Issue 14 / March 2005

newsletter

supported by the DG Research of the European Commission

SAMCO NEWS

Structural Assessment Monitoring Control Issue 14 / March 2004

contents

- **9th SAMCO Workshop in Berlin / Germany**
  page 1
- **2nd SAMCO SummerAcademy in Austria**
  page 2
- **News from the Profession & Practice**
  - Structural Health Monitoring Based on Global Flexibility Index: a Case of Highway Bridges

  page 3 – 7
- **News from the Profession & Practice**
  - System Identification of a Steel Frame: Comparison Between Frequency and Time Domain Analysis

  page 8 – 9
- **Company Profile**
  page 10 - 11

Published by VCE.

9th SAMCO Workshop

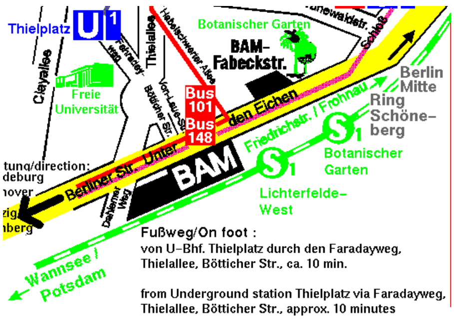
April 28th and 29th 2005 in Berlin / Germany

Venue

This year's workshop is taking place at the Federal Institute for Materials Research and Testing (BAM) in Berlin / Germany the 28th and 29th of April.

BAM / Berlin

The participants will find the venue within easy reach of public transport.



site plan

Aim and Scope

The idea of the workshop is in the first place to obtain a wide spectrum of opinions of the members of the SAMCO Community on what should be the main subject areas for the research agenda in the future.

Therefore we intend to arrange the workshop by a range of presentations and we kindly invite you to contribute to it. In case you would like to inform us of your opinion by giving a lecture we suggest choosing one of the following subject areas:

- Monitoring and Assessment
- Life Cycle Management
- Structural Control
- Natural Hazards in General and Detail
- Desaster Mitigation
- related Subjects (technical, organizational, strategic items)

The outcome of the concentration of opinions and ideas will be contributed in the relevant European Technology Platforms (in particular in the Construction and the Safety Sector), which will come up with a detailed agenda by September 2005. This agenda is one of the steps needed to create a new structure for the 7th European Framework Program for Research and Development.

Furthermore the workshop will deal with possibilities for the establishment of the SAMCO results and examples in ISO and CEN and with national platforms for research in civil engineering.

The result of the workshop will be presented at this year's Summer Academy in September in Zell am See / Austria.

Organizational Issues

In order to make a final program we ask you to give us the title of your lecture as soon as possible.

For your personal registration please use the registration form made available on the website:

http://www.samco.org/workshop/index.htm

Your Coordinator

2nd SAMCO Summer Academy

September 5th to September 9th 2005 in Zell am See / Austria

Aims and Scope

The Summer Academy is an initiative of SAMCO, an EC funded European network on structural assessment, monitoring and control, coordinated by VCE Holding GmbH. The event serves to present the current practice in the fields mentioned and to encourage knowledge exchange between researchers, scientists, practicing engineers and end users.

Structural assessment, monitoring and control become increasingly important for asset managers, but also designers and consulting engineers. SAMCO is offering first hand information on the current practice and state of the art.

First SAMCO Summer Academy

In July 2003 the first international Summer Academy already took place at Cambridge University / UK.

Cambridge University

86 persons participated in this successful event, among them 38% representatives from industry and 62% from research and development (including students).

This first Academy covered the fields of Monitoring and Assesment, of the 6th Framework Program, of Sensor and Monitoring System Development and of Risk and Whole Life Costing.

Summer Academy 2005 in Austria

This year's Academy will take place from September 5th to 9th in Zell am See, located in the middle of the Austrian Alps right at the beautiful mountain lake "Zeller See". Zell am See is one of the oldest settlements of the Pinzgau region and was already colonized in Roman times.

Zeller See

Summer in the Europe Sports Region offers you a lake with drinking water quality as well as numerous mountains, which invite you to go hiking enjoying the beautiful countryside.

Zell am See is situated in a driving distance of about 60 min from Salzburg Airport. A shuttle bus running between the Airport and the venue will be provided for the participants of the Summer Academy.

site plan

Reasons for your participation

In the course of The Academy novel trends and technologies, equipment and devices will be demonstrated.

We invited top-level researchers and engineers from all over the world to give lectures on their practice and the future development in the field of research.

Training and education of end users and young engineers is extremely important. Due to the high quality lectures this is an ideal training event for ongoing experts.

Further the Academy offers the opportunity to meet a range of persons, fruitfully involved in outstanding research projects and networks, as well as access to the leading research community in the fields of structural assessment, monitoring and control.

Besides the import of the event from the professional point of view joining us may also be of interest for you to become acquainted with a beautiful part of Austrian landscape, to take part in a sightseeing tour to the old town of Salzburg, declared Cultural Heritage of the World since 1997, or in a hike in the mountains nearby.

Call for Papers

In case you would like to contribute to the event, please keep to the deadline of March 31st to submit an abstract and consider the limited number (24) of possible contributions. A pattern for your abstract is available on the website:

http://www.samco.org/academy05

Fees and Registration

The fee ranges from € 400,- to € 500,- depending on the booking date and includes admission, proceedings, lunch and coffee breaks and the academy dinner.

Please register by filling in the registration form available on the SAMCO website and sending it via fax to VCE:

+43 / 1 / 90 292 / 2123.

Costs for accommodation (Hotel Hubertushof) are at € 41,-- per night and person including half–board. The booking will be made by VCE after your registration for the Academy.

For further information about the event and a detailed program please study the website mentioned above.

We hope to have convinced you of joining our Summer Academy and are looking forward to welcoming you in September in beautiful Zell am See.

News from the Profession & Practice

Structural Health Monitoring Based on Global Flexibility Index: a Case of Highway Bridges

Abstract

Structures such as bridges, buildings and infrastructure were constructed to serve the society over an expected long period of time. Today, many of them have decayed due to aging, deterioration, misuse or lack of proper maintenance. It is important to be able to identify and monitor the health status of these structures to prevent potential sudden structural failures.

The present study advocates monitoring of global weakening of the bridge structures.

An index is proposed in this study for inferring the health deterioration of highway bridges, which shall be known as the Global Flexibility Index (GFI). This index is the spectral norm of the modal flexibility matrix obtained in association with selected reference points sensitive to the deformation of the bridge structure.

