approximation coefficients previously obtained using the undamaged measured data combined with the actual detail coefficients would not be able to reproduce the newly obtained time history response of the damaged structure.

Furthermore, the increase in error would be maximized at sensors instrumented near the actual damage sources.

Introduction

The design of civil engineering structures is characterized by two features: carrying capacity and serviceability. However, the buildings undergo various environmental and loading influences during their service life, which can cause a significant damage accumulation. Consequently the structural carrying capacity and serviceability are enormously affected. Therefore the need of reliable non-destructive evaluation techniques and detection of damages at the earliest possible stage has been pervasive throughout the civil engineering community at the last decade.

As reported by Sohn et al. [1] the process of implementing damage detection strategies can be referred to as structural health monitoring. Vibration-based health monitoring techniques, also "global" monitoring methods [2], rely on the fact that damage causes changes in the local structural damping (energy dissipation) and stiffness, and therefore in the global dynamic properties of the structure.

Several tools for a continuous safety vibration-based monitoring during the structural service life are reported by Wenzel et al. [3] and [4]. To identify the presence of damage in a mechanical system, often the frequencies and other modal parameters are calculated only from measurements of the dynamic structural response without knowing the input loading force, e.g. *Operational Modal Analysis*. The process of damage identification is more than detection of changes in the dynamic structural characteristics.

Based on the work of [5], four levels of structural health monitoring and damage identification are discriminated: (1) *detection* of damage presence in a structure, (2) *localization* of damage source, (3) *quantification* of damage severity, and (4) *prediction* of the remaining structural service life. An ideal structural health monitoring system should be capable of providing cost-effective and reliable damage identification.

There are several methods operating either in the frequency or in the time domain. Consequently, often useful information about structural changes through the unused domain is discounted. Doebling et al. [6] referred that presence of damage is a local phenomenon which tends to be captured by higher frequency modes.

However, this fact adds difficulties to the implementation of damage identification through the frequency domain by the classical Fourier analysis. To overcome these deficiencies, the application of time-scale or time-frequency analysis is required. Staszewski et al. [7] used the Wigner-Ville time-frequency distribution to detect source of damage in a gearbox.

Another very useful time-frequency transform that inspire nowadays the attention of researchers is the wavelet transform (WT).

The authors present in this paper the structural health monitoring of frame structures in the context of a wavelet-based analysis. Two different systems are investigated: a numerically modelled (FEM) shear resisting steel frame with three storeys excited by an artificial generated $20\,Hz$ band-limited white noise ground motion.

Three damage scenarios are investigated on this structure, namely plastic hinge simulation underneath each storey respectively. The second mechanical system of interest is a prestressed reinforced concrete test beam under impact loading conditions. Seven structural states are observed; where the tendons are released successively (prestressing forces reduction).

The applied damage identification technique can be described as a five-part process: (1) operational evaluation, (2) data acquisition and standardization, (3) first level of wavelet decomposition, (4) data reconstruction, and (5) damage parameter development. The presented approach requires the availability of acceleration records from at least two structural states. The method is based only on the analysis of measured vibration data, making this technique very attractive for its implementation into automated health monitoring and decision support systems.

Fast Wavelet Transformation

The wavelet transformation of a signal $x(t)$ is a time-scale decomposition obtained by stretching and translating along the time axis a chosen basis function (mother wavelet). Thus, the one-dimensional wavelet transformation projects the signal into a two-dimensional space:

$$W_\psi^f(a,b)=\frac{1}{\sqrt{a}}\int_{-\infty}^{\infty}x(t)\,\psi^*\left(\frac{t-b}{a}\right)dt\ ,$$

where b is the parameter localising the wavelet function in the time domain, a is the dilation parameter defining the analysis window stretching, and ψ^* is the complex conjugate of the mother wavelet function. This basic function is used to generate a family of wavelet functions as follows:

$$\psi^{a,b}(t)=\frac{1}{\sqrt{a}}\psi^*\left(\frac{t-b}{a}\right). \qquad (2)$$

The process of wavelet analysis is represented in general by the wavelet transform in continuous or discrete version. For the continuous wavelet transform, the basis function can always be represented by an analytical function. For most of the applicable wavelets, however, the projection of the signal $x(t)$ into the continuous time-scale domain requires a considerable number of numerical operations. Thus, a discrete representation of the wavelet transformation is available, where the parameters a and b become discrete values:

$$W_{m,n}=\sum_{m\geq 1}\sum_{n\in\mathbb{Z}} x(t)\,\psi_{m,n}(t)\ , \qquad (3)$$

where the wavelet $\psi_{m,n}(t)$ is expressed as follows:

$$\psi_{m,n}(t)=2^{-\frac{m}{2}}\psi\left(2^{-m}t-n\right). \qquad (4)$$

The wavelet function in this paper is the well-known *Haar* wavelet (A. Haar, 1910) as shown in figure 1. The origin is the following function

$$\psi(t)=\begin{cases}1, & 0\leq t\leq 0.5;\\ -1, & 0.5<t\leq 1;\\ 0, & else.\end{cases} \qquad (5)$$

