

# **STRUCTURAL FAULTS + REPAIR–2003**

**Abstracts of the Tenth  
International Conference**

on

**'Extending the Life of Bridges  
Concrete + Composites  
Buildings, Masonry + Civil Structures'**

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# STRUCTURAL FAULTS + REPAIR-2003

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# **KEYNOTE PAPERS**



## **FRP DECK FOR WEST MILL BRIDGE, UK**

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**Keywords:** Advanced composites, FRP, optimisation, bridge decking, new-build

The use of Carbon Fibre Reinforced Polymer (CFRP) plates/wraps has become a recognised and cost-effective method for strengthening existing concrete, metallic, timber and masonry structures. The technique is now being employed extensively by clients in the UK, Europe, USA, Canada and Japan to increase flexural, shear, impact and seismic capacity. Advanced Composite structural members, made mostly from GFRP have also been widely used in the construction industry as secondary elements, and to a lesser extent for footbridges and cladding systems on bridges.

The construction industry is however now moving towards using FRP as the main structural load-carrying members in new build applications following on from the success of advanced composite materials in the aerospace and motor racing industries.

The USA has led the way in using FRP decks to replace corroded concrete or steel decks on bridge structures with success. The benefits of composites, lightweight, high strength, good durability, fatigue and creep behaviour, and the reduced installation costs have all contributed to the potential. Further projects, both actual and research, are continuing in this field.

The first all FRP bridge (deck & main beams) to be constructed on the public highway in Western Europe, West Mill Bridge, was recently opened in Oxfordshire, UK, and was the main deliverable of the 4 year European Commission funded research

and development project ASSET, that developed the technology to cost-effectively and efficiently produce FRP components for use in new build applications.

This paper gives details of the ASSET project, and describes the analysis, design and successful construction of West Mill Bridge.

## **FIRST CFRP PRESTRESSED CONCRETE BRIDGE IN THE UNITED STATES ‘BRIDGE STREET BRIDGE’**

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**Keywords:** Beams, bridges, carbon fiber reinforced polymer (CFRP), carbon fiber composite cable (CFCC), prestressed concrete, pretensioning, post-tensioning, strands, tendons

The Bridge Street Bridge in Southfield, Michigan, is the first vehicular prestressed concrete bridge ever built in the United States that uses carbon fiber reinforced polymer (CFRP) material as the principal structural reinforcement. The Bridge Street Bridge consists of two parallel and independent bridges (Structure A and Structure B) over the Rouge River in the City of Southfield, Michigan. Both structures are designed to accommodate one traffic lane and incorporate three 15° skewed spans, each over 62 m (204 ft) long. Structure A consists of new substructure and superstructure and incorporates five equally spaced conventional AASHTO type III girders in each of its three spans. Its cast-in-place concrete deck slab is placed continuously across the three spans. Structure B consists of twelve Double Tee (DT) beams prestressed using pretensioned

Leadline<sup>TM1</sup> tendons and post-tensioned carbon fiber composite cable (CFCC<sup>TM2</sup>) strands. This paper presents the design, fabrication, erection, instrumentation and long-term monitoring program details of structure B, and various measured response parameters during different construction stages.

## **PROGRESS ON UNDERSTANDING DEBONDING PROBLEMS IN REINFORCED CONCRETE AND STEEL MEMBERS STRENGTHENED USING FRP COMPOSITES**

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**Keywords:** Fiber reinforced plastics; repair, strengthening; debonding

Use of fiber reinforced plastic (FRP) composite materials for strengthening and repair of structural members has become an increasingly popular area of research and application in the last decade. However, the method is yet to become a mainstream application due to a number of economical and design related issues. From a structural mechanics point of view, an important concern regarding the effectiveness and safety of this method is the potential of brittle debonding failures. Such failures, unless adequately considered in the design process, may significantly decrease the effectiveness of the strengthening or repair application. In recent years, there has been a concentration of research efforts on characterization and modeling of debonding failures. This paper provides a review of

the progress achieved in this area regarding applications to both reinforced concrete and steel members.

## **UNDERSTANDING AND MODELLING THE BEHAVIOUR OF FRP-CONFINED CONCRETE**

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**Keywords:** FRP, confinement, concrete, behaviour, modelling, stress-strain models

In recent years, external confinement of concrete using fibre reinforced polymer (FRP) composites has emerged as a popular method for the retrofit of existing reinforced concrete (RC) columns for enhanced strength and ductility. As a result, many theoretical and experimental studies have been carried out on FRP-confined concrete. This paper provides a critical review of existing studies, with the emphasis being on the revelation of the fundamental behaviour of FRP-confined concrete, and the modelling of this behaviour. Aspects covered in this paper include stress-strain behaviour, dilation properties, ultimate condition, and stress-strain models. The paper concludes with a brief outline of issues which require further research.

## **MEASURING LAYER THICKNESSES WITH GPR – THEORY TO PRACTICE**

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**Keywords:** Nondestructive testing, ground penetrating radar (GPR), pavement layer thickness estimation

Ground penetrating radar (GPR) technology has been used to assess pavement performance and structure for the past 30 years in a variety of ways. Yet after all this time, the main issue remains: How well does GPR work and under what conditions? Results show that GPR works well for some situations but not as well for others. It is not currently used on a routine basis by the Departments of Transportation (DOTs) in the U.S. mainly because of difficulties encountered while interpreting GPR data. These difficulties are generally attributed to the fact that the GPR reflected signals that are collected depend largely on the a priori unknown dielectric properties of the structural materials. Additional difficulties arise from the fact that physically GPR cannot detect layers unless they have sufficiently dissimilar dielectric constants.

In practice, GPR has been used primarily for pavement layer thickness estimation and moisture accumulation localization within the pavement layers. To improve GPR prediction capabilities, different data processing techniques have been developed that use the GPR reflected signal to estimate the dielectric properties

of surveyed structures, thus determining their thicknesses. Other signal processing techniques have also been used successfully to enhance the quality of the GPR signal in order to increase the accuracy of the data interpretation results.

## **PIPERS ROW CAR PARK COLLAPSE: IDENTIFYING RISK**

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**Keywords:** Collapse, risk, appraisal, inspection, repair, deterioration, concrete

SCOSS had warned of the risks from the deterioration of car parks before 120 tonnes of top floor slab of Pipers Row Car Park collapsed early on 20th March 1997. For a decade before, signs of concrete deterioration were evident and various inspections and repairs were carried out. The potential consequences of this deterioration and the vulnerability of flat slab construction to punching shear failure and progressive collapse were not appreciated by those involved in management, assessment, inspection and repair.

New guidance on car park design and maintenance and more generally on the assessment, inspection and repair of structures, have highlighted the importance of a structural understanding as a precondition for the identification of problems and for successful remedial works for the growing number of deteriorating concrete structures. Health and Safety requirements make it essential for owners, operators, engineers, materials specialists, repair and demolition contractors to work as a team in developing overall risk assessments for deteriorating structures based on full exchange of information and records.

## **RAPID AND ECONOMICAL EVALUATION OF CONCRETE TUNNEL LININGS WITH IMPULSE RESPONSE AND IMPULSE RADAR NON-DESTRUCTIVE METHODS**

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**Keywords:** Concrete tunnels, grouting, nondestructive testing (NDT), impulse response, impulse, radar

Concrete tunnel linings, whether pre-cast or cast in place, are designed to distribute external soil pressures as uniformly as possible through the tunnel shell. To this effect, the contact between the lining and the surrounding soil is usually assured by grouting the annular space between. Any voiding in the grout at this interface negates the purpose of the grout. This paper describes the use of nondestructive testing to examine the efficiency of tunnel lining grouting programmes, with particular emphasis on results obtained by the Impulse Response and Impulse Radar methods. The rail, water supply and sewer tunnels discussed in this article vary in diameter between 1 m and 5 m, and emphasis is placed on the rapid results obtained by these methods.

## **MECHANICAL BEHAVIOUR OF MULTIPLE-LEAF STONE MASONRY: EXPERIMENTAL RESEARCH**

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**Keywords:** Multiple leaf, stone masonry, shear strength, compression strength, failure mechanisms

An experimental research has been carried out on three-leaf walls purposely built using two stones of different characteristics, following two geometric patterns, with and without stone offsets guaranteeing some degree of connection between leaves, trying to reproduce two masonry typologies frequently used in Italian historic centers. The first phase of the test was aimed to study the shear response of the interface between the masonry leaves, whereas the second phase tried to achieve some understanding of the bearing capacity of the structure after the perfect mutual collaboration has been lost.

# **Theme 1: Bridges**

## **Day 1:**

### **Bridge Management & Assessment**



## **PROVIDING FOR SAFETY IN BRIDGE MAINTENANCE**

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**Keywords:** Bridges, safety, maintenance work

This paper deals with the role that designers can play in making maintenance work on bridges a safer activity. In the first part, it offers some thoughts on how designers could ensure that their designs produce durable, ie, minimum maintenance, bridges. In the second part, it goes on to provide some ideas about how designers can make provision for safe access for inspection and maintenance.

## **QUANTIFYING THE REAL STRENGTH OF HIGHWAY STRUCTURES**

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**Keywords:** Bridges, failure, assessment, concrete, steel, slab, testing

The paper summarises a project on assessment carried out for the Highways Agency by Atkins. The recommendations are contained in a report which describes how additional strength can be obtained from highway structures which fail their assessment due to deterioration, lack of strength, increased loading or design inadequacies. Mobilising hidden strength in some circumstances could enable structures to remain in service, thus avoiding traffic disruption and expensive repair.

The objective of the project is to promote lateral thinking in assessment of older bridges which often show no signs of distress and the report has dealt with a number of aspects including calculations from first principles, yield line, compressive membrane action, consideration of partial safety factors, orthotropic action in stiffened web and flange plates, non-linear finite element analysis and initial imperfections, shear in prestressed concrete flanged beams, inclined neutral axis, bearing clamping, bent-up bars, and shear strength of circular pile caps.

The project entailed a literature search and a study throughout Atkins' Regional and Maintenance offices of preferred methods of analysis, common problems in carrying out assessments, and use of hidden strength techniques.

Additionally the project included model testing in shear of reinforced concrete slabs, designed by Professor Paul Regan and tested at Imperial College. The object was to assess the effect of traffic loading on bridge decks and to determine the extent to which the shear loading is distributed across the width of the deck. Tests included concentrated loads close to free and supported edges of the slab. The test results were compared favourably with analysis by the Hillerborg method, and demonstrated significant increases in capacity in comparison with assessment by BD44.

## **TOWARDS A MORE RATIONAL APPROACH FOR ASSESSING AND RATING CONCRETE BRIDGES**

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**Keywords:** Concrete bridges, assessment, non-linear finite element analysis, compressive-force path method

This paper presents two new methodologies (one formal (NLFEM), the other approximate (CFPM)) which show clear differences - often quite considerable – with regard to code predictions needed to assess and rate existing concrete bridges. The work has obvious implications in terms of both economy and safety, and can assist the engineer in reaching more rational and accurate decisions on the true structural capacity and mode of failure of a structure.

## **THE BENEFITS OF CONDITION MONITORING OF CONCRETE STRUCTURES**

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**Keywords:** Durability, condition, monitoring, diagnosis, maintenance

Government Agencies in Europe have now accepted that their concrete structures – for example buildings, dams, power stations, bridges – will be managed more cost-effectively when the condition of the structures are accurately known. Visual inspections alone are not sufficient. The condition of structures and the causes of any deterioration must be accurately determined if the structures are to be managed cost-effectively and if safety and operational requirements are to be achieved. The ideology currently used by maintenance engineers has to change.

The paper outlines how condition monitoring should be implemented, the lessons learnt by not carrying out condition monitoring and how it needs to be done in order to improve the cost-effectiveness of bridge maintenance. Problems can be nipped in the bud, and whilst initial costs may increase, there will always be significant long-term savings.

The spiralling costs of maintenance budgets has forced many European Governmental Agencies to recognise that the use of structural concrete does not necessarily result in maintenance free structures. At present many Agencies are endeavouring to develop or have already developed structural management systems

that will allow them to effectively manage the assets under their control with the limited resources at their disposal. The current legacy of deteriorating structures is a monument to poor design and construction techniques. It also proves conclusively that the attitude that 'if it looks ok, it is ok' has to be discarded .

If a structure is to remain operational throughout its anticipated design life, it is vital that the maintaining engineers understand not only the potential causes and mechanisms of deterioration but also the 'real' condition of insitu materials. Therefore corrosion and chemical testing of concrete structures is an integral part of any good structural maintenance strategy.

This paper outlines how condition monitoring should be implemented, the lessons learnt from previous mismanagement and the potential financial benefits that such testing affords. A case study will be presented which will demonstrate that how active corrosion in a real structure was diagnosed and a simple remedial plan suggested, thereby preventing a costly bridge replacement.

## **EVALUATING LIVE LOAD CAPACITY OR K-FACTOR RATING OF BRIDGES SUBJECTED TO UNEXPECTED DAMAGE**

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**Keywords:** Bridges, K-factor, load capacity rating, unexpected damage

The K-factor or remaining live load capacity is an established tool for evaluating the performance of a bridge over its life. The K-factor reduces with time because of deterioration caused by corrosion, fatigue or other degrading mechanisms. Various

methods have been proposed for evaluating the change in K-factor with time, under the effect of known mechanisms. However, consideration has not been given to damage from unexpected or unpredictable causes such as fire or bridge strike. In this paper a systematic procedure is proposed for evaluating the effects of unexpected damaging events on highway bridges.

The method is based on energy principles and finds the critical sequence of damaged members that will eventually cause collapse of the bridge. It is proposed that this sequence represents the worst case scenario for degradation or accidental damage to a bridge over its life. A finite element model of a real steel girder highway bridge was analysed and for each successive damaged member the residual live load capacity of the bridge was evaluated. Hence, a K-factor curve was obtained that represented whole-life performance of the bridge including the effects of unexpected damage. Moreover, the results identified members that are particularly critical and should be strengthened for greater robustness of the bridge.