The modal flexibility matrix can be evaluated from the dynamic responses at these reference points under forced vibration. A sharp increase in the index calls for further detailed investigation for appropriate actions.

In this study, laboratory tests were conducted to demonstrate the sensitivity of the proposed index against different levels of controlled damages imposed on the tested structure, followed by a field test on an existing highway bridge.

Introduction

Highway bridges can suffer structural deterioration due to aging, misuse or lack of proper maintenance. Being able to monitor the structural health of existing bridges is crucial for avoiding sudden bridge collapses leading to losses of lives and economy.

The present research focuses on developing a reliable technique to identify global health deteriorations of highway bridges using the combination of simple impact test and the modeling power of the finite element method.

A global health index of individual bridges can be monitored to identify functionally obsolete bridges that need rehabilitation. Early detection of structural degradation can prevent *runaway* catastrophic failure.

Basically, there are three key areas concerning the health monitoring of civil infrastructures (Chong et al. 2003), namely (a) deterioration science, (b) assessment technologies and (c) renewal engineering. This research deals with an assessment technology.

In practice, any method used to determine existing health condition of bridges in service should be non-destructive. Ambient vibration tests have been used in many engineering applications to detect and to evaluate structural damages.

Recently, forced vibration gains more interest (Bakht and Pinjarkar 1989). The powerful development of data acquisition and signal processing of both the excitations and the responses leads to a reliable and accurate determination of dynamic characteristics of the system.

The basic ideas of damage evaluation techniques based on vibrations can be referred to the literature (Abdel-Gaffar and Housner 1978, Biswas et al. 1989, Douglas and Reid 1982, Flesch and Kernbichler1988, McLamore et al. 1971 and Salane and Baldwin 1990).

Dynamic characteristics of a structure, namely natural frequencies and mode shapes, are known to be functions of its stiffness and mass distribution. Variations in modal frequencies and mode shapes can be an effective indication of bridge deterioration if the damage is global in nature (Raghavendrachar and Aktan 1995).

Deteriorations of structure result in a reduction of its stiffness, which causes the change in its dynamics characteristics. Thus, monitoring the change in these dynamic characteristics enables us to infer to a structural deterioration.

The existing condition of the dynamic characteristics of a structure can be evaluated under either ambient or forced vibration. For bridges, dynamic excitation under ambient condition may not be sufficiently significant for the purpose of inferring its structural deterioration. Thus, forced excitation is necessary (Hogue et al. 1991, Raghavendrachar and Aktan 1995).

In the present study, forced excitation in the form of multi-reference impacts (Raghavendrachar and Aktan 1995) will be induced by an impact hammer at a set of referenced locations on the bridge deck. These locations must be selected appropriately where responses are pronounced and sensitive to the potential damages.

Although modal characteristics can be evaluated by processing the vibratory responses alone, the results are not as reliable as in the case when both the excitations and the responses are considered.

As changes in frequencies and mode shapes are not sufficiently sensitive to structural deteriorations, a better index that can reflect the global weakening of in-service bridges is needed. This index should be established in relation to the global softening of the structure, based on the flexibility matrix associated with a set of referenced locations. This flexibility matrix can be evaluated based on the modal parameters obtained from the impact test. The norm of this flexibility matrix can be employed as an index to reflect the global flexibility of the bridge structure. This index is referred as the Global Flexibility Index (GFI) in association with a set of referenced locations of the bridge.

Modal Flexibility Matrix

In the literature, modal flexibility has been used as a reliable signature to reflect the existing condition of offshore structures (Rubin and Coppolino 1983). Theoretically, structural deterioration reduces stiffness and increases flexibility. Increase in structural flexibility can therefore serve as a good indicator of the degree of structural deterioration (Raghavendrachar and Aktan 1995). Numerically, the flexibility matrix of a bridge can be established with respect to selected degrees of freedom from the mode shapes and frequencies. For the purpose of monitoring the flexibility change, these referenced degrees of freedom should be selected in such a way that they can reflect dominant deformations of the structure under its service environment.

The flexibility matrix associated with the referenced degrees of freedom can be established for an existing bridge from the result of multi-reference impact test.

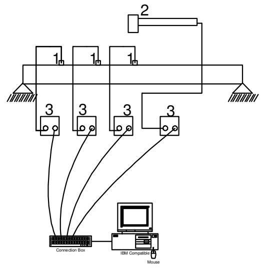


Fig. 1. Schematic impact test setup: (1) accelerometers(2) impact hammer and (3) signal conditioning

Based on the schematic test set-up in Fig.1, the response signals from the accelerometers and the impact hammer can be recorded each time. The time domain equations of motion can then be transformed into the frequency domain by the Fast Fourier Transform (FFT) resulting in a Frequency Response Function (FRF). Then, the modal flexibility matrix associated with the referenced degrees of freedom can be established from the following equation (Patjawit, 2004).

$$[F] = [\Phi]\left[\tfrac{1}{\omega^2}\right][\Phi]^T \qquad (1)$$

where [F] is the modal flexibility matrix; [Φ] the mass-normalized modal vectors; and [1/ω2] a diagonal matrix containing the reciprocal of the square of natural frequencies in ascending order. As flexibility matrix reflects global structural deterioration, its norm should serve as a good overall indication of its flexibility condition, namely the GFI, i.e.,

$$FMN = \max_i \sqrt{\lambda_i (F^T F)} \qquad (2)$$

where $\lambda_{max}(F^T F)$ is the largest eigenvalue of $F^T F$ matrix.

Calibration of finite element model

A finite element model can be established to represent an existing bridge based on its present in-service condition. Preliminary information can be obtained from as-built drawings and in-situ measurements, leading to the initial values of structural parameters, λ_i. The variation of these parameters after its usage shall be calibrated by tuning the flexibility matrix of the FE model to that observed from the test.

For relevant calibration, it is important that both matrices are associated with the same set of referenced degrees of freedom.

As shown in Fig. 2, the flexibility matrix, $[F_{ss}]$, of the finite element model can be obtained by inverting the reduced stiffness matrix $[K_{ss}]$ associated with the same set of referenced degrees of freedom $\{r_s\}$, after condensing it from the full stiffness matrix associated with the entire degrees of freedom of the finite element model.

Theoretically, all possible structural parameters can be tuned to calibrate the flexibility matrix of the finite element model to that obtained from the field test. As the geometrical parameters can be measured rather accurately, the remaining structural parameters to be tuned are (a) the elastic modulus, (b) the mass density of the structural material, and (c) the support conditions.