Note, that the functions $\{\psi_{m,n} \mid m,n\in\mathbb{Z}\}$ is an orthonormal base of $L^2(\mathbb{R})$. Considering the stepwise approximation of the function $x(t)$ (Bäni [8]), where $x(t)\in L^2(\mathbb{R})$ and $m\in\mathbb{Z}$, with the constant step width 2^m leads to the constant value

$$x_{m,n}=2^{-m}\int_{n2^m}^{(n+1)2^m} x(t)\,dt\ . \qquad (6)$$

This expression represents the mean value of the function $x(t)$ on the interval $[n2^m,(n+1)2^m[$. Furthermore, it can be represented that this is also the "mean value of the mean values" on the both equal subintervals $[2n2^{m-1},(2n+1)2^{m-1}[$ and $[(2n+1)2^{m-1},(2n+2)2^{m-1}[$, namely:

$$x_{m,n}=\frac{x_{m-1,2n}+x_{m-1,n+1}}{2}\ . \qquad (7)$$

Using the fact that the amplitude $\psi_{m,n}(t)$ is equal to 2^m gives for the wavelet coefficients

$$v_{m,n}=2^{\frac{m}{2}}\,\frac{x_{m-1,2n}-x_{m-1,n+1}}{2}\ . \qquad (8)$$

Using the Haar scale function (see figure 1), where its scale coefficients $u_{m,n}$ are defined as

$$u_{m,n}=2^{\frac{m}{2}}x_{m,n}=2^{-\frac{m}{2}}\int_{n2^m}^{(n+1)2^m} x(t)\,dt\ , \qquad (9)$$

the stepwise approximation of the function $x(t)$ can be represented by the following relationship:

$$x_{m,n}=2^{-\frac{m}{2}}u_{m,n}\ . \qquad (10)$$

Thus, modifying equations (7) and (8) by expression (10) leads to basic system equations of the fast Haar wavelet transformation:

$$u_{m+1,n}=\frac{u_{m,2n}+u_{m,2n+1}}{\sqrt{2}}\ ,\qquad v_{m+1,n}=\frac{v_{m,2n}-v_{m,2n+1}}{\sqrt{2}}\ . \qquad (11)$$

Inverting equation (11) gives the scale coefficients $u_{m,n}$:

$$u_{m-1,2n}=\frac{u_{m,n}+v_{m,n}}{\sqrt{2}}\ ,\qquad u_{m-1,2n+1}=\frac{u_{m,n}-v_{m,n}}{\sqrt{2}}\ , \qquad (12)$$

which allows to synthesize the stepwise approximation of the function $x(t)$. The transition from u_m to u_{m+1} and to v_{m+1} with respect to equation (11) can be represented by following relationships:

$$u_{m+1}=(\downarrow 2)\,A(u_m)\ ,$$
$$v_{m+1}=(\downarrow 2)\,D(v_m)\ ,$$

where $A(u_m)$ means the "*moving average*", $D(v_m)$ is the "*moving difference*" and $(\downarrow 2)$ stands for the "*downsampling*".

Equation (13) is also known as the "*analysis bank*" of the so called "*Haar filter bank*" shown in figure 1. The right part of the filter bank represents the "*synthesis bank*", where $(\uparrow 2)$ indicates the "*upsampling*".

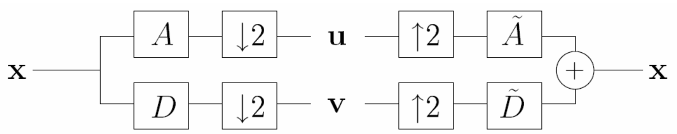

Figure 1: Haar filter bank

This filter bank is a "*perfect reconstruction*" filter bank, which means that every signal can exactly be reconstructed, if the coefficients u and v are not modified. Note, that figure 1 represents only the first level of Haar fast wavelet decomposition.

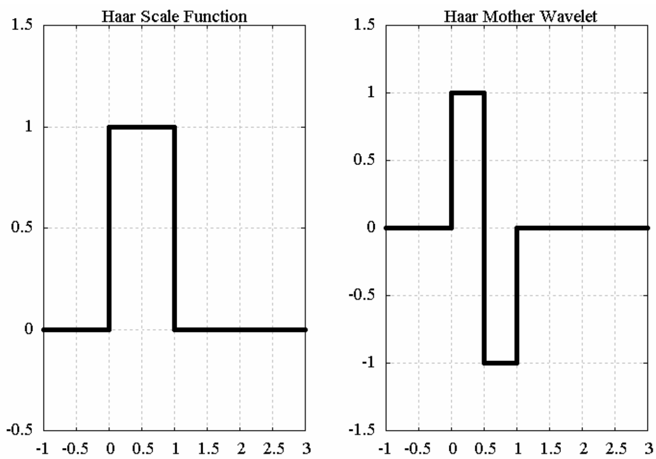

Figure 2: Haar scale function and mother wavelet

Damage Detection Procedure

The damage detection technique presented in this paper requires the existence of at least two monitored structural states. In general damage causes changes in the system vibration behaviour particularly with regard to the energy dissipation (damping) and the structural stiffness. Outgoing from an "undamaged" also "reference" structural state, the method consider the mechanical system of interest at a subsequent time instant. This supposes similar structural conditions to eliminate any serious influence of inconsistent boundary conditions, whereas the operational conditions can vary. Additionally an identical sensor layout is required in order to locate any detected system changes.

First, all discrete acceleration signals should be made comparable to each other. For this purpose they are standardized:

$$\hat{x}(t) = \frac{x(t) - \mu_x(t)}{\sigma_x} , \qquad (14)$$

where $\hat{x}(t)$ is the standardized time signal, $\mu_x(t)$ is the mean of $x(t)$, and σ_x is its standard deviation. However, for simplicity, $x(t)$ is used to denote $\hat{x}(t)$ hereafter.