# **Theme 1: Bridges**

## **Day 1:**

### **Concrete Bridges**



## **MONITORING OF ASR IN CONCRETE STRUCTURES: A 'SMART STRUCTURE' PROJECT**

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**Keywords:** Concrete, ASR, monitoring,  
bridges, decks, smart, structure

The first Dutch major smart structure project involves the continuous monitoring of 18 concrete bridge decks on the effects of ASR. Monitoring was needed because the safety had decreased due to a loss of shear capacity. This could lead to a brittle collapse in term. Experience on the monitoring of ASR is limited. Therefore, a pilot was performed on two bridge decks to determine effective monitoring techniques. A plan was made for the monitoring of the other bridges after a one-year evaluation. Since it was not possible to monitor structural effects directly, the effectiveness of a performed renovation was measured. The renovation was aimed at the drying of the concrete, in order to stop expansion.

The applied monitoring techniques involves innovative aspects. Modern communication techniques and web-based user interfaces help to gather and present large amounts of data on-line with little effort. Several aspects can be measured and presented simultaneously. In this way results can be correlated and trends can be identified. Besides the primary monitoring goal, the project can provide much information on the applied monitoring techniques, the behaviour of moisture in concrete and the effect of a 'drying' renovation strategy on ASR expansion in general.

## **COVER CONCRETE EVALUATION BY ELECTROMAGNETIC AND ELECTRIC TECHNIQUES. CASE STUDY: EMPALOT BRIDGE (TOULOUSE, FR)**

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**Keywords:** NDE, concrete, corrosion,  
moisture, radar, resistivity, half-self  
potential, capacitor

Various GPR and capacitive experimentations have been done on the deck of an old bowstring bridge in order to characterize the cover concrete. Built in 1916, this four-span bridge has presented classical faults such as working or under-design, concrete failure with visible corroded bars, very thin cover concrete and water ingress on abutment.

The top of the deck and the underside of the fourth span, have been investigated by mean of various non-destructive testing (NDT), such as ground-penetrating radar (GPR - classical profiles, different kind of mappings including the reinforcement mapping and the surface-reflection energy mapping), capacitor and electric techniques. The three last techniques have been mainly developed for moisture-content estimation of concrete. As expected, the electromagnetic techniques localize the reinforcement. Furthermore, as they are sensitive to the water content, one can obtain

the localization of wet areas, favorable to rebar corrosion.

Thus, these NDT have shown the advantage to give an accurate estimation of the high-risk areas, where the cover concrete is under-designed and above all ineffective. This kind of reliable information is fundamental for accurate repair estimation.

## **REPAIR OF SINKING BRIDGE OVER GUADALQUIVIR RIVER IN ALCALA DEL RIO. SEVILLE (SPAIN)**

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**Keywords:** Pier, abutment, deck, boring, pile, micropile, settlement, jet grouting, refusal, skin pile capacity, tip pile capacity

The bridge over Guadalquivir river, near Alcalá del Rio in Seville (Spain), that has nine spans of 30 m each with a total length of 270 m, has suffer in 1993 a sinking of 14 cm and 6 cm on two of the central piers located in the centre of the river. The superstructure is isostatic and is formed by six prefabricated concrete T-beams 150 cm. height. The foundation is constituted by two circular pier-piles of 1,50 m of diameter in each support. The bridge was constructed between July 1990 and October 1992.

In the first week of April 1993 it was observed that the handrails formed a vertical angle in the centre of the bridge, which indicated a sinking of piers P-4 and P-5 just in the middle of the river. The following topographic observation showed vertical movements of 13,9 cm and 5,4 cm in each pier.

After a revision of the project it was concluded that the security coefficient could be enough, but the next soil site

investigation showed a dropping of the compacity of the soil just in the area of piers P-4 and P-5. Using the new parameters of the soil due to the new geotechnical campaign it was concluded that the security coefficient for piers P-4 and P-5 was very low, explaining the sinking occurred. After studying different solutions it was concluded that the best technically and economically, was to use Jet Grouting injections.

By using to concentric circular crowns of nine Jet Grouting injections, the most interior vertical and the most exterior inclined to the axe of the pier, it was formed a kind of superpile of soil-cement raising dramatically the security coefficient and the most important lifting the pillars P-4 and P-5 10 cm and 2,5 cm respectively, reducing almost all the angular distortion of the deck. The repairing works were made in 1993.

## **EVALUATION OF THE LOAD BEARING CAPACITY OF A CORRODED REINFORCED CONCRETE BRIDGE**

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**Keywords:** Corrosion, reinforced concrete, chloride, mechanical behaviour, FEM, diagnosis

This article proposes a diagnosis method for corroded reinforced concrete members. Initially, the corrosion state of the reinforcements is deduced from a simple visual observation of concrete cover cracking due to corrosion, through an empirical model correlating the

reinforcement cross-section loss to the crack width. Distribution of this corrosion is then introduced in a mechanical model of corroded reinforced concrete behaviour. This model is based on a Finite Elements calculation, assembling sections of variable inertia function of the combined effects of corrosion : the reduction in bar section and the loss of the steel-concrete bond.

The methodology of diagnosis is applied to a real corroded bridge to re-evaluate its mechanical behaviour in service. The goal being to ensure of the reliability and the safety of the structure versus serviceability requirements and to assess the safety margin according to the evolution of the corrosion state.

## **SHEAR ASSESSMENT OF CONCRETE BRIDGES WITH POORLY ANCHORED REINFORCEMENT**

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**Keywords:** Shear, concrete, bridges, assessment, anchorage, plasticity, beams, slabs, analysis

A new method for shear assessment of concrete bridges allowing for poorly anchored reinforcement has been developed. The new assessment method is the result of research performed at Bath University, partly funded by Parsons Brinckerhoff Ltd (PB) and the government research council EPSRC.

The appropriate use of the assessment method would allow some bridges to remain

in service, rather than be strengthened or replaced, saving significant costs for bridge-owners and promoting sustainability by extending the life of structures and reducing unnecessary expenditure of resources.

The proposed method is based on rational theoretical analyses and has been verified by extensive laboratory testing of concrete specimens. Upper-bound and lower-bound plasticity analyses have been used to successfully model the test results, and subsequently simplified for convenient application in an Assessment Standard.

## **NEW METHODS FOR ROAD BRIDGES REHABILITATION**

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**Keywords:** Bridges in Romania, accurate execution, diagnosis process

The paper presents some new technologies for bridge rehabilitation using high performance materials. These technologies were applied with great success to repair many road bridges in Romania.

The rehabilitation of the road bridges comprises of the replacing of the waterproofing, pavement and expansion joints, as well as repair of the reinforced or prestressed concrete structures. The paper also presents some examples of road bridges in Romania that were repaired with high performance concrete.

## RECONSTRUCTION OF THE PAG BRIDGE

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**Keywords:** Concrete bridges, reinforced concrete arch, bridge repair, reinforcement corrosion

The Pag bridge was thoroughly reconstructed because of heavy damages caused by reinforcement corrosion. The design of new steel superstructure is presented. The repair of piers is briefly described. Effects of the superstructure replacement on the arch behaviour are discussed. The numerical analysis showed high sensitivity of the relatively elastic arch to the change of dead weight distribution.

## SPAN LENGTH RATIOS IN BRIDGES CONSTRUCTED USING BALANCED CANTILEVER METHOD

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**Keywords:** Balanced cantilever method, RC bridges, construction sequence, creep, span length, relaxation

This paper introduces a relation to determine the span ratio between exterior and interior spans, which is required in the preliminary design stage of bridges constructed by balanced cantilever method. On the basis of the numerical results obtained by rigorous time-dependent analyses, the moment distribution along the

spans and its variation with the construction sequence are reviewed, and a recommendation for a rational design is suggested. First, a relation for the initial tendon force is derived on the basis of an assumption that no vertical drift occurs at the far end of a cantilever beam due to the balanced condition between the self-weight and the cantilever tendons. In advance, the determination of an effective span ratio is followed with an assumption that the magnitude of maximum negative moment must be the same as that of the maximum positive moment along all of the spans. Finally, many rigorous time-dependent analyses are conducted to establish the validity of the introduced relations, and this paper shows that an effective span length ratio of the exterior span to the interior span ranges between 0.75 and 0.8.

## ON THE EFFECT OF REINFORCEMENT ON EARLY-AGE CRACKING IN HSC-BRIDGE FLANGES

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**Keywords:** Early-age cracking, high strength concrete, reinforced concrete

In a bridge flange made of HSC the predicted number of cracks overestimates by far the observed number of cracks. In a recently performed research project it was aimed to gain more insight into this phenomena and the behaviour of hardening reinforced HSC in general. Therefore the effect of reinforcement on early-age cracking in HSC has been tested on reinforced specimens in a Temperature Stress Testing Machine. In addition, the free

deformations of a plain and a reinforced specimen were investigated. Furthermore, the development of cube compressive strength, pull-out strength and E-modulus were determined. In order to separate thermal effects from autogenous shrinkage, experiments were not only performed under realistic (semi-adiabatic) but also different isothermal (20, 30 and 40°C) temperature conditions. It was found that reinforcement can induce smaller cracks which leads to an 'increase of the strain' of the bridge flange before major cracks occur. In addition, a new bond stress-slip relation was developed for early-age HSC. With the help of these two results it can be explained why fewer cracks were found in the bridge flange than predicted.

## **THE REBUILDING OF THE BRIDGE ON THE EXISTING FOUNDATION**

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**Keywords:** Bridge, concrete, bomb damaged, rebuild

Bridge across river Ponor on road section M5-2, Mrkonjic Grad – Bihac was destroyed during war activities in 1995. Bridge is located on international European road E-761. Formed bridge was built up in 1974. This paper describes the reconstruction of the destroyed bridge.



# **Theme 1: Bridges**

## **Day 1:**

### **Bridge Repair Using Advanced Composites**



## **APPLICATIONS OF FRP COMPOSITES FOR BRIDGE REHABILITATION & STRENGTHENING IN THE USA**

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**Keywords:** FRP composites, bridge  
rehabilitation, bridge strengthening

Approximately 30 percent of the 590,000 bridges, culverts and tunnels in the United States (US) are rated deficient. This includes bridges with main members that are deteriorated and/or under strength as well as bridges that are geometrically obsolete for today's traffic volumes and loads. The deficiencies related to structural capacity or performance include deteriorated concrete bridge decks, corrosion damaged or cracked concrete bridge pier caps and columns, beams with deteriorated concrete and/or excessive cracking and concrete or steel beams with reduced or substandard load carrying capacity. Tight budgets and the need to accomplish repairs with a minimum of disruption to traffic flow have necessitated the development of non-traditional rehabilitation schemes. Certain types of these structural deficiencies are amenable to rehabilitation and/or strengthening using bonded repairs with fiber reinforced polymer (FRP) composite laminates or Post-tensioning with FRP composite tendons. Highway agencies in the US have several years of experience in applying FRP materials for applications such as: rehabilitating and strengthening pier

columns and pier caps; repairing cracked concrete box girders and increasing shear strength; increasing flexural strength of concrete tee-beams, concrete box girders and steel truss members; and strengthening bridge piers for seismic loads. Examples of successful bridge rehabilitation with FRP composites are described along with methods of evaluating performance and durability of the bonded repairs.

## **DESALINATION AND COLUMN WRAPPING OF M6 CUMBRIA BRIDGES: ARAMID FIBRE**

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**Keywords:** Concrete repairs, desalination,  
strengthening, aramid FRP column wrap

Six over bridges between Junctions 38 and 40 of the M6 were identified through Principal Inspections as having piers with cracking and spalling concrete, especially on their traffic faces.

This paper discusses the repair and strengthening works carried out to the piers, from the feasibility study through technical approval to the site works.

The repair and strengthening works consisted of desalination and fibre reinforced polymer column wrapping. The scheme was the first one undertaken by the Highways Agency, which used desalination and aramid FRP column wrapping techniques together.

## **THE EFFECT OF CURVATURE ON STRENGTHENING WITH FRP**

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**Keywords:** FRP, concrete, strengthening, curvature effects

The use of fibre-reinforced polymers (FRP) has become a widely accepted solution for strengthening reinforced concrete structures. Good durability characteristics, low self-weight and ease of installation make FRP an attractive option in many strengthening schemes.

Although curved structural elements are not uncommon, there is limited understanding of the effect non-straight soffits have on the strengthening capability of externally bonded FRP when used to increase the flexural capacity of reinforced concrete structures. The effectiveness of the strengthening scheme is highly dependent on the bond between the composite and the existing structure. The presence of curvature induces tensile stress at the adhesive/concrete interface, which can lead to premature failure by separation of the plate. This paper describes the design and implementation of a programme of testing aimed at investigating the effect of curvature on the strengthening scheme.

A case study is presented illustrating where difficulties can be encountered in FRP strengthening of structures with non-straight soffits, together with the solution used to overcome the associated anchorage issues.

## **BRIDGE REHABILITATION USING ADVANCED COMPOSITES: ASHLAND BRIDGE SR-82 OVER RED CLAY CREEK**

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**KEYWORDS:** Bridge, steel, CFRP, strengthening

The continued decline of the nation's bridge infrastructure has created the need for repair and rehabilitation techniques involving innovative materials. The importance of advanced composites in bridge rehabilitation is increasingly being realized in both research and application. This project focuses on the rehabilitation of Delaware Department of Transportation (DelDOT) Bridge 119, the Ashland Bridge on State Route 82 over Red Clay Creek Bridge 119 is a steel through girder bridge whose rehabilitation included the application of carbon-fiber-reinforced polymer (CFRP) plates. To quantify improvement in stiffness, durability, and/or overall performance of the bridge, a nondestructive load test was conducted by the University of Delaware in the summer of 2002 with the assistance of DelDOT personnel prior to rehabilitation. This initial load test was used to quantify the baseline behavior for the bridge.

The rehabilitation of the bridge, which was performed in the fall of 2002, consisted of replacing the concrete deck with a new deck that was made to act compositely with the floor beams and the bonding of CFRP plates to the underside of two of the floor beams. The expected change in stress due to the rehabilitation was predicted using

transformed sections. A second load test to assess the rehab performance is scheduled for the summer of 2003.