Laboratory impact tests

Undamaged beam test

A simple steel beam of channel section was selected in the experiment to confirm the correlation between theoretical and experimental results. The setup detail and the locations of the accelerometers are presented in Fig. 3.

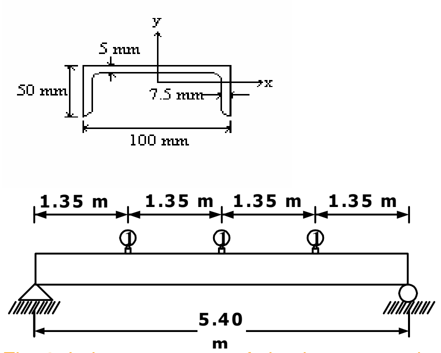


Fig .3. Laboratory setup of simple-supported steel beam, with mass density = 9.72 kg/m, Ix = 26.0×10^{-8} m4, E = 2.04×10^{11} N/m2

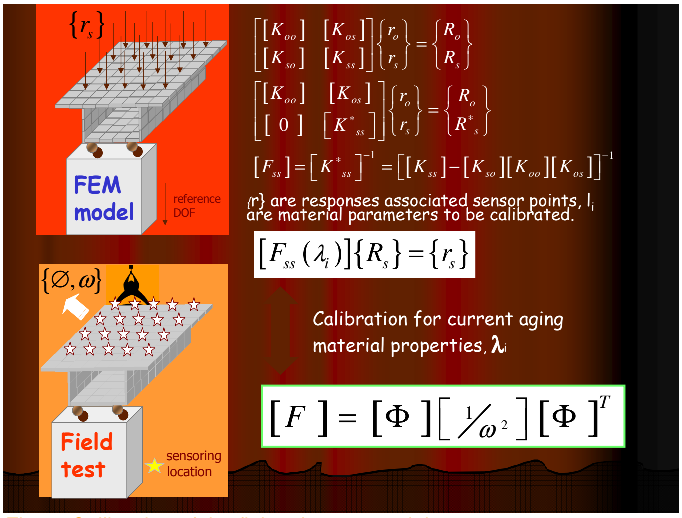


Fig. 2. Calibration of the finite element model.

Mode	Theory (Hz)	From test (Hz)
1	4	4
2	15.9	15.9
3	35.6	35.7
4	65.3	65.3
5	98.8	98.6
6	142	141
7	191.5	191

Table 1
Natural frequencies: theory and impact test

Table 1 lists frequencies of the first 7 modes obtained from the test in comparison with the analytical results. The corresponding FRF is presented in Fig. 4.

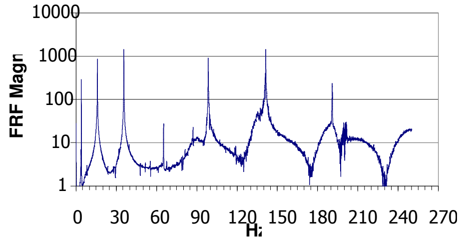


Fig. 4. Frequency-response function of steel beam under impact test

The modal flexibility matrix based on modal frequencies and mass-normalized mode shapes is evaluated using Eq. (1). It agrees exceptionally well with the corresponding theoretical result as shown in the comparison between Eqs. (3) and (4).

$$[F]_{theory} = \begin{bmatrix} 0.3479 & 0.4252 & 0.2706 \\ 0.4252 & 0.6185 & 0.4252 \\ 0.2706 & 0.4252 & 0.3479 \end{bmatrix} \times 10^{-4} \qquad (3a)$$

$$FMN = \|F_{theory}\|_2 = 1.220\times10^{-4} \qquad (3b)$$

$$[F]_{modal} = \begin{bmatrix} 0.3542 & 0.4264 & 0.2718 \\ 0.4264 & 0.6190 & 0.4160 \\ 0.2718 & 0.4160 & 0.3422 \end{bmatrix} \times 10^{-4} \qquad (4a)$$

$$FMN = \|F_{modal}\|_2 = 1.207\times10^{-4} \qquad (4b)$$

Impact Test on Steel Beam with Controlled Defects

A series of similar impact tests are conducted to evaluate the mode shapes and frequencies of the same C-shaped steel beam, but with some prescribed defects.

This test simulates different degrees of deterioration by introducing cuts in the bottom flanges at the beam mid-span.

For reference, No 0 is designated to the original beam without cut and No 1, No 2 and No 3 denote the same beam with cuts of 10 mm, 20 mm and 30 mm respectively. It was found that the alterations of mode shapes and frequencies due to adding the defects are found to be rather insignificant. However, the increase in GFI due to the increase in cut size is found to be more significant as shown in Fig. 5.

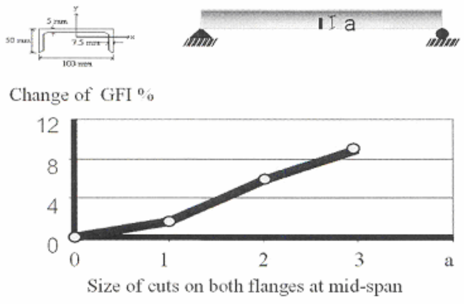


Fig. 5. Effect of defects on GFI in steel beam

This confirms that GFI is sufficiently sensitive to the defect built into the structure and its increase in magnitude is a good indication for structural deterioration.

Impact Tests on Reinforced Concrete Beam with Controlled Defects

Similar tests were conducted on reinforced concrete beam with various 10-mm deep cuts on the bottom zone of the beam as shown in Fig. 6.

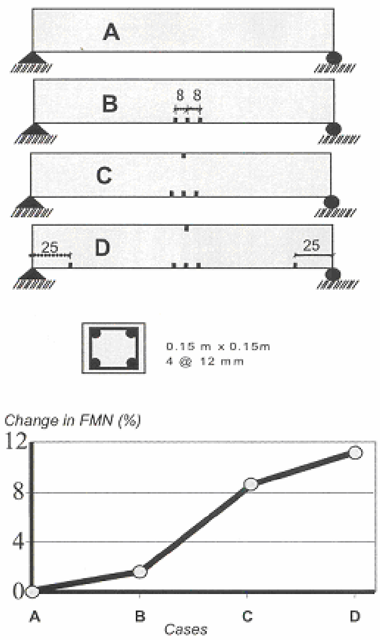


Fig. 6. Effect of defects on FMN in reinforced concrete beam

As in the previous case, only small changes in mode shapes and frequencies could be observed in the comparison due to the cuts.