For each time series $x(t)$ of all structural states considered, a first level of Haar wavelet decomposition is applied as mentioned above. This procedure provides two vectors per analysed acceleration signal, namely the approximations $\boldsymbol{u}$ and the details $\boldsymbol{v}$ of $x(t)$ (see figure 1). The approximations are the high-scale, low-frequency components, whereas the details represent the low-scale, high-frequency details of the signal. However, the presence of damage as a local incident is generally captured by the higher frequency modes, as reported by Doebling et al. [6]. Thus, information about any system changes especially due to damage shall be stored in the details vector $\boldsymbol{v}$.

Next, a simulation of the actual "damaged" structural state is performed by wavelet reconstruction. Using the Haar synthesis filter bank, the "reference" approximation coefficients are combined with the "actual" detail coefficients. In other words, the obtained damage information is superimposed on the approximation information for the "healthy" time history response.

Finally, synthesis error $\varepsilon_{synthesis}$ for the actual structural state can be obtained as follows:

$$\varepsilon_{synthesis} = x(t)_{synthesis} - x(t)_{actual} . \qquad (15)$$

When the reconstructed system response is not a good representation of the newly obtained time signal, there would be a significant change in standard deviation of $\varepsilon_{synthesis}$, $\sigma(\varepsilon_{synthesis})$. This consideration is simply based on the definition for standard deviation, i.e. *measure of the degree of dispersion of a data from its mean value.*

Examples

The presented approach is verified by means of two mechanical systems working in various operational environments.

<u>Steel Frame excited by White Noise Ground Motion</u>

A three storey shear resisting steel frame is investigated by means of the finite element method. The system properties are depicted in figure 3a. Presence of damage is simulated by means of plastic hinges. For this purpose cross section reduction underneath of the story of interest is applied. In other words, three damage scenarios are modelled. An $20\ Hz$ band-limited artificial generated white noise is used as ground motion (see figure 3b).

<u>Prestressed Reinforced Concrete Beam under Impact Load Conditions</u>

Next, a real structure is investigated: reinforced concrete beam prestressed by six tendons (see figure 5). The influence of the prestressing forces on the global system behaviour is tested. In other words, starting form a completely prestressed state, the tendons are released successively.

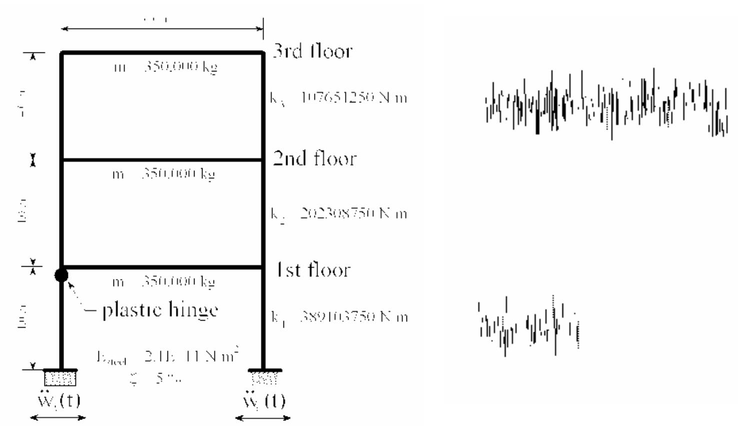

Figure 3: Frame Structure and Ground Excitation

Applying the damage identification approach by means of first level of Haar wavelet decomposition and reconstruction, and subsequently consideration of the standard deviation of the synthesis error $\varepsilon_{synthesis}$ leads to results shown in figure 4. It can be seen, that the largest increase in the damage parameter is obtained at the nearest measurement point to the damage site.

The final state is characterized by absence of any prestressing forces. The vibration behaviour is observed under impact load conditions (impact load of $120.0\ kg$ on the right free end), where structure is instrumented by eight sensors positioned on the upper surface. Note, the impact load history of each structural state differs from those of the other prestressing cases. Using the obtained acceleration time

Figure 4: Damage Distribution over the Frame Elevation

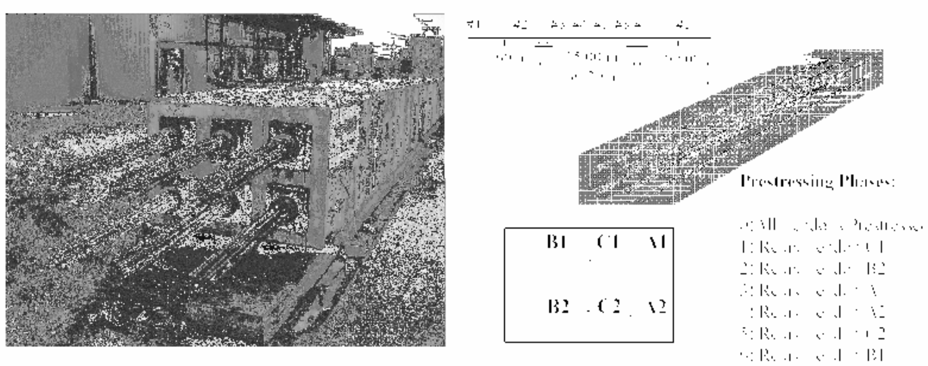

Figure 5: Beam Structure and Prestressing History

histories the concrete cracks are detected and localized by means of the wavelet approach presented above. The standard deviation is again as damage parameter specified, but from the square of the synthesis error $\varepsilon_{synthesis}$ at each prestressing state. Note, the completely prestressed structure represents the "reference" state in this analysis.