## **STRENGTHENING TWO LARGE CONCRETE BRIDGES IN SWEDEN FOR SHEAR USING CFRP LAMINATES**

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**Keywords:** CFRP laminates, strengthening, shear, bridges, concrete, cracks, service limit state

During 2002 severe cracking in the webs was found on two large freivorbau bridges in Sweden, the Gröndal and Alviks bridges. The size of the largest cracks exceeded 0.3 mm. The reason for cracking is at this time not yet fully clarified. However, the bridges have been temporarily strengthened with dywidag stays in the cracked sections. However, calculations have shown that there is a lack of shear reinforcement both in the service and ultimate limit state.

The bridges will be strengthened with both post-stressed dywadag stays and with carbon fibre laminates. The stays are used for the cracked areas and mainly in the ultimate limit stage. The carbon fibre laminates are used in uncracked areas and for the service limit state to avoid future cracking in these areas.

The strengthening design is complicated since the dead load of the structure is almost 80 % of the full load and it is not possible to unload the structure during strengthening.

This paper presents the design for strengthening for shear to avoid cracking in the service limit state as well as a description of the strengthening works.

## **REHABILITATION OF STEEL BRIDGE COLUMNS WITH FRP COMPOSITE MATERIALS**

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**Keywords:** Steel, bridge, FRP, retrofit

This paper describes a phase of the research program to determine the feasibility of a proposed FRP retrofit method to strengthen the corroded steel columns. This method consists in two steps: wrapping the corroded steel column with open FRP jacket and filling the jacket with expansive light-weight concrete. Seven steel columns were tested in the laboratory with five of them strengthened using the proposed technique. The first two were control units with one being a virgin shape and the other notched in the center zone to simulate the loss of section due to corrosion. The remaining five, all notched, were wrapped with FRP composite tubes in the damage area and the tubes were filled with light-weight expansive concrete. All specimens were axially loaded to failure while strain and displacement were measured to demonstrate the validity of this repair concept. This paper presents the experimental results and discusses the findings with preliminary conclusions on the feasibility of the proposed strengthening method.

## **CONSTRUCTION OF THE ASSET POLYMER COMPOSITE BRIDGE FOR HEAVY TRAFFIC LOADS**

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**Keywords:** FRP, composites, bonding,  
bridge, pultrusion, asset

The ASSET bridge project, founded by the European Commission, had its start 1998 and was finished in the autumn of 2002. The project has in brief covered the design, manufacture and construction of a fully polymer composite traffic bridge.

The reasons to build a polymer composite bridge are related to the problems of an ageing infrastructure and need for upgrading. In addition, in cases where the speed of construction or reduced weight is critical factors, the short construction time and low weight for a polymer composite bridge will be beneficial.

The size of the prototype bridge is 7 x 10 m and the bridge consists of four rectangular longitudinal polymer composite main girders manufactured of GFRP (Glass Fibre Reinforced Polymer) stiffened with carbon fibre flanges and a full composite bridge deck manufactured of GFRP. The bridge deck is built up of pultruded framework sections bonded together with an epoxy adhesive. The deck is then bonded to the girders.

This paper describes the benefits of a polymer composite bridge in relation to

traditional bridges. Further the manufacturing and construction processes are presented. In particular the focus is placed on the bonding procedure on site. The paper also includes a brief presentation of the full-scale loading on site.

## **CFRP STRENGTHENING OF CONCRETE BRIDGES WITH CURVED SOFFITS**

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**Keywords:** Concrete bridges, curved soffits, GFRP anchor spikes, wet laminate sheets, precured laminate sheets, premature peeling

The objective of this experimental program has been to study CFRP strengthening of existing concrete bridges that contain soffit curvature. In the presence of such curvature, the FRP laminates attempt to straighten under tension, leading to direct transverse tensile stress in the adhesive, which may cause premature peeling. This tensile stress could also lead to the cover being ripped off prematurely.

In this research program, six beams, each 6m in length and each having different extents of curvature, were tested under a three-point static load test setup at the University of Missouri – Rolla (UMR). One of the beams containing soffit curvature was anchored using GFRP anchor spikes to prevent the expected premature peeling.

## **APPLICATION OF FIBER OPTIC SENSOR SYSTEM TO MONITOR CIVIL STRUCTURES**

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**Keywords:** Fiber optic sensors, civil structures, structural health monitoring

A new fiber optic sensor system has been developed to monitor the structural health of civil structures. Applications to bridges and pipelines are described. A case study is presented utilizing these sensors together with a full wireless remote monitoring system that was employed to determine operational lifetime of a pipeline section. A new crack-monitoring sensor based on the same technology is also presented with test data demonstrating its capability to measure crack growth through a steel structure.

## **FRP COMPOSITIES OR EXTERNAL PRESTRESSING IN BRIDGE STRENGTHENING – COMPARISION**

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**Keywords:** Bridge strengthening, FRP composites, external prestressing, case study

In the paper two modern bridge strengthening methods, i.e. FRP composites and external prestressing, have been evaluated and compared. The comparison has been made for the existing reinforced concrete bridge, build in early 50's, which had to be strengthened due to heavy traffic. The detailed technical design with cost analysis for the both solutions was the background for this case study. The author's experience obtained in several bridge modernization projects has also been taken into account. Some results of the technical and economical evaluation have been discussed and listed in the attached tables. The main conclusion is that the optimal method of RC bridges strengthening seems to be the use of composites in shear areas and prestressing cables in bending regions.



# **Theme 1: Bridges**

## **Day 1:**

### **NDT of Bridges**



## USE OF ACOUSTIC MONITORING TO MANAGE CONCRETE STRUCTURES

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**Keywords:** Concrete, acoustic, monitoring, wire, breaks, unbonded, post-tensioned

Since its commercial introduction in 1994, the process of continuous acoustic monitoring of structures to detect and locate deterioration has evolved from a method of detecting wire breaks in unbonded post-tensioned buildings and parking structures to a widely-used asset management tool for many different kinds of structures. Its primary use is to identify hidden corrosion or fatigue-induced failure of tensioned elements in steel and concrete structures, although it has also been used successfully to detect and track cracking in concrete structures. To date, the system has been successfully deployed on grouted and unbonded and post-tensioned bridges, parking garages and nuclear containment structures, as well as on cable-stayed and suspension bridges. It is also used to identify deterioration in prestressed concrete cylinder pipe used for water and wastewater transmission.

In order to be considered as a viable infrastructure management technology, the method had to undergo independent verification to prove that it was accurate in identifying and locating events of interest in operational environments. It also had to be demonstrated that the system was capable of unattended operation at a high level of efficiency, and that the data acquired

by the system could be processed and disseminated in a reliable and cost-effective manner.

This paper briefly describes the development and testing of the system and discusses a number of case studies where the system has been utilized to help extend the life of concrete structures.

## A PRAGMATIC APPROACH TO THE DEVELOPMENT OF AN ACOUSTIC EMISSION BRIDGE MONITORING SYSTEM

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**Keywords:** Acoustic emission (AE), bridges, structural integrity monitoring, non-destructive testing (NDT)

The use of Acoustic Emission (AE) monitoring to provide information on the integrity of structures, including bridges, stretches back three decades. Throughout this period most developments in the technology have been aimed primarily at extracting greater information from a limited number of AE signals. As a result it has remained an exclusive technology used primarily by AE specialists.

An alternative approach would be to focus on that information which can be easily and reliably provided by AE and present this to operators and structural engineers as simply and cost-effectively as possible. In this paper such an approach is outlined and practical experiences and findings gained from prototype system proving trials on various structures are presented. It is found that AE can be readily applied to a wide variety of structures and can provide simple indications of when and where something, such as crack initiation, is happening.

As with many technologies the debate will continue regarding the value of information versus the cost of acquiring it. However it is felt that the ‘front-line monitor’ approach presented in this paper provides a viable alternative to that of high functionality ae systems whose use seems to be limited by their complexity and cost.

### **NDT OF GROUTING CONDITION IN PC TENDON DUCTS BASED ON ELASTIC WAVEFORM CHARACTERISTICS**

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**Keywords:** NDT, PC grout, impact elastic wave methods, FEM analysis, waveform parameters

This paper describes the use of elastic waveform characteristics obtained in Impact Elastic-Wave Methods for the evaluation of grouting condition in PC tendon ducts. Tests were carried out on slab specimens and the relationships between the grouting condition and the elastic wave parameters were examined. In order to identify the mechanism of variation in elastic wave propagation velocity depending on the voids in grouted tendon ducts, a finite element analysis was also performed using a three- dimensional model.

As a result, it is thought to be possible to estimate the grouting condition inside ducts by using elastic wave parameters.

### **EVALUATION OF STRUCTURAL INTEGRITY IN RAILWAY STRUCTURES USING TRAIN-INDUCED ACOUSTIC EMISSION**

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**Keywords:** Acoustic emission (AE), damage degree, Kaiser effect, railway structures, train passage

The damage in railway structures is in general visually investigated, while in substructures, the visual observation would be difficult to apply since they are embedded in the ground. In order to investigate the substructures, complementally NDI techniques have been used, namely UT, Rader, X-ray and so forth. Acoustic Emission is one of the NDI techniques and known as a passive technique, consequently the stress increase/variation would be a crucial condition to perform the monitoring. In railway structures, the condition for the AE application can be given by railway traffic passing over the structures. In this paper the concept of AE monitoring for the railways structures is explained. The Kaiser effect, showing the relation between the stress history and AE activity, is introduced to assess the structures, followed by trying to quantify the damage using the AE activity. In order to quantify the damage in actual structures, the RTRI ratio is proposed which originates from the Kaiser effect. The applicability of the AE based idea for the damage evaluation, is elucidated in laboratory experiments using model

substructures. The idea is further applied to in-situ AE monitoring for a concrete pier. Finally the procedure to evaluate the practical structures using AE activity is demonstrated.

## **THE USE OF A STATIONARY POINT MODAL ASSURANCE CRITERION FOR DAMAGE DETECTION IN BRIDGES**

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**Keywords:** Damage detection, bridges, vibration, modal assurance criterion (MAC), nodal points

Changes in the vibration characteristics of structures have frequently been proposed as means of detecting damage. However, it is known that changes in frequency are insufficiently sensitive for most practical purposes. On the other hand, changes in mode shape offer greater sensitivity and in this paper it is proposed that vibration should in particular be measured at modal stationary points, since it is known that their locations are highly sensitive to structural damage. The proposed method is demonstrated using a three-dimensional finite element model of a large historic suspension bridge for which experimental data exists. The first five modes of vibration were extracted and, for each mode, vibration data were measured in pairs of locations at stationary points and at adjacent anti-nodes and then analysed by the Modal Assurance Criterion before and after damage. The resulting value is referred to

as the Stationary Point Modal Assurance Criterion (SPMAC).

Structural damage, of a nature actually seen on the bridge in question, was simulated in the finite element model. Sample damage configurations were applied to the bridge and the SPMAC evaluated. It is shown that the SPMAC is sufficiently sensitive to enable detection of damage by monitoring vibration signals in this way. In particular, where there are two modes that are close in frequency the SPMAC is highly sensitive because of the phenomenon of 'mode switching'.

## **LONG-TERM WIRELESS REMOTE MONITORING OF THE LEHIGH RIVER BRIDGE**

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**Keywords:** Bridge, concrete, monitoring, four span, wireless

The SR-33 Lehigh River Bridge is a four-span continuous weathering steel deck truss with a main span of 181 m and a variable depth from 11 m. to 22 m. A unique feature of the bridge is that the concrete deck is fully composite with the upper chord of the truss. In order to better understand the effects of temperature, shrinkage, creep, and live-load behavior, a comprehensive field instrumentation and monitoring program was developed and implemented. Field instrumentation began in May 2001 and monitoring is expected to continue until January of 2005. This paper discusses the data acquisition system, sensors, and wireless communication techniques used for the project.

## **AE MONITORING OF A REINFORCED CONCRETE ROAD BRIDGE**

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**Keywords:** Acoustic emission, bridge maintenance, in-service monitoring, on-site loading test

The acoustic emission (AE) method is a statistical and theoretical ‘soundness’ evaluation method by detecting elastic wave occurred from defects such as cracks of material, which has large possibility as a non-destructive inspection for the soundness evaluation of concrete structures. However, application of AE technique (AET) to the actual bridge maintenance business is yet rare even now.

In this study, AE monitoring under the in-service traffic load and AE measurements under the on-site loading test using large heavy vehicles were carried out, because the opportunity of tentative adoption of AET was obtained in practical soundness investigation of a 45 years old reinforced concrete road bridge, and the basic consideration on the practical application

of AET to the maintenance business was carried out.

## **NDE OF A POST TENSIONED CONCRETE BRIDGE GIRDER USING ULTRASONIC ECHO AND IMPACT ECHO**

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**Keywords:** Ultrasonic, impact echo, concrete, bridge

In the frame of bridge inspection in accordance with the German standard DIN 1076 the condition of bridges and other constructions forming part of pathways and roads is regularly evaluated. The structural condition constitutes an essential input variable for the structure management system, which is currently being configured. In case of unusual damage more detailed structure assessments are initiated. These analyses involve entirely or mainly non-destructive tests. This article reports on the use of non-destructive testing methods for those examinations, especially for post tensioned concrete bridges.

Echo techniques are particularly qualified for non-destructive testing of concrete bridges, because they are applicable, when the construction is accessible from one side only. In the last decade round robin tests have been

performed at specimens in order to assess the application of ground penetrating radar, ultrasonic echo and impact echo (Krause et al, 1997), (Krieger et al, 2000), (Krause et al, 2001).

Radar and especially the acoustic methods (ultrasonic echo and impact echo) exist in several modifications, which differ in capability and accuracy, but also in handling, time exposure and expense. Round robin tests compared these modifications using an identical specimen and testing problems. The results of these research projects show that the present state of the art allows a successful application when the site conditions are suitable.

Apart from the methods mentioned here, there are other non-destructive testing methods, which are suitable for large area investigations, such as carriageways of highway bridges. These methods are e.g. the potential field method, measuring the electrical resistance and radar with horn antennas fixed at a measuring vehicle, indicating delaminations and inhomogeneities (Krieger et al, 2000). The echo methods mentioned can be used for a detailed investigation of special structure sections. These sections are identified as a result of the large area investigation or from visual inspection.