However, the flexibility matrix associated with the three sensor points can be evaluated for each of the four cases. In Fig. 6, it can be seen that GFI increases with the increase of defects prescribed in the reinforced concrete beam.

Impact Tests on existing bridge

The tests are performed on an existing bridge as a means for acquiring mode shapes and natural frequencies. Subsequently the flexibility matrix of these bridges can be evaluated in association with the referenced locations where sensors are installed. It is proposed that its GFI associated with these referenced locations shall be monitored periodically each year. Aging of a bridge over a period of time will be reflected by the gradual increase of GFI. Rapid deterioration of the bridge structure will be warned by its very sharp increase, signifying the need for a close attention to retrofit the bridge.

Fig. 7. The bridge under impact test

The selected bridge, shown in Fig. 7, was constructed in 1999 as a part of national highway No.33 over a canal in Nakhon-Nayok Province, Thailand. It consists of three simple 10- meter spans of slab girders. Impact hammer and an array of sensors coupled with computer controlled multi-channel data acquisition and signal conditioning are utilized for gathering test information.
Locations for the multi-referenced impact test were selected based on a set of grid lines along the centre lines of longitudinal girders and piers. The referenced locations for evaluating the flexibility matrix are shown in Fig. 8.

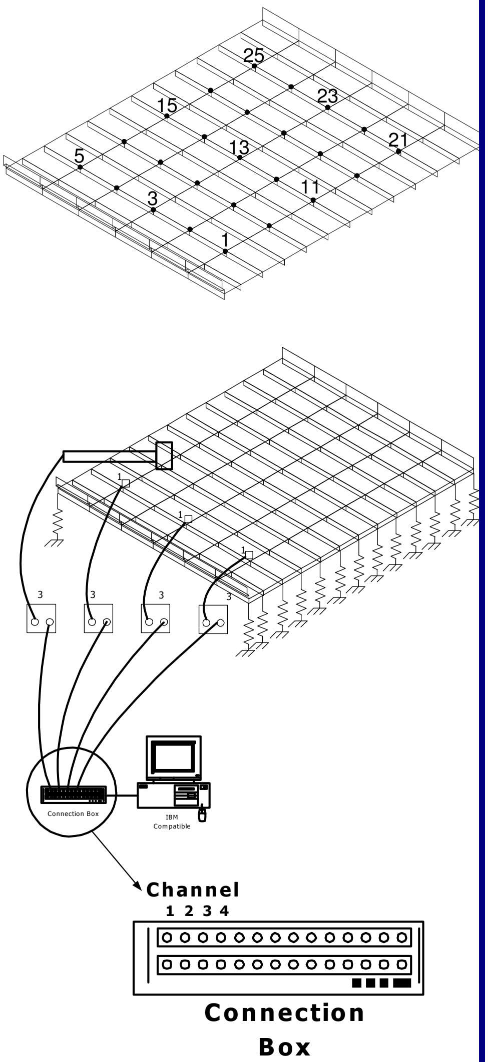


Fig. 8. Field equipment setup and selected locations for sensors

The impact hammer was "roved" about the structure to impact at referenced points, while the reference accelerometers were fixed.

Striking the test bridge at each of the selected referenced locations with impact hammer will impart a measured force, and induce vibratory responses at all seismic accelerometers installed at the referenced locations.

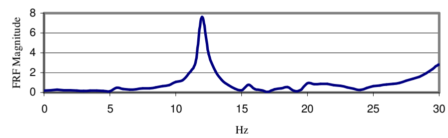
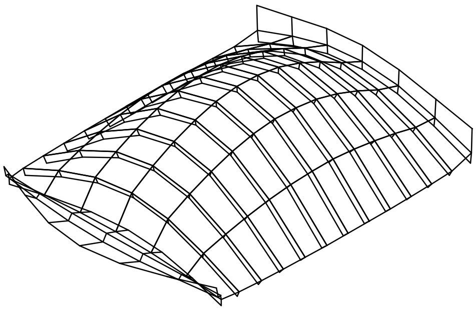


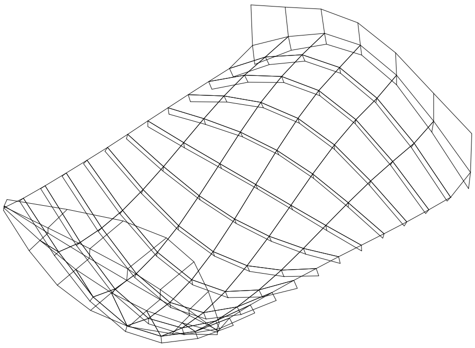
Fig. 9. A typical FRF obtained by impact test

A typical response in frequency domain is illustrated in Fig. 9 in the form of Frequency Response Functions (FRF), by which one can estimate the mode shapes and frequencies.



First Mode

Frequency = 12.7 Hz



Second Mode

Frequency = 15.59 Hz

Fig. 10. The first and second mode shapes of test bridge.

Figure 10 illustrated the first and the second mode shapes of the bridge. Based on Eq. (1), the modal flexibility matrix can be established from the modes shapes and frequencies with respect to the nine referenced locations shown in Fig. 8, as:

This index will be updated and its trend will be monitored every year. It is expected that the GFI of this bridge will increase gradually as the bridge ages.

The results of the modal test have provided sufficient information to facilitate the development of a finite element model for the test bridges. A three-dimensional finite element model was established for this bridge using four-node shell elements for the deck slab and a grid of beam elements for girders. Rigid links were employed to connect the mid-surface of the shell elements and the neutral axis of the grid beams. Cross-sectional properties of all structural members were obtained from the field measurements.

The material properties required to be calibrated with the field test were the mass density of concrete, elastic modulus (E_c) and Poisson's Ratio (μ). The calibration also included the spring modulus of the supporting spring elements, representing the support conditions. Starting with selected standard values, these parameters will be varied stepwise and finite element analysis can be performed for all combinations. The near optimal set of parameters was finally obtained that yield a GFI value of 1.1598×10-8 m/N compared with the value of 1.0554×10-8 m/N evaluated from the multi-reference impact test.

The operating rating factor, RFO, was introduced to check the absolute maximum live load that could safely be carried by the bridge.