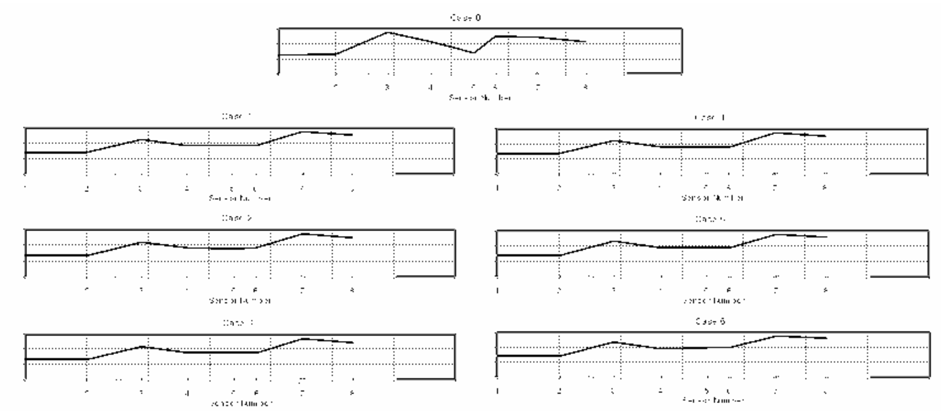

Figure 6: Damage Distribution over the Beam

The obtained damage distributions over the beam longitudinal axis are depicted in figure 6.

As expected, the main presence of concrete cracks is located at the supports. However, because of the impact load the damage parameter values at the right support are greater than those at the left one. Additionally, the more tendons are released the more damage at the middle of the span can be observed. Note, that the significance of the damage parameter is not influenced from the inconsistence of the impact load at each investigated structural state.

Conclusions and Outlook on Future Work

This paper presents a wavelet approach for damage identification in civil frame structures. The technique is based on the first level fast Haar wavelet decomposition. Combining the approximation coefficients from a "reference" structural state and the detail coefficients from the actual "damaged" state the vibration response is reconstructed. The standard deviation of the error between the measured and predicted acceleration time signal is chosen as a damage-sensitive parameter.

Finally, in order to verify the procedure, two civil structures working in various operational environments are observed.

The presence of damage and the damage sources can be detected by means of the presented technique. The method requires the availability of measured acceleration data of at least two structural states, where the first one is assumed as an undamaged "reference" state. Additionally similar structural conditions are supposed, in order to eliminate the influence of inconsistent boundary conditions. A significant advantage of the applied procedure is its robustness against varying loading conditions. The method is based only on the analysis of acceleration time history records, making this approach very useful for its implementation into automated structural health monitoring and decision support systems.

Future work will be devoted to the extension of the presented approach to quantification of damage and to prediction of remaining structural life. Furthermore, more complex mechanical systems and a wide range of operational and environmental conditions shall be investigated. The analysis of different damage scenarios, especially non-linear damage phenomena, will also be part of future activities of the authors.

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University College Dublin

About UCD

University College Dublin UCD is a dynamic, modern university. It is committed to becoming one of the top thirty research universities in the European Union, where cutting-edge research and scholarship will create a stimulating intellectual environment, the ideal surroundings for learning and discovery. UCD provides excellent facilities to support teaching and learning.

There are well-resourced libraries and extensive computing facilities. We are moving forward rapidly in the area of e-learning, and you will find more and more resources to support your learning available electronically both on- and off-campus. Student health, welfare and counselling services are second-to none and there are superb opportunities for sports and recreation. UCD provides the range of services that students need to make their time at UCD enjoyable and fulfilling, educationally and professionally.

With a new structure of 5 Colleges and 35 Schools UCD is Ireland's premier University offering a comprehensive range of undergraduate and postgraduate programmes in the humanities and sciences. Its student population is approximately 22,000, including 2,000 international students. Approximately 25% of the student body are engaged in postgraduate study and research. The University is committed to maintaining a high level of research activity and to further developing its collaborative links with industry and commerce, and with educational and research institutions internationally.

History of University College Dublin

The origins of University College Dublin date back to the Catholic University of Ireland which was founded in the mid-nineteenth century by Paul Cullen and John Henry Newman. In 1881, under the Royal Universities Act, the university was renamed University College Dublin. Among the professors during this phase of UCD's history was the poet Gerard Manley Hopkins and amongst its most famous pupils was the writer James Joyce. In 1908, University College Dublin was granted its own charter and was incorporated as a constituent college of the National University of Ireland. Under the Universities Act, 1997, University College Dublin was established as an autonomous university within the National University of Ireland framework.

Since its inception, University College Dublin has established a long and distinguished tradition of service to scholarship and to the community; succeeding generations of graduates have played a central role in the shaping of modern Ireland and in the conduct of international affairs. Today, University College Dublin is acknowledged as a centre of excellence for teaching and research, and its degrees are recognised and respected worldwide. For students, it is a stimulating and exciting place in which to spend some very formative years of intellectual and personal development.

Location of the University

The main campus of University College Dublin is situated at Belfield, a 132 hectare site 4 km south of the centre of Dublin city. This campus is an attractively landscaped complex of modern architectural buildings, accommodating most of the Faculties of the University as well as its student residences and numerous leisure and sporting facilities.

Other University buildings include Earlsfort Terrace, adjacent to St Stephen's Green in the city centre.

Facilities for the study of Medical Sciences will all move to a new, state-of-the-art facility at Belfield, the Health Sciences Complex, in 2005. The UCD Smurfit School of Business is located on the campus at Blackrock, and in Lyons Estate, Kildare, the Faculty of Agri-Food and the Environment runs a research farm.