This article reports on a research study, where a girder and a part of a carriageway of a highway bridge have been tested. This project has been carried out in co-operation between the Federal Highway Research Institute (BASt) and the Federal Institute for Materials Research and Testing (BAM).

The following problems have been examined:

- Localisation of metal tendon ducts and determination of the concrete cover
- Localisation of inhomogeneities in and around the tendon ducts (e. g. grouting faults)

- Localisation of compaction faults and honeycombing in concrete.

The experiments were carried out with radar, ultrasonic echo and impact-echo. The acoustic methods were applied in two different modifications each, ultrasonic echo in the frequency range around 100 kHz using synthetic aperture with 2D- and 3D-reconstruction calculation and impact-echo systems with scanning and imaging technique. The results of non-destructive testing have been verified by taking cores.

## **MONITORING OF BRIDGE GIRDER DEFLECTION USING LASER DOPPLER VIBROMETER**

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**Keywords:** Laser doppler vibrometer (LDV), bridge vibration, deflection, non-destructive technique (NDT), bridge health monitoring, bridge dynamic testing

The majority of bridges are designed for the ultimate limit state and are evaluated for serviceability. However, the new Load and Resistance Factor Design (LRFD) American Association of State Highway Transportation Officials (AASHTO) Bridge Specification no longer enforces deflection limits (e.g. L/800). Moreover, State Highway Departments specify their own deflection limits based on a rather arbitrary and conservative criterion. This will undoubtedly lead to non-uniformity in the design selections of bridge structures thus causing a wide range of variances in the girder stiffness. There is a need to accurately measure deflections/vibrations on girder bridges under normal conditions without

causing any obstruction of traffic or adversely affecting its functionality. Additionally, all girder bridges have a clearance height that renders the use of any contact sensors (such as Linear Variable Differential Transducer-LVDT) impractical. This paper introduces the use of the Laser Doppler Vibrometer (LDV) in measuring deflections on the new Doremus Avenue Bridge. Prior to opening the bridge to traffic, measurements were made to calibrate equipment and establish deflection limits. LDV deflection measurements were taken parallel to another deflection measuring device that consists of a stretched metal cable, LVDT, data logger, solar unit, modem, and battery. Peak deflections were recorded for various trucks passing over the bridge. Measured deflections were used to validate a detailed finite element model and those from a reliability-based simulation as well as various code limits.

# **Theme 1: Bridges**

## **Day 1:**

### **Bridge Scour**



## **EVALUATION OF BRIDGE SCOUR MONITORING METHODS**

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**Keywords:** Scour, remote monitoring,  
sonar, magnetic sliding collar

The main objective of this study is to evaluate and implement the National Cooperative Highway Program (NCHRP) Project 21-3 'Instrumentation for Measuring Scour at Bridge Piers and Abutments' (Lagasse et al., 1997) designated system(s) for monitoring bridge scour. The proposed project ascertains the method(s) and procedure(s) that most accurately identify the severity of scour in bridge foundations. Two systems were recognized: 1) Magnetic Sliding Collar (MSC) and 2) Sonar systems. For this purpose more than ten bridge sites, rated scour critical by the New Jersey Department of Transportation (NJDOT), have been inspected for possible installation of equipment. Two bridge sites have been selected, and the equipment and methods are currently observed under closely controlled conditions. Both bridges were selected based on scour activity, accessibility, and streambed conditions. On each bridge, both systems, MSC and Sonar, were installed near the pier and connected to a data logger. Continuous scour data monitoring was initiated. The accuracy of each system and the effect of various parameters are studied.



# **Theme 1: Bridges**

## **Day 2:**

### **Steel Bridges + Steel-Concrete Composite Bridges**



## AN OVERVIEW OF INSPECTION AND REPAIR WORKS OF NAMHAE SUSPENSION BRIDGE

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**Keywords:** Bridge, suspension, steel, box girder, repair

Namhae Bridge was constructed in 1973 and connects Namhae Island to the southern part of mainland Korea. It is a three span suspension bridge with a main span length of 404m, and side spans of 128m each. The main cables are made of parallel wires and the stiffening girders consist of welded steel boxes. Since the traffic volume and weight had been increased compared to construction time, the fatigue cracks in U-ribs under steel deck were developed and were found during in-depth inspection in 1993 and 1996. To control these fatigue cracks and upgrade the bridge from DL-18 to DL-24, the girders was strengthened from 1998 to 2000. As a result of this work, the self-weight of the stiffening girders are increased up to 114%. Recently, we, KISTEC, had performed 3rd in-depth inspection. We did visual inspection, NDT, profile surveying, measuring hanger cable forces, load test, structural analysis and repair works suggestion. The purpose of this paper is to introduce an overview of the inspection activities and the examples of repair works, which we recommended.

## ASSESSING THE STRUCTURAL ADEQUACY OF A 3-SPAN STEEL-CONCRETE COMPOSITE BRIDGE USING DYNAMIC METHODS

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**Keywords:** Bridge, steel, concrete, composite, assessment, dynamics, case study

This paper describes the field testing and assessment of a three span steel-concrete composite highway bridge based on a cost-effective dynamic technique. It describes the field-testing procedures utilised to assess the structural condition of Redbank Creek Bridge based on a recently developed dynamic technique.

The data obtained from the field tests is presented and the method for predicting the load-deflection response and load capacity based on this data is detailed. The results obtained from conventional static load tests and from the dynamic and static finite-element analyses undertaken as part of this investigation are also given.

Comparison of the stiffness and strength results obtained from the dynamic tests with those based on the results of static load tests and finite element modelling show excellent agreement.

The case study described in this paper as well as a large number of bridge tests conducted as part of a major project show that the dynamic techniques that were used provide a reliable cost-effective method for the assessment of the structural condition

of a wide variety of short and medium span bridges. The case-study presented illustrates that the methods described in the paper provide quantitative information on the structural behaviour and integrity required for the rational long-term management of bridge assets.

## **THE STRENGTHENING OF SWING BRIDGES ON THE LEEDS AND LIVERPOOL CANAL**

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**Keywords:** Steel, swing bridge, strengthening, heritage

British Waterways (BW) is a private bridge owner that maintains approximately 940 road bridges for public highway use. The majority of these bridges are older structures which chronicle the development and heritage of the canal network so it is British Waterways policy to maintain, refurbish or strengthen them when practicable.

Steel swing bridges with timber decks, pushed open by boaters, are a regular feature on the Leeds and Liverpool canal as both accommodation and public road bridges.

They tend to have assessed capacities to BD 21 of between 3 and 7.5 tonnes with the decking often being the critical element.

This paper will describe how similar projects have been developed to refurbish and strengthen two road swing bridges and introduce safety features to reduce the risks associated with the interface between canal and highway traffic.

The paper will cover:

- Design concepts and protection of canal heritage.
- Partnership with the highway authorities to agree layouts, safety features and the required reduced level of traffic loading.

- Cost comparisons between refurbishment and replacement schemes.
- Benefits gained from having common features on the waterway.

## **JACKING CONFIGURATION FOR RETROFIT AND REPLACEMENT OF BEARINGS ON STEEL GIRDER BRIDGES**

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**Keywords:** Bridge, bearings, retrofit, steel, girders, jacking

Movements and forces due to temperature variations, seismic events, wind, and other service loads are all accommodated in bridges by bearings that mitigate the transfer of forces within the structure. To ensure that the bridge does not receive the brunt of these forces, bridge bearings must be maintained by providing seismic retrofits, removing deteriorated bearing components, or increasing the capacity of existing bearings to meet new loading conditions. However, jacking of the superstructure for replacement or retrofit of these bearings can be even more disruptive and costly than a dysfunctional bearing. This paper explains an efficient jacking method that allows the superstructure to be jacked for bearing retrofit or replacement while simultaneously mitigating costs and maintaining traffic. Typically, jacks required to access the bearings are placed above jacking frames or brackets and below jacking stiffeners located on the span side of the bridge bearing. Alternatively, this paper presents a jacking configuration in which the superstructure is jacked from the joint side of the bearing by jacking from the steel girder overhang or bottom flange extension.

Cost savings are substantial, particularly for bridges with tall piers or for structures with access issues. Disruption is minimized to the traffic above and below the bridge, to utilities, railroads, or slope protection around the bridge, and to the substructure under the bridge. Geometric and structural considerations required for use of this jack configuration are explained with an example of a bearing replacement designed for the Route 21 Viaduct in Newark, New Jersey, USA. This curved steel plate girder viaduct was jacked using the technique proposed in this paper and 88 pot bearings were replaced with new pot bearings to maintain proper functionality of the existing bridge. Use of this jacking configuration can ultimately lead to more efficient bridge design and maintenance.

## **EVALUATION OF STEEL OPEN-GRID DECKS ON A U.S. / CANADIAN SUSPENSION BRIDGE**

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**Keywords:** Steel, bridges, open-grid decks, instrumentation

In July 1999, Modjeski & Masters, Inc. (M&M) and the Center for Advanced Technology for Large Structural Systems (ATLSS) at Lehigh University conducted an instrumentation study and assessment of stress conditions in the Ogdensburg, NY-to-Prescott, ONT suspension bridge across the St. Lawrence River. The need for the study was precipitated by an ongoing review by the Ogdensburg Bridge and Port Authority (OBPA) of the feasibility of increasing the allowable (without a permit)

weight limit on the bridge, and by an observation of weld cracks and bar fractures in the bridge's open-grid steel deck. M&M conducted a new bridge rating based, in part, on the results of the instrumentation study. This paper describes the instrumentation study and its results.

## **LIFETIME CALCULATIONS FOR ORTHOTROPIC STEEL BRIDGE DECKS**

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**Keywords:** Orthotropic steel bridges, fatigue, lifetime calculations, inspection, asphalt wearing course

Fatigue cracks are one of the most devastating problems for orthotropic steel bridge decks. Well-known examples of fatigue cracks are those observed in the bascule bridge Van Brienenoord in Rotterdam in summer 1997. These were cracks in the deck plate at the crossing of the crossbeam and the longitudinal girder and are known as the most dangerous cracks for traffic safety. The number and amplitude of stress cycles, which are closely related to amount of axles and their loads, govern the fatigue phenomena. The paper starts with an overview of the different locations where fatigue cracks are likely to occur in orthotropic steel bridge decks.

These unexpected cracks in the Van Brienenoord Bridge urged the ministry of Transport, Public Works and Water Management to develop a system to

guarantee the safety of the bridge deck for the users. Reliable lifetime predictions are one of the essential parts of such a system. This paper describes the system that has been developed to calculate lifetime predictions for cracks in the deck plate at the crossing of the crossbeam and the longitudinal girder. Such a system enables bridge owners to switch from a time based inspection program to a risk based inspection program.

Aspects, which are related to the number and amplitude of the stress cycles, are investigated and described in the paper. These are traffic properties and measurements, axle load distribution measurements and the determination of a fatigue classification. A major aspect is the calculation of the stresses at the location of the cracks. Special attention has been paid to the effect of the asphalt wearing courses, which are applied to the top of fixed bridges. Asphalt layers have a reducing effect on the stresses in the steel parts, but due to the strong temperature dependency of bituminous materials the modelling is complicated. The paper describes how these effects are taken into account.

The results of the lifetime predictions are in accordance with several detected fatigue cracks. The predictions are used to schedule inspections and renovations for the bridges.

## **INFLUENCE OF CUTOUT GEOMETRY ON WELDED RIB-TO-DIAPHRAGM CONNECTIONS IN STEEL ORTHOTROPIC BRIDGE DECKS**

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**Keywords:** Orthotropic bridge deck, fatigue, finite element analysis

The geometry of the cutout at the intersection of longitudinal ribs and transverse diaphragm plates in steel orthotropic bridge decks can have significant impact on the stress in the region of the welded rib-to-diaphragm connections. This paper presents the results of a finite element parametric study. Parameters considered included, overall cutout shape, cutout depth, diaphragm plate thickness, and deck plate thickness. The results indicate that the suggested cutout geometry shown in the current (2002) AASHTO LRFD Bridge Design Specifications for closed-rib orthotropic bridge decks results in increased demands on this fatigue sensitive connection. An improved geometry is proposed to replace that currently presented in the Specification.

The results of this study indicate that larger cutout geometries offer less resistance to out-of-plane displacements induced by longitudinal rib rotations. As a result, out-of-plane stresses are decreased at the connection. However, cutouts that are excessively deep will increase in-plane stresses at the welded rib-to-diaphragm connection. If the cutout is too shallow, out-of-plane stresses may become prohibitively high due to restraint of longitudinal rib rotations. Cutouts that are between  $1/3$  and  $1/2$  the depth of the rib with transition radii at the top of the cutout of 50 to 75 mm and

vertical cuts are most favorable. The cutout geometry shown in the AASHTO LRFD Specification results in an overly stiff cutout detail and a proposed improved geometry is presented [AASHTO, 2001].

## **TECHNIQUES AND SOLUTIONS FOR REHABILITATION OF ORTHOTROPIC STEEL BRIDGE DECKS IN THE NETHERLANDS**

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**Keywords:** Orthotropic steel bridge deck, fatigue, lifetime enhancement, concrete wearing course

In the Netherlands a substantial part of our main road infrastructure are steel bridges. These structures often have often orthotropic deck constructions. In 1997 we discovered fatigue cracks in the deck construction of the Van Brieneoord bascule bridge in Rotterdam. This resulted in the complete reconstruction of the bascule bridge. This unfortunate event in October 1998 gave reason for the Ministry of Transport, public Works and Water Management to start a project 'Fatigue Problems on Steel Bridge Decks' (Problematiek Stalen Rijnvloeren'). The aim was to investigate the cause, to understand and control the fatigue mechanism for the 80 steel fixed and movable bridges in the Netherlands and to develop practical solutions for cost effective rehabilitation and renovation.

## **STRUCTURE REPAIR OF SUSPENSION BRIDGE OVER VRBAS RIVER IN BANJA LUKA**

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**Keywords:** Suspended bridge, rocker tower, residual deflections, damage, repair

The suspension bridge over the Vrbas River in the city of Banja Luka was designed as a pedestrian bridge. The construction of the bridge was completed in the 1960s.