On the other hand, the inventory rating factor, RFI, will serve to check the maximum live load that a bridge can continue to carry for an indefinite period of time. Both these rating factors can be expressed as follows:

$$RF = \frac{(C - 1.3D)}{2.17L(1+I)} \tag{7}$$

$$RF = \frac{(C - 1.3D)}{1.3L(1+I)} \tag{8}$$

in which C is the strength capacity of the member, D and L are the effects of dead and live loads respectively and I is the impact factor. Rating factor lower than one implies that the test bridge is unsafe. In that situation, a more rigorous investigation must be initiated that may lead to a major retrofitting of the bridge.

Based on the calibrated finite element model and the standard loads specified by AASHTO, the current ratings of this bridge can be evaluated as presented in Table 2. Based on the results, the present structural condition of this bridge is considered to be safe.

	Capacity	Dead load	Live Load	Inventory Rating	Operating Rating
Moment (N-m)	7.394×10^5	1.283×10^5	1.639×10^5	1.2	2.0
Shear (N)	1.031×10^6	5.237×10^4	2.297×10^5	1.5	2.5

Table 2
Rating with respect to moment and shear of the test bridge, considering the most critical girder

$$[F] = \begin{bmatrix} 0.0728 & 0.1457 & 0.0728 & 0.0662 & 0.1187 & 0.0662 & -0.0297 & -0.0461 & -0.0297 \\ 0.1457 & 0.2914 & 0.1457 & 0.1325 & 0.2374 & 0.1325 & -0.0594 & -0.0922 & -0.0594 \\ 0.0728 & 0.1457 & 0.0728 & 0.0662 & 0.1187 & 0.0662 & -0.0297 & -0.0461 & -0.0297 \\ 0.0662 & 0.1325 & 0.0662 & 0.1254 & 0.2392 & 0.1254 & 0.0457 & 0.1112 & 0.0457 \\ 0.1187 & 0.2374 & 0.1187 & 0.2392 & 0.4580 & 0.2517 & 0.1083 & 0.2553 & 0.1083 \\ 0.0662 & 0.1325 & 0.0662 & 0.1254 & 0.2392 & 0.1254 & 0.0457 & 0.1112 & 0.0457 \\ -0.0297 & -0.0594 & -0.0297 & 0.0457 & 0.0982 & 0.0528 & 0.0726 & 0.1506 & 0.0726 \\ -0.0461 & -0.0922 & -0.0461 & 0.1112 & 0.2334 & 0.1112 & 0.1898 & 0.3890 & 0.1898 \\ -0.0297 & -0.0594 & -0.0297 & 0.0457 & 0.0982 & 0.0457 & 0.0934 & 0.1898 & 0.0934 \end{bmatrix} \times 10^{-8} \tag{5}$$

Based on this flexibility matrix, the existing value of the GFI for this bridge can be evaluated from the spatial norm of the flexibility matrix, as

$$GFI = \sqrt{\lambda_{\max}(F^T F)} = 1.0554\times10^{-8} \tag{6}$$

Figure 11 shows the full finite element model for one typical span of this bridge. With the availability of the finite element model, one can evaluate the margin of safety of this test bridge based on the procedures recommended in the AASHTO *Manual.*

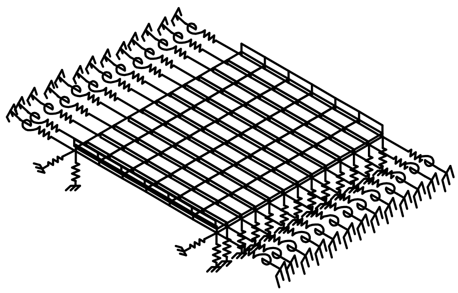


Fig. 11. Finite element model of the test bridge.

Conclusion

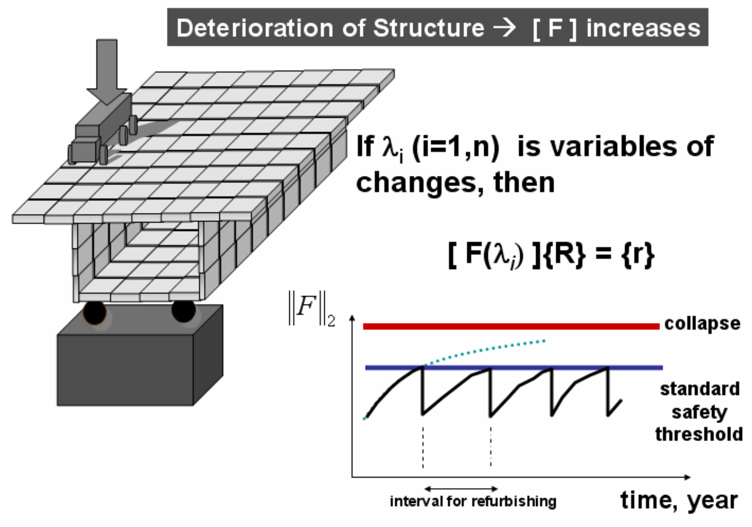


Fig. 12. Recommended maintenance program of a bridge.

The multi-reference impact test is a simple, practical, and reliable non-destructive method for determining the key structural characteristics of bridges.

At any decaying state of an existing bridge, its vibratory responses in terms of fundamental mode shapes and frequencies can be evaluated by this test. However, the alteration of mode shapes and frequencies due to a structural deterioration may not be sufficiently significant to infer the health condition of the structure.

On the other hand, in conjunction with the modern finite element modeling, fundamental mode shapes and frequencies can be used to establish the present status of the structural flexibility with respect to key referenced points, where vibratory sensors are installed. Global Flexibility Index (GFI) is introduced based on the spectral norm of the flexibility matrix.

In a bridge maintenance program, the GFI of a bridge can be monitored to see the trend of its structural health deterioration. In this study, change in GFI has been shown to be sufficiently sensitive to the global weakening of the structure, caused by deteriorations.

This research recommends that the present impact test be implemented as a routine maintenance for major highway bridges in Thailand under the Department of Highway. This regular monitoring of any bridge will provide an advanced warning for any sharp decay in its GFI, which is directly related to the global weakening of the bridge.

In practice, a monitoring program can be set in such a way that when GFI increases beyond a standard safety threshold, a major investigation will be conducted to strengthen the bridge, and thus restore the safety margin of the bridge. The maintenance program is demonstrated in Fig. 12. This program will ensure that the bridge will never fall into a state beyond repair and becomes unsafe to the public.