UCD and the Universities Act 1997

University College Dublin is one of the seven Irish Universities recognised under the Universities Act 1997 which sets down the legislative provisions which must be met for an educational institution or college to be established as a university in Ireland. The seven universities, which are the only ones recognised under the Act, are as follows:

- University of Limerick
- Trinity College, Dublin
- University College Dublin
- University College, Cork
- National University of Ireland, Galway
- National University of Ireland, Maynooth
- Dublin City University

School of Architecture, Landscape and Civil Engineering

The UCD School of Architecture, Landscape and Civil Engineering is home to the university's community of staff and students engaged in research, teaching and learning on many facets of the designed environment. Their interests are diverse – buildings, urban spaces, rural environments, transport systems, water supply, flood control, bridges, tunnels, energy, historical fabric, landscapes - to mention just a few!

The wide range of undergraduate programmes are offered in a modular format – UCD Horizons – allowing students to undertake accredited degree programmes while shaping their course syllabus to their personal interests and talents. Postgraduate courses and research opportunities are constantly on offer. Interdisciplinary research clusters are available to undertake studies for industry and agencies.

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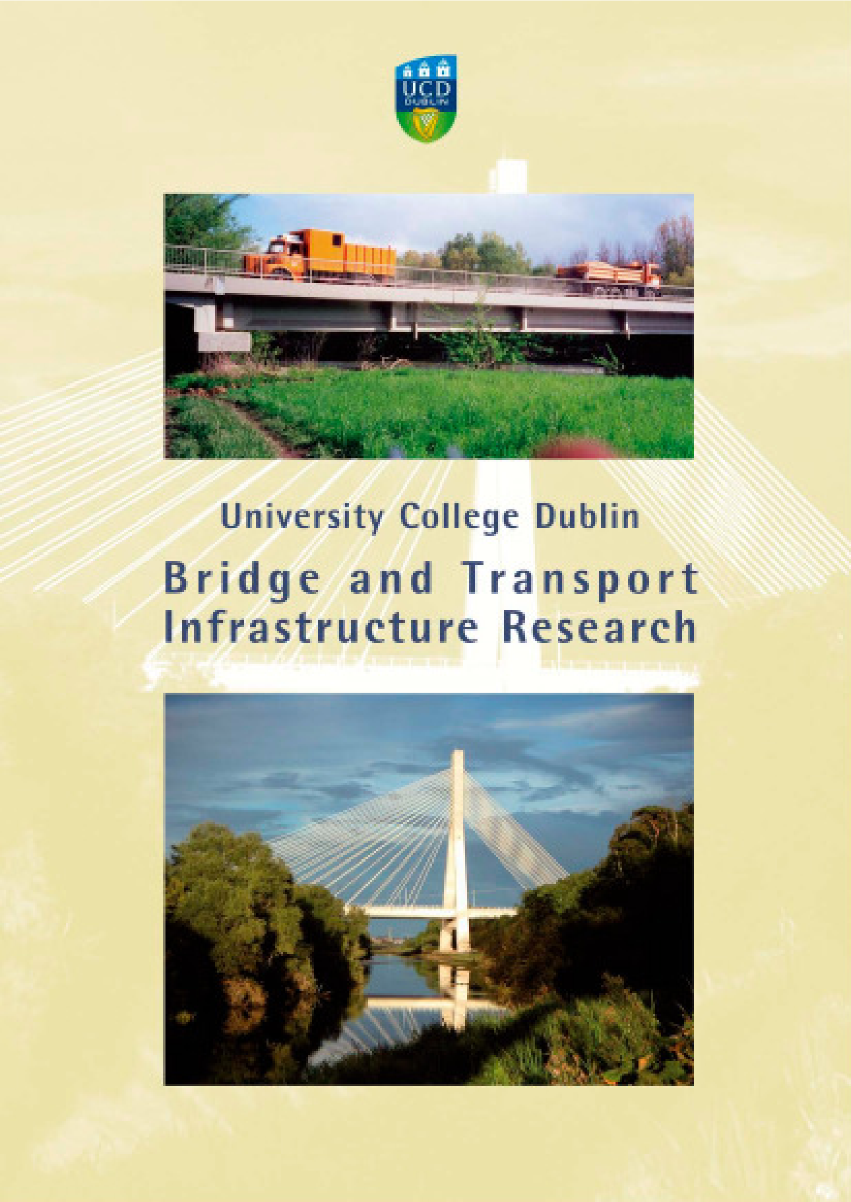
Research Report



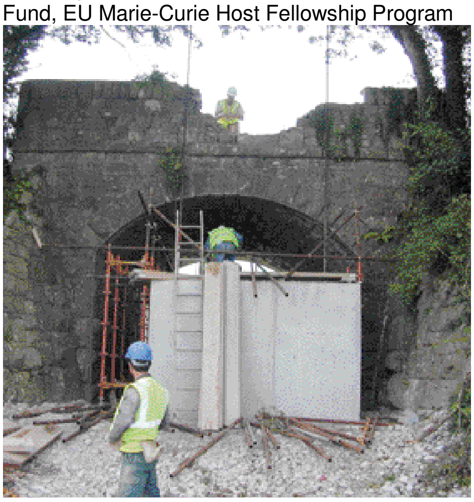
Bridge Monitoring and Loading

P. Fanning, E. OBrien

Stone Arch Bridges - Modelling and Assessment

Service load testing, high level load testing and three dimensional nonlinear finite element simulations were conducted for a range of stone arch bridges spanning 5.0m to 32m. Traditional assessment techniques were demonstrated to be excessively conservative in certain circumstances and novel assessment procedures for the determination of both longitudinal and transverse bridge strengths were developed, and justified on the basis of bridge test results.