During the employment of the bridge a necessity occurred to strengthen it and strengthened for carrying both pedestrians and motor traffic, limited to one vehicle of 3.5 t gross mass.

The basic structural element of the bridge is a parabolic cable suspended over two pylons anchored on both sides of the bridge. There are two strands rope  $f$  40 mm (each made of 61 wire  $f$  4.45) on both sides. The stiffening beam is suspended on the parabolic cables through the system of suspenders (hangers) distributed, at 2.0 m from one another and made of mild steel ( $\bullet 24/36$ )  $f$  22 mm. The bridge deck consists of a layer of asphalt  $d = 3.0$  cm with a reinforced concrete slab  $d = 11.0$  cm. The slab is composed through the upper chord with a steel bridge truss having triangular web bars. The pylons - rocker towers of the bridge are space steel truss structures about 15 m high. In the middle they are widened to about 2.0 m, while in the base and on top they are narrowed and connected with a hinge at joint to the foundation structure.

Due to long lasting irregular use of the bridge and inadequate maintenance damage appeared which manifested as residual deflections of the middle part of the span. The repair work was to re-establish the regular condition of use with the restricted intensity of traffic. Before the repair design was made the structure of the bridge was monitored for a longer period, existing technical documentation was studied and deviations in the design in relation to the real state recorded. Accordingly, the condition of particular elements of the bridge was analysed and their classification was made. Depending on the size and intensity of damage all elements were classified in three groups for which corresponding repair measures were prescribed.

The computing analysis conducted during the process, of the repair design used two calculating models. In the first the structure of the bridge was treated as a structure in the plane with the stiffening beam as a line element with equivalent stiffness, while the second model treated the bridge as a space structure with real stiffnesses of particular elements. Comparing the results obtained through the Theory of the first and Theory of the second order relatively small differences were found. The analysis results in both calculating models (space and plane) do not significantly differ from the designing aspect.

## EVALUATION OF A BRIDGE LOAD TESTING/RATING SYSTEM

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**Keywords:** Bridge testing, load rating, bridge evaluation, bridge modeling

The problem with an aging and rapidly decaying infrastructure system is an issue facing many agencies charged with maintaining a fully functioning traffic system. Numerous bridges of marginal condition must frequently be posted resulting in increased travel time and distances. However, when tested, these bridges often exhibit strength greater than traditional codified parameters. The use of diagnostic load testing for the purpose of load rating has become an accepted practice for addressing these bridges for many public agencies. Easy to use commercial tools, like the Bridge Diagnostics, Inc. (BDI) system, have simplified the process of testing, modeling, and rating bridges.

This paper documents efforts underway at Iowa State University (ISU) to evaluate and document the applicability, ease-of-use, and accuracy of such an integrated bridge testing system. For this work, a typical bridge was instrumented with 36 strain transducers and tested with known loads using the BDI system. A finite element model of the bridge was then developed and calibrated based on the observed behavior and the field measured strains. Results from the calibrated model were then used to carry out load rating calculations and then compared to traditional rating calculations. The resulting ratings were in general greater than the traditional codified ratings.

**CABLE STAYED BRIDGE OF INTERCHANGE NEAR MINISTRY OF COMMERCE RIYADH – SAUDI ARABIA – INVESTIGATION CAMPAIGN AND REHABILITATION DESIGN**

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**Keywords:** Cable stayed, suspended spans, bridge, concrete

This fly-over, designed in 1977 and constructed in 1980, is part of a large interchange located in the Ministry of Commerce square in Riyadh. The history of the cable stayed bridges was at that time at its beginning and most of the knowledge gained recently by building hundred of them were unknown.

Upon the request of the Municipality of Riyadh, was carried out a campaign of investigation having the scope of checking the static condition of the structure.

A series of non destructive tests were carried out. The results have pointed out that the bridge was seriously damaged in some of its most important parts. On the basis of these data was studied the design for the rehabilitation of the bridge.

**EFFECTS OF DECK POUR SEQUENCING ON GIRDER ROTATIONS IN A SKEWED STEEL I-GIRDER BRIDGE DURING CONSTRUCTION**

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**Keywords:** Skewed, steel, bridge, construction, deck, pour, sequence, field, testing, numerical, modeling

Skewed steel I-girder bridges have offered economical solutions for interchanges and river crossings in the United States due to reduced site preparation requirements when compared to similar orthogonal, or ‘right,’ bridge solutions. These economic advantages have resulted in an increase in the design and construction of skewed steel I-girder bridges in the U.S.

The effect of skew angle on live load response has been reported in the literature with researchers investigating skew influence on transverse load distribution and forces in the concrete deck; however, the response of skewed steel bridges during construction has received limited attention. Effects of bridge skew are magnified during construction due to the response of the steel superstructure under the differential loads that can be applied. There is a need for the study of long-span, skewed girder bridges at all stages of construction to justify imposing initial construction out-of-plumb positions into the girders to counteract anticipated rotations and to evaluate deformations and loads that may result should the girder webs remain out-of-plumb at the completion of construction.

This paper will summarize certain aspects of a research project that has investigated the behavior of a 74.5 m (244'), single-span, skewed, steel, I-girder bridge during placement of the concrete deck. The research program has included both field-monitoring and numerical modeling of the bridge superstructure.

## **BEAM-IN-SLAB LOW VOLUME ROAD BRIDGE SYSTEM**

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**Keywords:** Low volume roads, off system bridges, composite action, simple span bridge

In Iowa, there are over 20,000 bridges on the secondary road system. The majority of these bridges are the responsibility of the local county engineers who with limited budgets, frequently design and construct short span bridges with their own work forces. The overall objective of the research presented in this paper is to develop a bridge alternative that counties can design and construct with such labor. This project involves modifying an existing system of steel beams with concrete fill between them. Variations of this system in which there is no reinforcing steel or connection between the steel beams and the concrete have been used by several Iowa counties as low water stream crossings for more than 20 years. With the proposed modifications, which include an alternate shear connector (ASC) for composite action and removing the ineffective concrete from the tension side of the system, less material will be required and longer spans will be possible.

Development and testing of the ASC was presented in a paper 'A New Shear Connector for Composite Action', at the Structural Faults & Repair – 2001 Conference [Klaiber and Wipf, 2001]. This paper will provide information on how this connector has been tested in the laboratory in several full-scale test specimens and in demonstration bridges.

A total of five additional laboratory specimens have been constructed and tested. Two single bay specimens, 8 ft (2.4 m) wide and 2 ft (0.60 m) long, were constructed to test the applicability of two formwork systems. Two single bay specimens, 8 ft (2.4 m) wide and 15 ft (4.6 m) long, were constructed to investigate the strength of the Modified Beam-in-Slab (MBIS) system. The specimens were tested at service levels and at ultimate load to obtain the behavior of the system under simulated wheel loads.

The fifth specimen was a three bay, 20 ft (6.1 m) wide, 31 ft (9.4 m) long bridge constructed in the Iowa State University (ISU) Structures Laboratory. This model bridge, which contained slightly more than 21 cu yd (16.1 m<sup>3</sup>) of concrete, was constructed to investigate the load distribution characteristics and ultimate strength of the MBIS system. This specimen was also subjected to service loads at various locations before being loaded to failure.

Two demonstration bridges using the modifications investigated in the laboratory have been constructed. The first demonstration bridge, 31 ft (9.4 m) wide and 50 ft (15.2 m) long, was constructed in Tama County during the fall of 2001 using the MBIS system. The structure is currently in service and will be field load tested during the summer of 2003. The second demonstration bridge (32 ft (9.8 m) wide by 70 ft (21.3 m) long) also in Tama County

was constructed in November 2002. This structure utilizes 6 rolled W sections with the MISB. Construction of the second demonstration bridge was fully documented to assist others with the construction of similar MBIS structures. This bridge will also be instrumented for measuring strains and deflections and tested during the summer of 2003.

### **LIFE TIME ESTIMATION OF STEEL STRUCTURES AND ASSESSMENT OF CRITICAL DETAILS**

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**Keywords:** Monitoring, fatigue, life time assessment, sensitivity investigations

The prediction of a realistic lifetime and the prolongation of the service life of a structure is an important task to reduce costs. The usual theoretical predictions are not very reliable. The prediction model used consists of a load model, a system-transfer model and a damage model. The results of these sequentially coupled models are usually unreliable, especially the influence of the uncertain load and damage models controls the reliability of the result. A method based on monitoring strategies is presented, which avoids these problems. Expected trends of future traffic can be considered. Also, the remaining life time of existing structures could be assessed.

The critical points which should be monitored are difficult to find, especially new structures show an equally distributed failure level. A way to determine these points using probabilistic methods is presented.

### **EVALUATION OF VARIOUS IMAGE RECOGNITION METHODS FOR BRIDGE PAINTING RUST INSPECTION**

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**Keywords:** Bridge, steel, painting, rust, imaging

Digital image recognition methods have been utilized for bridge painting rust inspection in the recent years. Through the use of digital image recognition methods, the rust percentage in a bridge painting image can be accurately computed, which is what an experienced bridge painting inspector cannot achieve. The rust percentage is a crucial indicator in bridge painting warranty contracts which decides whether the painting contractor should redo the painting work at the end of the warranty period. However, to ensure the level of accuracy, appropriate recognition methods should be selected with care.

In this paper, several recognition methods are proposed and evaluated based on their recognition performance. The recognition methods fall into two categories: one uses artificial intelligence (neural networks and fuzzy logic) as the backbone for recognition, while the other uses statistical approaches to segment the rust images. Illumination will be considered in some of the proposed methods to see how it affects the recognition results. To test the performance of the proposed methods, a series of comparisons will be conducted based on four different conditions:

brightness, angle, distance, and cleanness. After the comparison, conclusions of the papers will be drawn and recommendations will be made.

### **VIBRATION PROBLEMS IN CHINA'S STEEL BRIDGES UNDER RAISED TRAIN SPEED AND THEIR REINFORCEMENT**

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**Keywords:** Railway bridge, steel girder, raised train speed, reinforcement

Many vibration problems of steel bridges have been found in the project of raising train speed in China's railway, which influences the serviceability of bridge structures and the safety of running trains on the bridges. This paper studies these problems and their solutions adopted in China.

### **EFFECTIVENESS OF INTER-MEDIATE DIAPHRAGMS IN PC GIRDER BRIDGES SUBJECTED TO IMPACT LOADS**

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**Keywords:** Bridges, concrete, diaphragms, impact loads

Bridge engineers are concerned about the response of precast concrete (PC) girder bridges, which are hit by over-height-vehicle loads. The role of intermediate diaphragms in providing impact-damage protection to the PC girders is not clearly defined. An analytical study was conducted to assess the effectiveness of intermediate diaphragms in reducing the damage to the girders of a PC girder bridge that is struck by an over-height object on a highway vehicle. Also, the study investigated whether a structural steel, intermediate diaphragm would essentially provide the same degree of impact protection to the PC girders as that provided by a reinforced concrete (RC), intermediate diaphragm.

Finite-element models were developed for non-skewed and skewed, PC girder bridges. Each model was analyzed with one RC and two types of steel intermediate diaphragms that were located at the mid-span of an interior span of the bridge. The bridge models were analyzed for a lateral-impact load that was applied to the bottom flange of the exterior girders at the intermediate diaphragm location and away from the diaphragm location. The induced

strains and displacements in the girders were established for each intermediate diaphragm case.

When a lateral-impact load was applied at the diaphragm location, the RC, intermediate diaphragm provided more protection for the girders than that provided by the two types of structural steel, intermediate diaphragms. The three types of intermediate diaphragms provided essentially the same degree of impact protection for the PC girders when the load was applied away from the diaphragm location.

## **REPAIR AND STRENGTHENING OF KAROON RAILWAY BRIDGE**

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**Keywords:** Bridge, steel, concrete, repair

Karoon Railway bridge links Imam Khomani port to the Iranian railway network. It has 65 years old and constructed on Karoon river with Debby of app. 250 to 4000 cubic meter per second. From structural point of view, it has 51 spans of 20.75m and simple steel girders attached to the concrete supports with articulated joints. The sixth support of the bridge has cycling movement and destroyed track geometry during last year due to excessive water pressure below the support and water cracking. This hidden movement approved by monitoring bridge support. After realizing the support movement, water pressure on the span was reduced through deviating the water flow of the river to other span. Then a proposal to strengthen the bridge through strutting around the bridge and strengthening support bed presented. In this paper, the structural problems &

difficulties arisen on the bridge were studied and strengthening as well as repair approaches were described.

## **CONDITION ASSESSMENT OF A 19th CENTURY STEEL-TRUSS RAILWAY BRIDGE**

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**Keywords:** Condition assessment, steel, truss, railway bridge

The task is pursued through static and dynamic field measurements as well as laboratory tests. A validated analytical model is employed to evaluate the capacity of the bridge to carry seismic and wind loads specified by current design codes as well as the heavier trainloads set by the owner in order to propose strengthening and replacement measures for bridge upgrade.

## **STRUCTURAL ASSESSMENT OF AN HISTORIC CABLE-STAYED BRIDGE**

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**Keywords:** Ambient vibration, Cable-stayed bridge, Dynamic testing, Experimental modal analysis, Frequency domain decomposition, Finite element model, Spectral analysis.

Theoretical and experimental investigation of an historic cable-stayed bridge is described in the paper. The bridge at study was designed by R. Morandi in the 70's and

is characterised by the adoption of pre-stressed concrete stay-beams, a common feature of Morandi's bridges.

Full-scale tests were performed to measure the dynamic response of the bridge, with the excitation being associated to the traffic and to the environmental loads, and a total of 13 vibration modes were identified in the frequency range of 0-4 Hz. Full details on the experimental procedures, instrumentation and data analysis techniques are given.

In the theoretical study, vibration modes involving deck, towers and cables were determined by using a three-dimensional finite element model based on as-built drawings of the bridge and accurate in-situ geometrical survey. The comparison between measured and predicted modal parameters was then used to verify the main assumptions adopted in the model. Specifically, a good match between theoretical and experimental modal analysis was found provided that geometric non-linearity was properly accounted for in the model.