Contact

School of Civil Engineering (SCE)
Asian Institute of Technology

Prof. Worsak Kanok-Nukulchai
and Anun Patjawit (Doctoral Candidate)

P.O. Box 4 Klong Luang

Pathumthani 12120

Thailand

t: +66 / 2 / 524 / 5535
f: +66 / 2 / 524 / 6059 or 524 / 6432
m: worsak@ait.ac.th

References

Abdel-Gaffar, AM., Housner, GW. Ambient vibration tests of suspension bridge. Journal of Engineering Mechanics Division, ASCE 1978; 104(EM5): 983-99.

Bakht, B., Pinjarkar, SG. Review of dynamic testing of highway bridges. Transportation Record Broad Paper 880532. Ontario Ministry of Transportation. 1989.

Biswas, M., Pandey, AK., Samman, MM. Diagnostic experimental spectralmodal analysis of a highway bridge. Int. J. Anal. Experimental Modal Analysis, 1989; 5(1); 33-42.

Chong, KP., Carino, NJ., Washer G. Health monitoring of civil infrastructures. Electronic Journal of Smart Materials and Structures, 2003; 12(6); 483-93.

Douglas, BM., Reid, WH. Dynamic tests and system identification of bridges. Journal of the Structural Engineering. ASCE 1982; 108(ST10): 2295-2312.

Flesch, RG., Kernbichler, K. Bridge inspection by dynamic tests. In Natke and Yao (editors), Proceedings of Structural Safety Evaluation Based on System Identification Approaches; 1988

Hogue, TD., Aktan, AE., Hoyos, A. Regional identification of constructed facilities. Journal of Structural Engineering. ASCE 1991; 117(1): 128-148.

McLamore, VR., Hart, GC., Stubbs, I.R. Ambient vibrations of two suspension bridges. Journal of Structural Engineering, ASCE 1971; 97(ST10): 2567-2582.

Patjawit A. Structural identification of concrete girder bridge for strength evaluation. M. Eng. Thesis. Asian Institute Of Technology, Thailand; 2004.

Raghavendrachar, M., Aktan, AE. Flexibility by multireference impact testing for bridge diagnostics. Journal of Structural Engineering. ASCE 1995; 118(8): 2186-2203.

Rubin, S. Coppolino, R. Flexibility monitoring evaluation study. Mineral Mgmt. Service. U.S. Dept. of Commerce, Washington D.C.; 1983.

Salane, HJ., Baldwin, JW. Identification of modal properties of bridges. Journal of Structural Engineering. ASCE 1990: 16(7); 2008-21.

News from the Profession & Practice

System Identification of a Steel Frame: Comparison Between Frequency and Time Domain Analysis

Abstract

Structural SI using transfer function versus time series analysis is presented in order to provide damage identification.

The first method is based on changes in the interstory TF (CTF), whereas the second one uses the residual error in ARMA models as damage-sensitive feature.

Structural Model

A three storey "shear resisting" steel frame is modeled by FE to study the effectiveness of the proposed SI techniques. A set of twenty $20\,Hz$ band-limited white noise signals is generated and each of them is applied as acceleration support excitation, while the acceleration time history at each floor is posted.

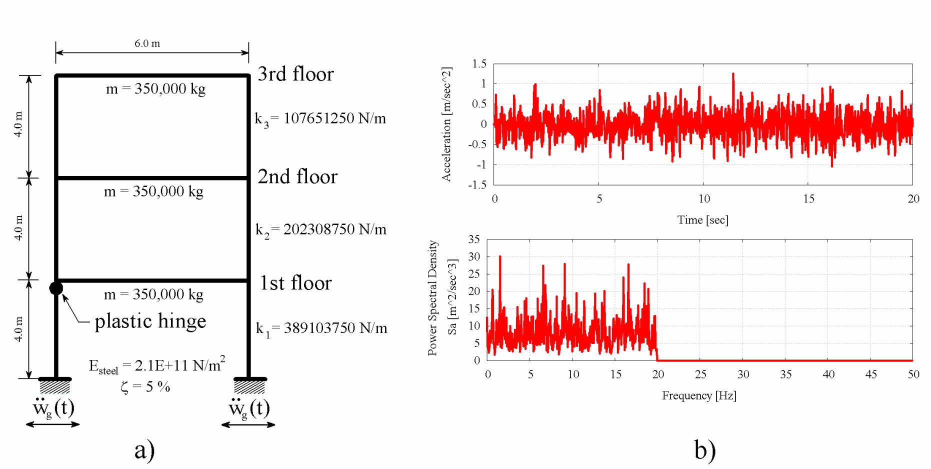


Fig. 1. System of consideration: a) structural model; b) typical 20 Hz band-limited white noise support excitation and its PSD

Introduction

The interest in practicing structural health monitoring (SHM) and then detecting damage at the earliest possible stage has been increased throughout the civil engineering community in the last decade.

Four levels of damage identification are known to date: (1) *is the structure damaged*; (2) *where is the damage located*; (3) *what is the damage extent*; (4) *what is the residual structural serviceability*. In general damage can be classified as linear or nonlinear. Linear damage is observed in the case when an initially linear-elastic system remains linear-elastic after occurrence of damage, whereas if the structure behaves inelastic nonlinear damage can be determined.

In this paper a comparison between frequency- and time-domain based approaches is presented, namely the Component Transfer Functions [1] and Auto Regressive Moving Average time series method [2]. A three storey "shear resisting" steel frame is analyzed, where nonlinear damage effects are simulated by implementation of a plastic hinge. Damage identification is then performed by each of the two methods respectively.

In order to affect nonlinear damage effects, a plastic hinge is simulated immediately below the first floor by means of cross-section reduction.

Fig. 1. depicts the structural model and a typical white noise signal.

Component Transfer Function Method

Background

In general the transfer function can be represented as the relationship between the input and the output of a system: $H_{ij}(j\bar{\omega}) = W_{ij}(j\bar{\omega})/P_j(j\bar{\omega})$.

Consequently the CTF can be defined as the relationship between any two outputs of a MDOF system:

$$\hat{H}_{vu}(j\bar{\omega}) = \frac{W_{vj}(j\bar{\omega})}{W_{uj}(j\bar{\omega})} \qquad (1)$$

If the peaks of these transfer functions, regarding to the actual system state, shift in comparison to those of a reference system state, there is structural change observable. In particular, if the peaks frequency values decrease and assuming the mass is kept constant, a loss of stiffness is occurred.

In other words, linear damage effects are detected. In addition, decrease of the peaks relative amplitude values is caused by an increase of the structural damping, which characterizes the presence of nonlinear damage.