Collaborator: Pennsylvania State University
Clients: National Roads Authority (Ireland), ICE Enabling
Fund, EU Marie-Curie Host Fellowship Program



Greenfield's Bridge, Co. Cork, Ireland – high level load testing

Pedestrian Loading

Current design codes offer no guidance for lateral load effects as a result of pedestrians on a footbridge nor do they make allowance for the interaction between a footbridge and a traversing pedestrian. Novel vertical and lateral interactive load models, for a single traversing pedestrian, have been developed. Currently these are being extended for multiple pedestrians.

Client: European Commission Marie-Curie Host Fellowship Scheme

Condition Monitoring

Commissioned vibration tests were recently completed on the newly opened Sean O'Casey footbridge in Dublin city centre. Knowledge of the static and dynamic properties of structural systems enables owners to include formal condition monitoring as part of their management and assessment programs. With the purchase of a dedicated operational modal analysis suite of hardware and software, and the increasing realisation amongst design consultants that confirmation of the static and dynamic properties of new build bridges is both necessary and instructive, it is anticipated that activity in this area will grow significantly.

Sean O'Casey Bridge – Dublin city centre

Bridge Traffic Loading

Considerable progress has been made in identifying the combinations of trucks that are critical for bridge traffic loading. In this study, the importance of the gaps between following trucks has been identified. Statistical methods of calculating the characteristic stresses have been greatly improved and it is now possible to accurately calculate an assessment traffic load effect based on measured site-specific data. It has been found that 3 and even 4 trucks can feature in critical bridge loading events, something previously thought to be unrealistic.

Client: European Commission Samaris project

Tests of two trucks on Mura River Bridge (courtesy ZAG, Slovenia)

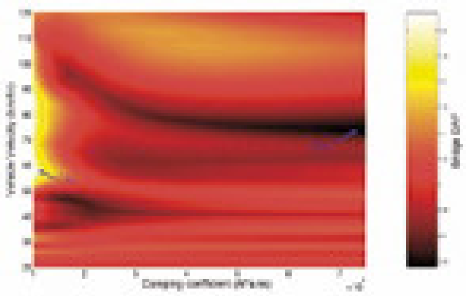
Bridge Dynamics

A. González, E. OBrien

Bridge-Frie Truck Suspensions ndly

Short-span bridge dynamic responses to heavy vehicle crossing events can be reduced through adjustment of the vehicle suspension damping coefficient just before the crossing. It is shown that a single optimum damping coefficient may be determined for a given velocity and any specified road profile.

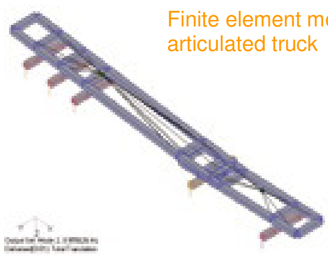
Client: Embark Initiative



Variation in bridge dynamic amplification factor with vehicle velocity and damping coefficient

Bridge Truck Interaction

The Eurocode normal traffic load model for bridges is derived by applying a Dynamic Amplification Factor to the worst static case. This in turn is obtained by extrapolating load effects using free flowing traffic simulations and weigh-in-motion data. The Eurocode specifies a dynamic amplification for a particular bridge that depends on the shape of its influence line and one single variable, i.e., bridge length. This project proposes to use bridge and vehicle dynamic characteristics, to provide a more realistic upper bound on the dynamic bridge load model.



Finite element model of 5-axle articulated truck

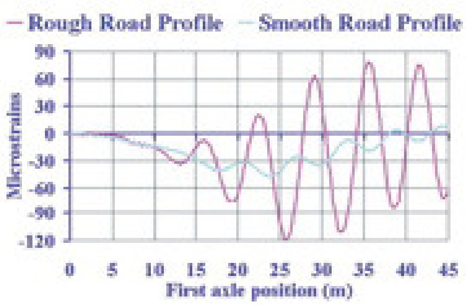
Load Identification in Bridges

First order Tikhonov regularisation is applied in conjunction with dynamic programming, to predict the unknown traffic forces from bridge strain measurements. Static weights are estimated more accurately than is possible with existing Bridge Weigh-In-Motion algorithms and additional information on the dynamic characteristics of the applied load is provided.

Bridge weigh-in-motion system in Luleå, Sweden

Road Roughness & Bridge Dynamics

Profile irregularities affecting bridge dynamic amplification can be characterised with a 'response surface' giving dynamic amplification due to a 'unit ramp' at any location. Even though the dynamic interaction problem is non-linear, the effects of all ramps which together make up a road profile can be approximated well using superposition and the 'response surface'.



Bridge strain responses to smooth and rough pavements

Golden Gate bridge, San Francisco

Transport Geotechnics

K. Gavin, D. Laefer, M. Long

Piled Foundations

Significant advances in the prediction of the short-term axial capacity of piles have been achieved through instrumented field tests. Uncertainties remain about the effects of time, with a trend for pile capacity to increase (even after excess pore-water pressure dissipation) in a range of soil types. There is also a need for research on the effect of previous loading, e.g., of piles which remain in the ground following demolition of a structure or in situations where additional loading is being applied to a bridge. UCD are investigating these effects using instrumented piles in a range of soil types.