# **Theme 1: Bridges**

## **Day 2:**

### **Corrosion + Cathodic Protection in Concrete Bridges**



## **RISK ASSESSMENT OF CORROSION IN CONCRETE BRIDGES**

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**Keywords:** Bridges, reinforcement corrosion, structurally critical areas, preventative maintenance, ladder probes, risk analysis

This paper describes an improved strategy for managing reinforcement corrosion in bridges, which is the most common cause of their deterioration. The problem with the existing approach is that corrosion is not detected until it has reached an advanced stage, which makes repair costly and difficult. If the corrosion takes the form of pitting it may not be detected until significant weakening has occurred. The improved strategy combines knowledge of structurally critical areas of a bridge and parts exposed to the de-icing salts, which cause corrosion. A risk analysis applying this knowledge is used to identify those parts of a bridge at high risk from reinforcement corrosion. A programme of testing and preventative maintenance can then be targeted at these areas to reduce the probability of reinforcement corrosion. The risk analysis requires only basic information and can be applied prior to construction, enabling ladder probes to be embedded in high risk areas. These probes give early warning of corrosion initiation and defects in corrosion prevention systems thereby allowing effective maintenance to be carried out before corrosion starts.

## **STRUCTURAL ASSESSMENT OF CORROSION DAMAGED BRIDGES**

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**Keywords:** Corrosion, residual, concrete, bridge

Corrosion of reinforcement is the principal cause of deterioration of concrete bridge structures. Corrosion may affect residual strength in several ways: section loss of reinforcement is the most obvious, but corrosion induced cracking and spalling may also lead to a reduction in the concrete cross section and to loss of anchorage of links, as well as a loss of bond capacity. The various mechanisms are described and the controlling parameters for each briefly discussed.

A programme of research has been carried out to develop 'residual strength functions' to represent the relationships between residual strength and damage, and to incorporate these within a procedure for assessment of the residual strength of corrosion affected structures. The procedures are broadly similar to that of the CONTECVET manual, but contain some significant differences in detail. Additional data for plain bars extends the range of application of the CONTECVET procedures. The functions have then been validated against test data from studies contained within the present programme and from independent studies, including results from the CONTECVET programme itself.

The paper describes the derivation of the residual strength functions and their application to test data.

## **CATHODIC PROTECTION – M60 JUNCTION 12**

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**Keywords:** Corrosion, concrete, cathodic protection

This paper reports on a programme of major refurbishment work at Junction 12 of the M60 motorway, one of the busiest motorway junctions in Europe.

Having carried out statutory bridge inspections to the various bridges that comprise Junction 12, Parkman, agents for Area 15 on behalf of the Highways Agency, had concluded that five structures were suffering from severe chloride ingress due to the use of road salts. They recommended extensive traditional concrete repairs along with the installation of an impressed current cathodic protection (ICCP) system and re-painting of the steelwork in order to prolong the life of the bridge structures.

The contract was carried out under a Partnering arrangement between the Highways Agency, Parkman, Greater Manchester Police, the principal contractor Eric Wright Civil Engineering Limited, Brookes (Northern) Limited, Jack Tighe and McAlpine Traffic Management.

This paper reports the major problems faced during the contract and the innovative solutions that were employed to make it a highly successful contract from everybody's perspective.

# **Theme 1: Bridges**

**Day 2:**

**Timber**



# **VAL CADINO TIMBER BRIDGE: NON DESTRUCTIVE TESTS, ANALYSIS AND DIAGNOSIS**

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**Keywords:** Timber bridges, durability,  
inspection, non destructive tests, design  
considerations

The paper deals with the possibility of identifying the actual structural behaviour and the residual life of a timber bridge by means of global tests (static or dynamic); an experimental and theoretical investigation on a case study will be presented. It is a timber road bridge, built in 1992, for one-way traffic and utilised by trucks for transportation of logs. It is located in Val Cadino (North-East of Italy), near Trento. Some static tests have been carried out with the aim of monitoring the structure in service and, if possible, of appreciating a damage of the material, if there is any.

The case study has pointed out also some additional topics, such as the importance of: the quality of the wooden material; the correct design and the accurate manufacturing of structural details for durability; the importance of preservative treatments of wood; the great importance of an adequate maintenance program of the structure.



# **Theme 1: Bridges**

## **Day 3:**

### **Masonry Arch Bridges**



## THE RECONSTRUCTION OF BRICK ARCH BRIDGES ON THE CHESTERFIELD CANAL

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**Keywords:** Brick arch bridges

British Waterways owns and maintains around 2400 accommodation bridges. Many of these are original masonry or brick arch bridges, which form an important part of the heritage of the canal network. It is British Waterways' policy to preserve the historic infrastructure of the canals through preventative maintenance. In the case of bridges which are, or have become, under-capacity or have suffered structural or foundation failure, strengthening or even reconstruction may over-rule this policy. However, major works of this nature will always strive to retain the original features, form and material where practicable.

Osberton bridge was a failing brick arch that had become unstable and dangerous and the arch barrel of Manor Farm bridge had started cracking into segments. The boating envelope was restricted at both bridges and boat impacts had displaced some bricks.

This paper will cover:

- how features of the existing bridges have been retained and the brick arch bridges rebuilt using traditional methods and materials to preserve the heritage of the Chesterfield canal;
- the design philosophy for the brick arch structures;
- how the habitat for a protected species was maintained;
- how measures were taken to improve safety features without compromising traditional appearances.

## LABORATORY STUDY OF INFRARED THERMOGRAPHY ON MASONRY ARCH BRIDGES

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**Keywords:** Masonry arch, infrared thermography, moisture

This paper investigates the use of infrared thermography for detection of moisture behind the surface of masonry arch bridges. The paper will describe the laboratory experiments of a laboratory built masonry arch bridge. This is the first application of infrared thermography on masonry arch bridges in the UK. The outcome of this work shows that infrared thermography can generally be used to determine the presence of moisture within the fill of a masonry arch bridge.

This work formed part of a project sponsored by the Highways Agency at Edinburgh University.

## **CASE STUDY OF RADAR LABORATORY WORK ON THE MASONRY ARCH BRIDGE**

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**Keywords:** GPR, masonry arch, laboratory  
model, moisture, fill

The objective of this case study was to undertake a variety of radar tests on a laboratory controlled masonry arch bridge. To vary the moisture of the fill. To use a number of antennae to chose the optimal antenna to identify the change in moisture content.

## **NONLINEAR MODELLING OF A MULTI-SPAN ARCH BRIDGE UNDER SERVICE LOAD CONDITIONS**

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**Keywords:** Masonry, arch, bridge, multi-  
span, FE analysis

The response of a 19th-century multi-span masonry arch bridge, Queen's Bridge in Belfast, Northern Ireland, is studied using a three-dimensional non-linear F.E. model under service load conditions. The full five-span bridge, with spandrel walls, fill

material and surrounding soil is modelled. The interface between the masonry and the fill is characterised as a frictional contact surface to facilitate sliding or movement of the fill material relative to the arch barrel and the spandrel walls without generating tensile stresses. Physical tests are simulated by modelling passage of the test truck over the bridge model in a series of sequential static loadsteps. The numerical predictions, for crown and abutment deflections, are compared with experimental data and sensitivity analyses are performed by varying both the geometric and material properties of the bridge. While demonstrating the ability of modern analyses techniques in replicating the response of such complex bridge systems the paper also highlights some of the difficulties often encountered in modelling the response of masonry arch bridges; for example the lack of original construction drawings, incomplete knowledge of the geometric and material constituents, and the lack of detail relating to modifications undertaken after construction.

## **LABORATORY STUDY OF A CONDUCTIVITY SURVEY OF MASONRY ARCH BRIDGES**

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**Keywords:** Masonry arch, bridges,  
conductivity, laboratory modelling

This paper investigates the use of electrical conductivity measurements for determination of moisture behind the

surface of masonry arch bridges. The paper will describe both laboratory experiments. The laboratory results demonstrate the repeatability of the method. The laboratory shows that electrical conductivity measurements can be used to determine the presence of moisture within the fill of a masonry arch bridge.

This work formed a part of a project sponsored by the Highways Agency at Edinburgh University to provide advice on the use of conductivity measurements for obtaining information on the condition of highway structures.

## **THE USE OF CFRP PLATES TO STRENGTHEN MASONRY ARCH BRIDGES**

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**Keywords:** Masonry arch bridges, advanced composites, mechanism analysis

A mathematical modelling technique is presented that can be used to predict the load carrying capacity of a voussoir arch either with or without CFRP plates attached only to its intrados.

The analysis is carried out by applying the upper-bound theorem of collapse to an arch comprising a sufficient number of blocks of masonry to allow collapse to occur in a feasible manner.

In order to prevent a hinge forming at the extrados beneath the applied load, CFRP plates can be attached to the intrados of the arch. The formation of a kinematically admissible collapse state requires inward movements of the arch beneath the applied load to be accompanied by outward movements elsewhere. However, the use of CFRP to prevent the formation of an extrados hinge will postpone the

development of hinges elsewhere and thus increase the load carrying capacity of the structure. Since CFRP plates are currently considered to improve only the flexural strength, there is a limit to the extent of the improvement in the capacity of the structure. To quantify this, other forms of failure such as shear and crushing are included in the analysis. Finally, the practical application of CFRP to masonry that may be friable, damp, or coated with efflorescence is discussed.

## **3-D RECORDING OF A MASONRY ARCH BY LASERSCANNING & APPLICATION OF PROVEN TECHNOLOGIES OF BUILDING'S DOCUMENTATION**

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**Keywords:** Masonry, arch, bridge, reconstruction, photogrammetry

The tremendous flood-disaster of the Elbe and Mulde rivers, in August 2002 caused catastrophic damages to many cultural monuments and historical buildings in Saxony. The landmark of the town of Grimma was the Poeppelmann Bridge, built from 1716 to 1719 by M.D. Poeppelmann, the architect of the king of Saxony. The bridge had just been renovated in 2000. It did not withstand the terrible flood and was destroyed on the Eastern side of the bridge. Using modern photogrammetric techniques, it was possible to tag every identified block on the photogrammetric images of the bridge. Different colours and numbers

marked the location and the state of the individual elements. Thus a general overview and evaluation of the salvaged and deconstructed areas was possible and the bridge was reconstructed.

# **Theme 1: Bridges**

## **Day 3:**

### **Post-Tensioned Concrete Bridges**



## THE MANAGEMENT OF POST-TENSIONED BRIDGES

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**Keywords:** Post-tensioning, bridges, durability, insitu testing.

In the course of the major upgrading and extension of highway networks in the last fifty years, the use of post-tensioned concrete has been found to be an economically competitive form of construction. The application of prestress forces in either pretensioned or post tensioned form has enabled concrete to be used in significantly longer span bridges than was previously possible using conventional reinforced concrete.

The paper briefly reviews the development of post-tensioned concrete bridges over the last fifty years and the difficulties associated with the construction and monitoring of this constructional form. The nature, severity and diagnosis of problems reported in several countries will also be reviewed. Discussions will be presented on methods of investigating the insitu condition of post-tensioning systems that have been developed and the resulting improvements in the quality of the investigations. Finally a case study using the three-phase approach adopted in Technical Guide 2 is outlined.

The aim of this paper is to discuss the findings of both ongoing research and site investigations and will endeavor to demonstrate their implications for bridge owners and managers.

## EXPERIMENTAL INVESTIGATION OF INTERNAL TENDON CORROSION PROTECTION AT PRECAST SEGMENT JOINTS

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**Keywords:** Segmental construction, post-tensioning, corrosion, internal bonded tendons.

The moratorium in the UK after 1992 that still remains in effect for precast segmental construction using internal grouted tendons with discontinuous not fully sealed ducts and the problems encountered in the US in 2000 that included two external tendon failures at the Mid-Bay Bridge and corroded vertical tendons in segmental piers of the Sunshine Skyway Bridge, are only a few examples of the urgent need for adequate guidelines to achieve reliable corrosion protection in precast segmental structures. The need for the guidelines was emphasized at the 2001 fib-IABSE Workshop held at Ghent University, on the Durability of Post-Tensioning Systems. In 1993, aware of unfortunate experiences in Europe, a research study was started at the University of Texas at Austin, with the main purpose of investigating the corrosion protection of internal tendons at segmental joints. Half of the laboratory specimens were autopsied in 1999. This paper documents the final results, after the second half of the

specimens were autopsied with over eight years of very aggressive exposure. A number of changes occurred from the preliminary conclusions. Main among these was some corrosion (away from the joint) in epoxy jointed specimens and corrosion at one epoxy joint that was found to be incompletely filled with epoxy. Autopsies confirmed that dry joints should not be used under aggressive exposure conditions, match-cast epoxy joints provide good corrosion protection, gaskets in epoxy joints do not appear to be beneficial, plastic ducts provide excellent corrosion protection and good grouting procedures and materials are essential. The use of Calcium Nitrite in the grout did seem to provide enhanced long term strand corrosion protection.

## **LABORATORY EVALUATION OF REPAIRS TO PRETENSIONED CONCRETE BRIDGE MEMBERS**

**Dr Mohamad Nagi & Dr David Whiting (deceased)**

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**Keywords:** Bridges, chlorides, coating, concrete, corrosion, patching, prestressed, pretensioned, repair.

A laboratory test program designed to evaluate performance of repairs on corroded pretensioned concrete bridge members was carried out over a 4-year period. Near full scale pretensioned slabs and beams were cast and instrumented. Specimens were then subjected to accelerated corrosive conditions so as to induce severe corrosion on the prestressing strands and reinforcing

steel. Concrete in corroded areas was then removed and replaced with a variety of repair materials. Repair Materials evaluated included conventional portland cement concrete, latex-modified fiber-reinforced patching mortar, and silica fume concrete containing either organic or inorganic corrosion inhibitors. Embedded steel was coated with zinc-rich or liquid epoxy coatings after preparation of the steel surface. All specimens were patched, cured, and then subsequently exposed for approximately 200 weeks to a 15% solution of sodium chloride (wet-dry cycles). At the conclusion of monitoring, patches were removed from repair specimens and the steel and coatings were examined. In many of the specimens significant deterioration of the coatings had occurred over the 4 years of severe exposure. The distress was greater for the liquid-epoxy coated steel than the zinc-rich coated companion areas. Typically, there was more disruption of coating and corrosion of base steel in areas where latex-modified mortar had been used as repair material than where conventional concrete or silica fume concretes were used. Corrosion was observed in repair areas where bulk chloride ion contents were below commonly accepted threshold levels. When tendon bundles were cut and pulled apart, corrosion was observed on the interior surfaces of the individual strands. It is likely that chloride ions penetrated into the interstices of the strand bundles and initiated corrosion prior to repairs.