Results

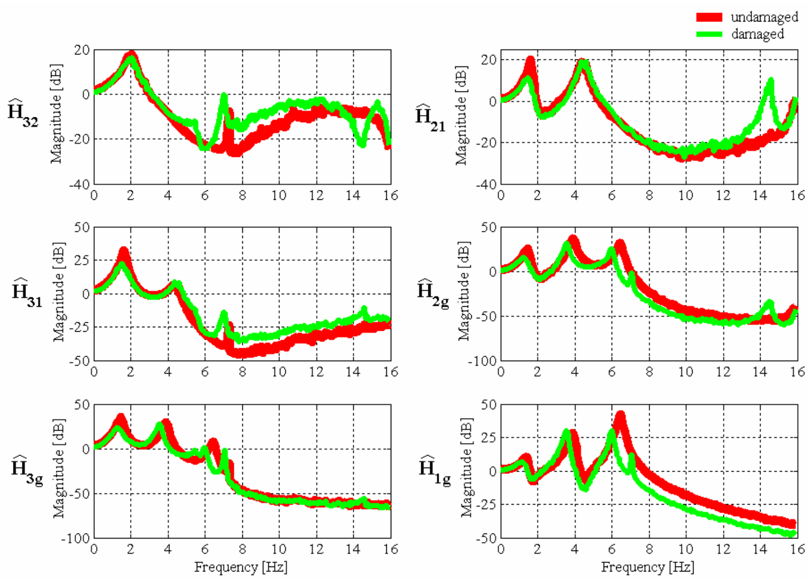


Fig. 2. Component Transfer Functions: undamaged versus system with nonlinear damage

Using Eq. (1) the CTF's are calculated by means of the averaged Power Spectral Density of the input ground motion and of the corresponding individual floor outputs. The obtained results are shown in Fig.2.. Note, that in $\hat{H}_{32}$, $\hat{H}_{31}$ and $\hat{H}_{21}$ there is not observable loss of stiffness, which means that no damage is occurred between the third and first floor. However, nonlinear damage effects are detected in $\hat{H}_{3g}$, $\hat{H}_{2g}$ and $\hat{H}_{1g}$. In other words, the occurred damage is located between the first and the base floor.

Arma Time Series Technique

Analysis procedure

For each time series $x(t)$ an ARMA (p,q) model with p AR terms and q MA terms can be constructed, as follows:

$$x(t)=\sum_{i=1}^{p}\phi_i x(t-i)+a(t)-\sum_{j=1}^{q}\theta_j a(t-j) \qquad (2)$$

This step is repeated for all samples obtained from the FE simulation of the undamaged system. The order of each ARMA model is obtained automatically as reported by [3].

In the next step all of the sample data is simulated by the obtained ARMA coefficients, both for the undamaged and for the damaged system. The mean idea is, that the constructed time prediction model regarding to a reference signal $x(t)$ should be able to appropriately predict any other signal $y(t)$, which is recorded under "close" structural conditions to those of the reference signal. Otherwise, by presence of damage there will be a significant error in prediction of the "new" signal $y(t)$. Therefore the standard deviation ratio of "similar" signals, $\sigma(\varepsilon_y)/\sigma(\varepsilon_x)$, can be defined as a damage-sensitive parameter, which is reaching its maximum value near the damage source.

Results

As shown in Table 1. the standard deviation ratio reaches its maximum value at the first floor, which localizes clearly the observed damage source.

Conclusions and Outlooks on Future Work

Level 2 of damage identification is provided by the presented techniques. Notice that using ARMA method no signal combination is needed. Future work will deal with the extension of the both methods to Levels 3 and 4.

References

[1] Caicedo, J., Dyke, S. J., and Johnson, E. A.: Health Monitoring Based on Component Transfer Functions. ICASD. Hong Kong. 2000, Dec. 13-15.

[2] Sohn, H. and Farrar, Ch. R.: Damage Diagnosis Using Time Series Analysis of Vibration Signals. Smart Materials and Structures. 10 (2001) 1-6.

[3] Broensen, P. M. T.: Automatic Spectral Analysis with Time Series Models. IEEE Transaction on Instrumentation and Measurement. Vol. 51, No. 2, April 2002.

Contact

VCE – Vienna Consulting Engineers

Dr. Helmut Wenzel
And Konstantin Savov

Hadikgasse 60

1140 Vienna

Austria

t: +43 / 1 / 90292
f: +43 / 1 / 90292 / 5000
m: wenzel@vce.at
savov@vce.at

	Load Case																			
$\sigma(\varepsilon_y) / \sigma(\varepsilon_x)$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1st Floor	**3.99**	**4.51**	**3.50**	**2.82**	**2.36**	**3.78**	**5.74**	**5.81**	**2.70**	**6.13**	**5.61**	**6.60**	**3.90**	**5.13**	**3.42**	**4.75**	**5.24**	**3.24**	**4.16**	**3.32**
2nd Floor	**1.57**	**1.67**	**1.94**	**1.67**	**1.25**	**1.32**	**1.41**	**1.75**	**1.56**	**1.71**	**1.64**	**1.30**	**1.34**	**1.87**	**1.60**	**1.65**	**1.50**	**1.24**	**1.56**	**1.13**
3rd Floor	**1.26**	**1.08**	**1.32**	**0.93**	**1.26**	**1.10**	**1.34**	**1.05**	**1.09**	**1.16**	**1.00**	**0.79**	**1.26**	**1.36**	**0.92**	**1.22**	**1.09**	**0.87**	**1.07**	**0.81**

Table 1. Standard deviation ratios for the various excitation cases

Company Profile

School of Civil Engineering

Asian Institute of Technology

Asian Institute of Technology (AIT)

AIT, a member of the Greater Mekong Sub-region Academic and Research Network, is an international graduate institution of higher learning with a mission to develop highly qualified and committed professionals who will play a leading role in the sustainable development of the region and its integration into the global economy.

Greater Mekong Subregion

AIT is located about 40 km. north of Bangkok.