Client: Arup Consulting Engineers, Allied Irish Bank and Cementation Skanska

Static load test on 20m long Instrumented 1m diameter bored pile

Characterising Peat

Trial testing is being carried out on bog roads in Ireland (County Kildare) in order to compare falling weight deflectometer (FWD) data with ground proving radar (GPR). The purpose is to permit characterisation of the underlying peat soils. Tests will be carried out on sites where the peat properties are known. The goal is to develop techniques which will permit the thickness and characteristics of the peat to be determined by FWD / GPR without any intrusive investigation. This will be of significant practical use in the assessment of non-primary roads across peat areas.

Client: PMS, Kildare Co. Co.

Foundation Settlement

Recent research on footing performance has concentrated on prediction of ultimate resistance but there is a dearth of guidance for designers on how to estimate settlement.

Although non-linear models have been proposed for settlement prediction, these tend to be complex and require input parameters that are not generally available. A new settlement prediction model, which uses only the small strain stiffness measured using low cost in-situ techniques and the ultimate footing capacity as input parameters, has been developed at UCD. The method allows for non-linear soil behaviour and recognises the effect of stress history and footing dimension in its formulation.

Stability of Cuttings and Embankments

The stability of steep slopes is an issue of concern, particularly the effect of rainfall given changing global climate patterns. Research is ongoing at UCD on the effect of suction on the stability of 150 year old railway slopes using reliability based computer software developed inhouse.

In addition, a combination of field techniques and high quality laboratory tests are being utilised in an assessment of operational shear strength parameters for the construction of deep motorway cuttings in a geologically unusual glacial till material.

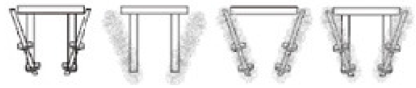
Sponsors: Irish Rail, Site Investigations

Road failure, Malvik, Norway

Composite Ground Reinforcement / Ground Improvement Systems

As urban areas continue towards increased density, the ability to reuse and upgrade existing deep foundation systems continues to gain in importance. Critical to this is the establishment of a widely accepted design methodology from which to generate safe loading values. This joint experimental program uses 1-g and centrifuge testing to explore the validity of varying design principles, including superposition when grouting and/or helical piers are introduced to the existing piling system.

Client: National Science Foundation, University of California Irvine and University of California Davis



Testing arrangements of deep foundation components

Rail Transport & Tunnels

A. Ahern, P. Fanning, K. Gavin, A. Gibney, D. Laefer, M. Long

Predicting Tunnelling Induced Settlement

Recent developments in tunnelling equipment now facilitate the automated collection of unprecedented levels of data related to the performance of tunnel boring machines. This study exploits this newly available capability, to create a continuum that facilitates the prediction of above-ground building damage based on below-ground tunnel equipment performance metrics.

Major parameters include rate of advance, quantity of spoil removed, distribution of head pressure, and depth of overburden.

Client: ARUP

Dublin Port Tunnel

Rail choice

Quality of service and user-satisfaction levels are declining on Ireland's interurban rail networks. This study looks at the modal choices of rail passengers on inter-urban routes in Ireland and models these choices using discrete-choice modelling and stated-preference techniques. The modal choice models estimated from this analysis reveal what factors are important to an individual's choice of travel mode and the relative importance of each of these factors.

Rail Track Bed Assessment

For safety reasons and due to operational demands it is very difficult to carry out intrusive surveys on railway lines. This project aims to develop an investigative technique for rail systems using the MASW (multi-spectral analysis of surface waves) geophysical approach. Tests will be carried out to determine the system stiffness using MASW.

Deflections under train loading will be predicted and then measured. The overall intention is to develop a methodology for simple track bed condition assessment.

Clients: Irish Rail, APEX Surveys

Rail Investment

Capital investment on transportation projects is generally high and incorrect investment decisions lead to misallocation of resources and money. Since transportation projects affect social and economic development and the environment, decisions regarding transportation investment must not be made solely on the basis of money or any other single criterion, but rather involve multiple criteria, some of which may not necessarily have directly measurable monetary values. This research constructs a multiple-objective optimisation model to rank transportation projects for investment.

A goal programming technique has been used to develop the model as it can incorporate externalities, land use and regional policies. The technique has been applied to the inter-urban rail system in Ireland to make recommendations of where funding and investment should be targeted for the greatest returns.

Developing the Coupled Falling Weight Deflectometer Test for Railway Embankment Integrity

This research project explores the technical viability of the Coupled Falling Weight Deflectometer (FWD) test, to assess the quality of rail foundations. An assessment of rail foundation quality is essential to determine both the load capacity and safe train speed of railway systems. In this FWD test, the rail and sleeper remain attached which is quicker, cheaper and more convenient than the current approach. The new system including the rail is, however, more complex and research is being carried out to assess if the test can still yield accurate information about the foundation conditions.

Clients: Enterprise Ireland, Pavement Management Services

Field trials using falling weight deflectometer

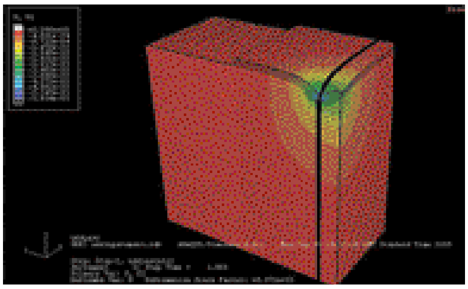
Transport Materials

A. Gibney, C. McNally, M. Richardson

Stone Mastic Asphalt (SMA)

The superior resistance of SMA to permanent deformation has been confirmed without doubt in comparison to Hot Rolled Asphalt mixes. A number of issues including mix design, binder drainage, the use of fibres and the use of polymer modified binders in the Irish context have been investigated in this project. In addition the development of surface texture over time is being monitored using a full scale on-site trial section.