## **CORROSION STABILIZATION IN PRE-STRESSED CONCRETE CABLES BY INJECTION OF INHIBITORS USING POWER ULTRASONICS TECHNOLOGY**

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**Keywords:** Pre-stressed concrete,  
corrosion, ultrasonic, inhibitor

The corrosion of pre-stressed concrete steel wires encased in sheaths results from imperfections and voids in the surrounding protective cement grouting. Such defects facilitate the contact between cables and corrosive agents such as calcium chloride. The ensuing deterioration may lead to cable failure.

The PMD-ATEAV process stops corrosion and is little intrusive. It consists of saturating the grout with a passivating solution, thanks to the propagating properties of power ultrasonics generated by a high frequency reciprocating pump. The pulsating effect applied to the inhibitor solution at low pressure drives the liquid into every space of the grout.

A decade of tests and applications shows entirely satisfactory results. The inhibitor has been successfully used for more than thirty years. In the latest application, 34 irreplaceable cables imbedded in concrete were passivated with power ultrasonics to stop corrosion and to increase cable longevity. The procedure consisted of drilling openings alongside the cable paths through the concrete and the sheaths. Inserting tightly sealed tubes inside each hole allowed for the fitting of reciprocating

pumps. The pumps' compression chambers were filled with inhibitor solution. Finally, with the data mapping obtained, a micro-cement grout was injected by traditional method to restore the grout condition.

## **PROTECTING UNBONDED PRESTRESSED TENDONS**

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**Keywords:** unbonded, post-tensioned,  
tendons, concrete, polymer, protection

Prestressing of structural elements was first into the North American market during the 1950's. Unbonded prestressed tendons have been used extensively in buildings, bridges, pavements tanks and pressure vessels.

Time and the elements are taking their toll on the unbonded tendons. The protective measures instituted to prevent corrosion, most commonly a grease, have a finite life after which the potential for corrosion occurs. To extend the life of these tendons a new corrosion protection system must be applied to protect the existing tendons.

This paper will address a procedure to test the existing tendons, evaluate the existing condition that is designed to extend the life of the prestress tendon and subsequently reduce the life cycle cost of the structure.

# **IDENTIFYING VOIDS IN PLASTIC P-T DUCTS IN P-T CONCRETE BRIDGE BEAMS – USING I-E, SIBIE & TOMOGRAPHY**

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**Keywords:** Concrete, bridge beams, plastic  
ducts, impact echo, SIBIE, tomography,  
GPR

A series of standard concrete beams with plastic P-T tendon ducts were tested at the University of Edinburgh using a range of NDT techniques including impact echo (I-E), stack imaging of spectral amplitudes based on the impact echo (SIBIE) and ultrasonic tomography. The findings were confirmed by comparison with earlier experiments undertaken using GPR.

It has been argued that I-E cannot detect voids in plastic post-tensioned ducts readily. However it has been shown that whilst I-E is less effective on plastic ducts, the SIBIE analysis is more certain. This technique is easier to use than ultrasonic tomography and gives a credible evaluation.

The paper goes on to analyse the above tests on a number of beams with confirmation for ultrasonic tomography and GPR

# **Theme 1: Bridges**

## **Day 3:**

### **Concrete Bridge Deck Inspection + Repair**



# **MONITORING DAMAGE IN REINFORCED CONCRETE BRIDGE DECKS USING VIBRATION DATA**

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**Keywords:** Structural health monitoring, reinforced concrete, bridges, vibrations, dynamic testing

The School of Civil Engineering at the University of Nottingham has recently completed a major project funded by the Highways Agency to investigate using vibration data for the structural health monitoring (SHM) of bridges. Ten approximately quarter scale reinforced concrete (RC) beam and slab bridge decks were tested to determine whether variations in modal properties with damage caused by incremental overloading observed in RC beams could be replicated in more realistic bridge models. The results confirmed that similar trends in natural frequency did occur and the size and location of the stiffness loss could be identified using an informed finite element model updating procedure. However, the study also highlighted some specific problems associated with using this

system identification approach for damage detection, notably in comparing vibration modes from different damage states. The statically indeterminate nature of the support system also caused problems. In conclusion, the study has demonstrated that repeatable variations in vibrations properties do occur with damage, but these are probably best monitored using statistical pattern recognition rather than system identification.

## **SERVICE AND ULTIMATE BEHAVIOR OF HYBRID COMPOSITE BRIDGE DECK**

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**Keywords:** Bridges, infrastructure, composite bridge decks

This paper presents the results of experimental and analytical studies conducted on a new generation of all-composite bridge deck. The carbon/fiberglass reinforced polymer composite deck system was designed to replace the existing low profile welded steel gratings on the lift span of the Schuyler Heim Bridge in Long Beach, California. The experimental test results indicated that the composite bridge deck has exceeded both the predicted design and ultimate capacities. The span-to-deflection ratio at the mid-span was  $L/738$  based on a span length of 48' (1.22 m). The average safety factor (SF) of

the composite deck prototype was 6. In all tests, the ultimate failure was initiated either by a punching shear under the loading steel plate, or/and by the delamination of the curved portion of the drop sandwich panel. In modeling the performance of the composite deck, the GENOA progressive failure analysis numerical code was used to perform virtual *testing* of the composite decks under both quasi-static and fatigue loading conditions. The GENOA progressive failure code succeeded in predicting not only the stresses and strains, but also the major mode of failure observed during the full-scale laboratory tests.

# **Theme 1: Bridges**

## **Day 3:**

### **Case Studies of Bridge Repair**



## STRENGTHENING OF PUTTESUND BRIDGE

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**Keywords:** Strengthening, shear, prestressed concrete, creep, cantilever bridge, cable-stayed bridge, nonlinear analysis, jacking

Puttesund Bridge, located about 100 km south of Oslo, was completed in 1970 and built by the cantilever construction method. It is a prestressed single span box girder bridge with a hinge in the centre. Over the years the main span has deflected about 450 mm at the hinge. Also, the bridge was found to have insufficient shear capacity, which is the cause for the strengthening. The bending capacity, however, was found to be adequate. It is reason to believe that the sag is caused by a number of factors but not necessarily in connection to any weakness of the bridge. The extension system consists of two pairs of stay cables for each cantilever connected to inverted Y- shaped steel towers at the existing supports. By applying 3.15 MN tensioning force in each pair of stay cables, about 300 mm of the sag has so far been eliminated and the analyses show that the shear-relieved girder now meets full traffic load requirements. The state of the structure has been analysed based on advanced nonlinear finite element technique. Also measurements of concrete stresses have been carried out using the so-called stress-relief coring technique. Measured stresses compare quite well with corresponding stresses from analysis.

## A STRUCTURAL HEALTH DIAGNOSTIC SYSTEM (SHD) FOR TWO RAILWAY BRIDGES

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**Keywords:** Monitoring, sensors, prognosis, communication, long- and short-term measurements.

Infrastructure systems that provide transportations of people and goods are essential for a modern society. Such a system that has existed for a very long time and has had great impact on the industrial development is the railway system. Today with take the railway for granted, however, as for all types of civil structures, the need for maintenance and upgrading is also prevalent for the railroads. Considerations must not only be taken to the ongoing deterioration of materials, such as steel and concrete, but also the need to increase the load on the trains. Recently the Swedish and Norwegian Railroad Association decided to upgrade the Iron Ore railway transport system going from Luleå to Narvik. To increase the transportation capacities for iron ore taken out from the mines, it is necessary to increase the axle load from 25 to 30 tons. This load increase resulted in new calculations for the entire railway, including foundations, railway track and bridges. For a number of structures calculations showed that strengthening was necessary. However, to avoid strengthening, monitoring of strains in the real structure in combination with more refined calculations was suggested. This paper describe a Structural Health Diagnostic (SHD) system developed at Luleå University of

Technology and in particular applied on one of the bridges that was in need of strengthening.

The SHD system described in this report includes Prognosis, Sensor system, Acquisition system, Communication system, Storage system and a Diagnostic system. The application of the SHD system to one of the bridges, the Luossajokk Bridge, located in the very north of Sweden, was successful, and in spite of minor problems - it was decided to undertake a long term monitoring scheme of the bridge instead of strengthening it.

## **EXTENSIVE RESTORATION OF THE COLOMBO BRIDGE (SARDINIA)**

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**Keywords:** Repair, deterioration, prestressed concrete, NDT

The Colombo bridge was built across the Mannu river in Sardinia, (Italy) between 1966-68. This bridge consists of 15 spans, each 15 m in length, 12 of these span the Mannu river and 3 span a railway.

The bridge deck is constructed out of precast pretensioned concrete I-beams, 0.80 m spacing with overlaid precast parts. It is based on a continuous pier cap, which is supported by 4 piers, each made of 2 circular columns. Continuous foundation beams distribute loads down to 0.60 m reinforced concrete piles.

In 1992 serious static damage was identified and the 2 circular columns were

connected together, thus becoming a unique structure.

In 2002 due to increased heavy traffic, serious static risk and serious deterioration of the building materials, a total renovation of the structure including all structural aspects, from bridge deck to foundation piles was undertaken.

Core samples of the concrete from the piers and foundation were examined and reinforcing rebars mapped, direct load testing on the foundation piles were also carried out.

The renovation project, the extensive non destructive experimental tests and the testing of the load carrying capacity of the piles are disclosed in the following report.

## **INSPECTION, MONITORING & REHAB OF THE SAN BERNARDO VIADUCTS**

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**Keywords:** Bridge, viaduct, monitoring, inspection, damage, strengthening, design solutions

Recent growth of the traffic in European road network, together with an aging of the structures have lead people involved in the structures' maintenance to study a clever way to detect damage in the concrete bridges and to develop more detailed structural rehabilitation design.

In this paper are presented some bridge analysis methodologies, based on inspection and monitoring finalised to a practical repair work management system.

Some details on the Italian survey and control standards on bridges are also proposed together with some innovative way to improve the control of the bridge before and after strengthening work, based

on dynamic analysis, a non-destructive technique with a less influence on traffic.

The paper presents the investigation done on 31 viaducts of the San Bernardo connection road, a typical thirty years old reinforced concrete structure. An inspection survey, finalised to damage assessment, was carried out in order to produce a systematic approach, in other words a 'bridge management system', with the aim to define a priority list of the repair works.

Some examples of strengthening designs produced by Sineco S.p.A. for repair and upgrade the viaducts of this road are presented. The strengthening works performed are in general oriented to solve problems on the deck and girder or on complementary elements like bearings and joints, that are in general more sensitive to external agents and leakage problems that reduces the resistance of the structures.

The case study presented describes problems that more or less explain the typical situation of aged concrete bridges and the solutions proposed trying to solve, in a convenient and practical engineering way, some old structural designs that have proved to be inefficient.

## **FIELD INSTRUMENTATION & LONG-TERM MONITORING OF THE FRP BRIDGE OVER DUBOIS CREEK IN GREAT BEND TOWNSHIP, PA, USA**

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**Keywords:** Fiber reinforced polymer (FRP), bridge, long-term monitoring, instrumentation

A fiber reinforced polymer (FRP) bridge has been constructed in Great Bend Township, Pennsylvania, U.S.A. The bridge carries SR1037 over Dubois Creek and spans 21 feet 6 inches. The deck is 32 feet wide on a 70 degree skew. The superstructure consists of an FRP slab composed of top and bottom FRP 'plates' separated by a series of FRP webs on 8 inch centers oriented in both the transverse and longitudinal directions. The FRP slab thickness varies from 20 to 24 inches.

In order to study the behavior of this unique bridge, an instrumentation and testing program was implemented. This consisted of performing controlled static and dynamic load tests, in addition to remote long-term monitoring. Strains and displacements were measured on the deck and concrete parapet. Internal strains were measured using a new and innovative procedure developed specifically for this project at Lehigh University. The internal gages provide stress and strain data within the FRP material (including through-thickness stress distributions).

Peak vertical displacements measured during controlled load testing were very relatively low, equal to 0.07 inches, or L/3600. Maximum local stresses due to

concentrated wheel loads were on the order of  $\pm 5$  ksi. The measurements also confirmed that the concrete parapet contributes significantly as a structural component in this slab bridge.

This paper presents and discusses the unique details related to instrumentation, results of the controlled load tests, and long-term monitoring of this new and innovative bridge system.

# **Theme 2: Concrete + Advanced Composites**

## **Day 1: Concrete**



## CRITICAL CHLORIDE CONTENT – STATE OF THE ART

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**Keywords:** Threshold, corrosion, reinforcement, passive film

Deterioration of concrete structures has become an important issue over the last decade. The most frequently observed form of deterioration is chloride-initiated corrosion of the reinforcement. Corrosion is initiated when the chloride content at the reinforcement exceeds the critical or threshold chloride content. However the threshold values reported in literature show a tremendous scatter.

This paper will describe the chemical processes that take place when corrosion of the reinforcement is initiated. Based on published critical chloride content values, a most likely value of the critical content is suggested.

## COMPARISON OF TOPICAL CRACK REPAIR MATERIALS

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**Keywords:** Concrete, crack repair, monomer, resin

Five monomer/resin systems were evaluated for the repair of cracked portland cement concrete. The systems consisted of two methyl methacrylates, one modified high molecular weight methacrylate, one high molecular weight methacrylate, and an epoxy. The five systems were tested on three crack sizes (0.1 to 0.2-mm, 0.3 to 0.4-mm, and 0.8 to 1.0-mm) at three temperatures (40°F, 75°F, and 120°F) (4.4°C, 23.9°C, and 48.9°C). Ninety 5.5-in. × 12-in. × 14-in. (140-mm × 305-mm × 356-mm) reinforced concrete specimens were cracked using center-point loading. Each monomer/resin system was then evaluated as a repair material for the cracked slab specimens. The specimen was cut in half with one half being sectioned in thirds to evaluate the percentage of the crack length filled, and the other half re-cracked in flexure. The initial modulus of rupture was compared to the second modulus of rupture, the monomer/resin system filling time of each specimen was recorded, and the mode of failure, based on percentage of cohesion and adhesion within the concrete, was also evaluated. Additionally, the viscosity of each material at the three temperatures was determined. Comparisons between each monomer/resin system for each repair parameter for each crack size at each temperature were made.