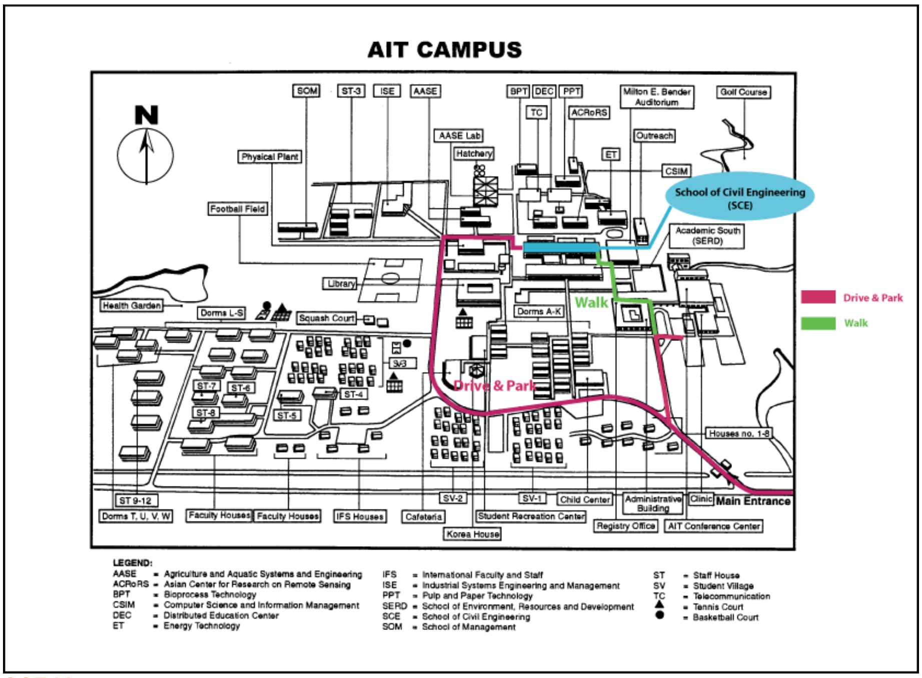
School of Civil Engineering (SCE)

View of SCE

The SCE is one of four schools within the AIT and is composed of five fields of study offered at the Institute in Bangkok:

- Construction, Engineering and Infrastructure Management (CEIM)
- Geotechnical and Geo-environmental Engineering (GTE)
- Structural Engineering (STE)
- Transportation Engineering (TRE)
- Water Engineering and Management (WEM)

In addition to these regular degrees, the School offers two-staged Programs in Viet Nam resp. in Indonesia:



SCE Map

- Master of Professional Engineering (MPE) Program in Civil Engineering
- Petra Christian University - AIT Dual Master Degree Program in Civil Engineering (PETRAIT)

Within these initiatives, students complete the initial semesters of their studies in their home countries and finish the remaining semesters at AIT in Bangkok.

More information on fields of study in the School of Civil Engineering, can be read up in the School Brochure to be found as PDF on the website:

http://www.sce.ait.ac.th/programs/fields.htm

Since September 2002 the SCE at the AIT also offers an Interdisciplinary program as Area of Specialization under the Geotechnical and Geoenvironmental Engineering (GTE) field of study.

The Geosystem Exploration and Petroleum GeoEngineering (GEPG) Program was launched to respond to the high demand in the region for professionals skilled in prospecting for mineral resources, petroleum exploration and production, near shore reclamation, and offshore construction as well as other infrastructure development works.

As a further educational opportunity the SCE recently launched new online courses on the web. Students have full permission to access in all areas. However, visitors can also access the online course in limited sections. The online courses available are:

- Structural Engineering and Construction Program
- Construction, Engineering and Infrastructure Management

In addition to these online courses a Regional Centre for Southeast Asia has been established at the Asian Institute of Technology (AIT) providing CDROM and Internet-based distance learning opportunities. The Water Virtual Learning Center (WVLC) Program offers distance based learning in Integrated Water Resources Management (IWRM) since January 2005.

Further information about this Program can be read up on the website:

http://www.sce.ait.ac.th/courses/wvlc/

The School's academic offerings lead to the award of Doctor of Engineering, Doctor of Technical Science, Master of Engineering, Master of Science, the AIT Diploma, and Certificate.

The Institute is home to faculty, staff and students from over 48 countries, an highly diversified international environment, in which students learn to interact across cultural borders.

With a large number of alumni occupying distinguished positions in various organizations in Asia and worldwide, the school's regionally pertinent programs provide a strong foundation for professional practice in a range of civil engineering disciplines.

Focus and Values of SCE

The School of Civil Engineering (SCE) is committed to academic excellence in postgraduate education and research across a broad spectrum of disciplines in civil engineering and in multidisciplinary areas that integrate technology, planning, design, construction and management of infrastructure and other built environments.

The School focuses its research initiatives on fields of regional relevance as well as on innovative and advanced technology.

One of the guiding values of SCE is the concept of being a personal "lifetime learning organization" for its graduates. It upholds cultural diversity, teamwork and synergy of diverse backgrounds and promotes a sense of justice and fair play amongst its faculty, staff and students.

While endeavouring to deliver state-of-the-art knowledge, the School underlines its important role in equipping students with the skills of research, i.e. "the learning process".

SCE Strategy

The School of Civil Engineering's internationally recognized reputation is built on a unique incorporation in its academic services of the five pillars of relevant higher engineering education:

- Information Technology
- International Perspective
- Innovation
- Integration (of environmental and social issues)
- Industrial Partnership

Within this framework, the School's efforts are directed towards establishing a holistic academic portfolio that spans not only the regiments of a traditional civil engineering curriculum but also the integration of such subject areas as management, economics, finance, environment-related courses as well as legal issues.

While maintaining a strong disciplinary identity, learning leans towards topic-based programs and applications that support environmentally sustainable economic development.

Emphasis is placed on training and equipping engineers with the capability to understand processes; to analyze, synthesize, and address problems and formulate solution strategies; to think across disciplines laterally and vertically; to communicate ideas; and to recognize the social, economic and political contexts of engineering practices.

Students are motivated to acquire the knowledge base and intellectual capacity for lifelong learning. They are exposed to extensive collaborative works with the industry making them broadly sophisticated yet technically versed.

Admissions

Candidates applying to the School of Civil Engineering have to keep to the deadlines and indicate, in order of preference, two out of the five fields of study offered at the Institute in Bangkok.

August is the normal entry month for candidates to the four-semester (two-year) Master Program, the two-semester (one-year) Diploma Program, and the one-semester (six-month) Certificate Program. Doctoral candidates may join the School in any semester beginning in January or August.

Contact

School of Civil Engineering (SCE)
Asian Institute of Technology

P.O. Box 4, Klong Luang

Pathumthani 12120

Thailand

t: +662 524 / 6053 or 6422
f: +662 524 / 6059
e: sce@ait.ac.th

http://www.sce.ait.ac.th