Client: Enterprise Ireland



Finite Element model of airport pavement

Chloride Ingress in Concrete

A key parameter in determining structural service life is the resistance of the concrete to environmental effects, such as chloride ingress. Service life models that use chloride diffusion coefficients are readily available for use, but difficulties exist with the lengthy times required to calculate appropriate parameters. Research is ongoing into accelerated testing methods and test conditions that will allow practitioners to determine useful parameters that can be assessed in the short term.

Recycled Pavements

Each year 2.7 million tonnes of construction waste are consigned to landfill, despite the inherent potential of large quantities of this waste to perform a role as part of a flexible pavement system. Selected waste streams are being characterized through laboratory testing. Constitutive models are being developed which will be used to predict in-service response. Full scale field testing is also being undertaken using instrumented road sections constructed using recycled materials.

Client: Enterprise Ireland ATRP

Corrosion Inhibitors in Reinforced Concrete

The application of corrosion inhibitors is a most promising technique for the corrosion protection of concrete structures. Corrosion inhibitors are chemical compounds which can reduce, or even prevent, corrosion of metals. In general, these compounds act only if they are present in adequate concentration (otherwise their action is insufficient, or even aggressive localised corrosion may be induced).

Mixed organic and inorganic compounds may have a significant role to play as new effective corrosion inhibitors in extending the service life of deteriorated structures. Surface-applied inhibitors are being tested. If effective, they could greatly reduce the disruption to traffic during repair works by shortening the repair contract period considerably.

Client: European Commission Samaris project

Galvapulse testing

Vehicle Dynamics and Weigh-in-Motion

A. González, E. OBrien

Weigh-in-Motion

The accuracy of multiple-sensor weigh-in-motion systems is severely limited by the magnitude of noise and vehicle dynamics. Neural Networks (NNs) have been recently tested for removing noise and identifying patterns of spatial repeatability. However, this technique might require an impracticaly large data set for training the NN. This project investigates the accuracy of NN and an alternative functional network (FN) algorithm in estimating static weights. Unlike NNs, which are “black boxes”, FNs arise directly from the equations governing weigh-in-motion.

Client: Dutch Ministry of Transport (DWW)

Calculation of Road Quality using Vehicle Sensors

This project proposes the collection of data from accelerometers in a fleet of vehicles and the use of this data to estimate road surface roughness. A roughness estimate derived from vehicle data can be used by road managers to identify sections of road where the profile roughness has increased and hence to prioritise sections and optimise the use of profilometers for more detailed investigations.

Road Profilometer

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Contact

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Notable Dates

2006

MARCH

30th and 31st

Final SAMCO Meeting

EMPA / Switzerland

EMPA / Switzerland

APRIL

18th -22nd

100th Anniversary Earthquake Conference

San Francisco, CA / USA

JULY

16th – 19th

IABMAS'06

Porto / Portugal

IABMAS'06 will be the 3rd International Conference on Bridge Maintenance, Safety and Management

AUGUST

3rd to 5th

EASEC-10

Bangkok / Thailand

EASEC

East Asia-Pacific Conference on Structural Engineering & Construction

OBJECTIVE

The conference will be held to mark the 20 years anniversary of EASEC.

The objective of organizing EASEC conference is to provide a forum for academicians, researchers, and engineers working in broad areas of Structural Engineering and Construction in the East Asia and Pacific region to exchange information leading to close collaboration and cooperation.

GEOGRAPHIC COVERAGE

Initially, the geographic focus of EASEC covers all countries in East Asia, Southeast Asia, Australia, New Zealand, Papua New Guinea, as well as Hawaii and the West Coasts of USA and Canada. However, participation in the conference shall be open worldwide.

Contact

Asian Institute of Technology

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Jobs

Post-Doctoral Fellowship in Bridge Research

School of Architecture, Landscape & Civil Engineering

UCD Dublin, Ireland

The Bridge and Transport Infrastructure Research Group at UCD Dublin, National University of Ireland – Dublin, has the largest group of bridge researchers in Ireland and its members are known throughout the world for their outstanding achievements in Bridge Engineering Research -http://www.ucd.ie/civileng/berg/

The group currently has a vacancy for a post-doctoral researcher in the broad area of bridge engineering – particularly bridge assessment, bridge dynamics, condition monitoring and damage detection. Applicants should hold a Doctoral degree and have a background in Civil / Mechanical Engineering, Materials Science or a related discipline. Preference will be given to those with expertise in the following areas:

- Computer modelling of vehicle-infrastructure interaction.
- Modelling of deterioration mechanisms in concrete bridges.
- Modelling of bridge structures for assessment.
- Condition monitoring and damage detection.

UCD Dublin is an equal opportunities employer.

The positions are funded under the EU Marie Curie Development Host Fellowships. The eligibility criteria and conditions are available from:

http://www.cordis.lu/improving

(Contract Number: HPMD-2000-00018, Core Project Title: Bridge Assessment Research for Europe (BARE)). Under the conditions of the contract the fellowships are not open to Irish nationals.

The duration of the fellowship is up to ten months commencing in January 2006. The fellowship salary is 3062 Euro per month plus an additional travel and mobility allowance of approximately 400 Euro per month.

Interested applicants should submit a CV (hard copy or e-mail) to:

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