## **BEM ANALYSIS OF DYNAMIC COMPACTION FOR PLACING INTERVALS ON COLD JOINTING**

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**Keywords:** Dynamic compaction, boundary element method (BEM), two-phase theory, cold jointing, placing for interval

Recently, some accidents on delimitation of concrete fragments have been reported in Japan, as found at Fukuoka Tunnel in the Sanyo bullet train (Shinkansen) line. After detailed investigation, one of causes is elucidated as resulting from a cold jointing. According to the committee report, an interval of consecutive placing is one key factor to prevent from the jointing.

In this paper, the influence of placing intervals and vibrating conditions are studied. Mechanisms of dynamic compaction are clarified analytically by the boundary element method (BEM). Bending strengths of jointed members are experimentally investigated to study the effect of placing intervals. Thus, pore pressure distribution in fresh concrete under compaction is correlated with quantitatively the strength of interface.

## **NUMERICAL SIMULATION OF ITZ QUALITY**

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**Keywords:** Modelling, ITZ, porosity, moisture movement

Providing proper durable concretes is the challenge of every nowadays-concrete technologist. The broad variety of possibilities put at the disposal by scientists, is expanding continuously, leading to an increase of decisions to be made for achieving the quality objective.

As research on cementitious material is proceeding, scientists more and more focus on the development of micro-numerical methods, which can be applied to predict the evolution of material properties in the longer term. Clients request material properties of building and construction elements to last for an increasingly longer lifetime. As a matter of fact, long-term quality of cementitious building materials and material properties find its roots in the development of the microstructure in the structures early lifetime.

Once the properties of the microstructure are known, degradation processes in bridge decks caused by the intrusion of aggressive chemical substances into the concrete can, in principle, be simulated. For that purpose numerical tools can be applied that simulate, on the one hand, the evolution of the micro-structural properties and, on the other hand, the transport phenomena occurring in the pore structure which lead to degradation of the concrete.

In this paper, simulations of the evolution of micro-level properties will be presented and shown to be applicable for quality judgments on higher modelling level. Focus is on simulating the matrix-aggregate interfacial transition zone (ITZ) and how the formation of this cement paste-aggregate zone affects the concretes' internal quality and transport of aggressive substances into the concrete. Results of internal damage and potential ITZ debonding in relation to the concretes internal integrity are presented.

## **THE USE OF STAINLESS STEEL TO REDUCE OR PREVENT CORROSION DAMAGE TO REINFORCED CONCRETE**

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**Keywords:** Reinforcement, stainless steel, corrosion resistance, cost benefits, whole life costing

In the past stainless steel reinforcement has been seen as difficult to obtain and expensive when compared to ordinary carbon steel materials. Because of these perceptions the possible use of stainless steel reinforcement has not always been given the fullest consideration even though its use offers, at the very least, a higher resistance to corrosion, and at the very best in practical terms, complete protection.

Recent changes in production techniques have reduced the cost of stainless steel reinforcement, and it is now being made more readily available.

It is now realised that for many structures durability is of major importance and that there is a need to minimise the risk of damage due to reinforcement corrosion in the aggressive environment.

The improved performance obtained, and the whole life cost benefits, from the use of stainless steel reinforcement can now be more readily recognised. There is a strong technical and economic case for giving consideration to the use of a reinforcement that gives the highest possible levels of long term resistance to corrosion thus reducing the need for maintenance and repair operations.

The economical case can be even more compelling if stainless steel is used for those areas in a structure exposed to the aggressive environment combined with the use of ordinary carbon steels in less aggressive situations such as the interior sections of a structure.

## **PHYSICAL AND MECHANICAL PROPERTIES OF MORTARS MODIFIED WITH HOMO OR CO-POLYMER OF METHYLMETHACRYLATE**

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**Keywords:** Polymer modified mortar, methylmethacrylate, latex, strength

This study evaluates fundamental properties of polymer mortars which were developed for the use in building and repairing concrete structures. The mortars were made of portland cement, fine aggregate and water with constant ratio. Methylmethacrylate or a co-polymer of methylmethacrylate emulsions were used as additives in ratios ranging from 5-20% by weight of cement. Physical and mechanical properties such as compressive strength,

flexural strength, bonding strength, chemical resistance, heat resistance, were experimentally evaluated and compared with those of conventional cement mortars.

## **SUSTAINABLE 'GREEN' OVERLAYS FOR STRENGTHENING AND REHABILITATION OF CONCRETE PAVEMENTS**

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**Keywords:** Concrete, pavements, sustainability, overlays, strength, polymers, qualitative, quantitative, analysis

A cost effective, minimal disruption, sustainable and environmentally friendly alternative to the wholesale demolition, removal and complete reconstruction of the existing structural concrete pavement is proposed, by developing a 'Green' pavement overlay.

A series of laboratory tests have been carried out aiming to improve the workability of fresh and the mechanical properties of the hardened concrete on a series of selected mixes. The initial series incorporated plain (OPC) concrete mix designs prepared with different sources of fine and coarse aggregate obtained from various locations around the UK, to achieve a high Modulus of Rapture (MOR). The addition of Pulverised Fuel Ash (PFA), enhanced the workability and the mechanical properties of the 'plain' mix and the further incorporation of a highly active pozzolanic residue, used for the partial replacement of cement, has yielded the most promising results so far. Third generation superplasticisers and polymers such as glenium C315, styrene butadiene rubber latex (SBR) and poly-vinyl alcohol (PVA)

aiming to transform the behaviour of the fresh mix and enhance the mechanical properties of the hardened concrete, are currently implementing the first phase of the investigation.

Additional tests are underway to assess the shear resistance, bond strength and fatigue performance of the material. Also, efforts are directed towards current environmental issues and sustainable, low cost solutions. Hence, the possibility of recycling used polymers and waste obtained from the motor vehicle and aircraft industries is also under investigation.

The paper contains an in-depth discussion of the results from the studies until now and the conclusions drawn from them. A significant number of tables, charts, graphs and diagrams provide a useful supplementary background. Emphasis is given to the experience built up so far, so essential for outlining future work.

## **DRYING-INDUCED DEBONDING IN STRUCTURAL ELEMENTS CONSISTING OF CONCRETE OF DIFFERENT AGES**

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**Keywords:** Repair, strengthening, hybrid element, monolithic behavior, debonding, interface, drying shrinkage, tensile creep, fracture mechanics, connectors, reinforcement

In a structural element consisting of concretes of different ages (herein called hybrid elements), deformations induced by

the drying of the new concrete layer are restrained by the old concrete layer. Depending on the amplitude of these deformations, the degree of restraint of the hybrid element and the level of superimposed mechanical loading, cracks and debonding are induced. A numerical investigation of the long term behavior and failure of hybrid elements has demonstrated that debonding depends on the thickness ratio of the new and old concrete layers, the tensile strength of the interface and the amount of reinforcement placed in the new layer. It was also observed, depending on these parameters, that it is possible to have mono-lithic failure behavior of an hybrid element even without using mechanical connectors. In this paper the conditions for which no long term debonding occurs in hybrid elements due to drying are given.

## **STRENGTHENING OF REINFORCED CONCRETE BEAMS USING EXTERNAL REINFORCEMENT: EFFECT OF LOAD AT INSTALLATION**

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**Keywords:** Retrofitting, strengthening,  
reinforced concrete, external bars

This paper describes a novel strengthening technique for reinforced concrete beams which employs non-prestressed external reinforcing bars anchored at the supports of simply supported beams or slabs. External reinforcement can be easily retro fitted to existing reinforced concrete

structures. The simplicity of the proposed technique offers advantages in terms of ease of installation, quality control on site and future inspections in comparison to other methods such as plate bonding. With many structures being subject to redevelopment and possible change of use, such a method could prove to be financially beneficial thereby enhancing the viability of rehabilitation projects by enabling existing structures to meet tougher standards.

For practical application it is preferable to install strengthening without the need to relieve the structure of load. This short study reports results of physical tests and numerical analyses in which installation of external bars was carried out while the beam was under load and results compared with those for an identical beam relieved of load during retro-fitting. The aim of the study is to determine whether external unbonded reinforcement remains a viable strengthening technique when retro-fitting is carried out with the beam under load.

## **MONOLITHIC BEHAVIOUR OF REINFORCED CONCRETE STRENGTHENED COLUMNS**

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**Keywords:** Finite element analysis,  
jacketing, monolithic behaviour

The primary objective of the research was to study the behaviour of reinforced concrete members strengthened by full jacketing in order to determine values for monolithic behaviour coefficients. The ANSYS finite element program was used during the project to simulate the nonlinear behaviour of the members that were tested. The analysis was carried out in order to

study the monolithic behaviour of reinforced concrete strengthened members. A parametric study of the monolithic behaviour of reinforced concrete strengthened members was performed. During the study, two parameters were examined: These were the coefficient of friction between two sets of concrete and the axial load. In the parametric analysis, the monolithic coefficients were calculated for three different situations for each strengthened member 1) when the first crack appears, 2) at steel yield and 3) at failure of the member. The results of this research, which represents reality to a very high degree, are very useful in understanding how the monolithic coefficients change and may be used to determine values for all circumstances.

## **BOND STRENGTH IN REPAIR MATERIALS WITH & WITHOUT SILICA FUME**

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**Keywords:** Concrete, repair, bond strength, shear strength, silica fume, test method.

This investigation was aimed at studying the effect of test methods on bond strength between concrete substrate and repair material. Four test methods with cementitious or riched-cementitious repair materials, and two surface roughnesses were studied. The methods used were pull-off, slant shear, splitting prism and a new direct shear named Bi-Surface shear test. While the coefficient of variation for each type of

test was acceptable, the bond strengths from those repair materials containing silica fume had an increase up to %30. This shows that silica fume can be used for a better bond.

## **CHARACTERISTIC OF CONSTRUCTION JOINT BETWEEN NEW AND OLD CONCRETE**

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**Keywords:** Construction joint, SEM, curing, hydrate, interface

After surface treatment of old concrete using water-jet technology, placing of new concrete is conducted usually in Japan. In this case, it is important to produce effective adhesive strength between new and old concrete. This report mainly describes the results of microscopic study on the interface of the construction joint using Scanning Electron Microscope (SEM) to confirm the weak point of joint. It is considered that the bond strength of a construction joint is significantly affected by the hydration reaction by the side of the interface.

The hydration reaction is closely connected with curing method. And to confirm the process of the hydration reaction is needed. However, the visual study of the interface affected by curing method and curing process is not yet clarified.

Three different curing methods are used for the experiment to make a fundamental study of microscopic observation in the construction joint. And the relation between the process of hydrate and the curing is studied by SEM.

## **BOND PROPERTIES IN CRACK INJECTION REPAIR RELATED TO HARDENING PROCESS OF INJECTIONS**

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**Keywords:** Crack injection repair, flexural bond strength tests, softening behavior

For crack injection repair, the bond property of the repair material is an important factor that affects the performance of the repaired structural components. The performance of the repair method depends not only on the bond strength, but also on the cracking behavior, such as fracture within the bulk concrete, the crack injection material itself or the interface between the concrete and the repair material. The bond strength tests in laboratory are required for the evaluation of material performance and material selections. However, the properties of injections, which are organic and cement based materials, would be changing because of its aging (hardening process). This paper presents the influence of hardening process of the injections on the test results through flexural bond strength tests at the specific age, i.e. Epoxy injection: 1, 2 and 7 days, Polymer cement slurry: 1, 2 and 24 month. Especially, not only the bond strength but also shape of softening region in load-crack mouth opening displacement (CMOD) relation are used as indices.

## **REINFORCED CONCRETE FLAT SLABS STRENGTHENED AGAINST PUNCHING WITH HIGH STRENGTH BOLTS**

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**Keywords:** Strengthening, flat slabs, punching shear, high strength bolts, reinforced concrete

Tests were made in eight (8) flat slabs, six of them strengthened with high strength bolts, after the slabs were loaded above its cracking load. The bolts were distributed radially from the column in two layers (three slabs) and three layers (three slabs). These tests were part of the M.Sc. Thesis of the first author (Carvalho 2001) under the supervision of the second author. The slabs were 1800 x 1800 x 130 mm, submitted to symmetric punching with concrete resistance between 40 and 45 MPa, and the main variables considered in each group were the type of anchorage for the bolts: only epoxy resin (Type A - two slabs); epoxy resin and steel plates, washers and nuts (Type B - two slabs); and only steel plates, washers and nuts (Type C - two slabs). Results of ultimate loads, failure types, cracking, deflections, ductility, concrete and reinforcement strains were analyzed together with comparisons of ultimate loads estimated by the codes ACI 318/99, BS8110/85, CEB-FIP/MC90, NB6118(1978) and NB6118 (2002). Best results were reached for the slabs with bolts anchored with epoxy resin, steel plate, washer and nuts (Type C), reaching ultimate loads 28% to 58% bigger than the reference slabs, respectively for slabs with two layers (Group 1) and three layers (Group 2) of

bolts. The slabs with bolts anchored only with epoxy resin (Type A) reached bigger ultimate loads than the slabs with bolts anchored by steel plate, washer and nuts (Type B). For ductility, however, the slabs with bolts anchored by steel plate, washer and nuts (Type B) behaved better than the slabs with bolts anchored only with resin (Type A). Best estimates were found for the ultimate loads with the CEB-FIP/MC90 and the Brazilian code NB6118 (2002).

# **Theme 2: Concrete + Advanced Composites**

## **Day 2:**

### **Concrete + Advanced Composites**



## STRUCTURAL INTEGRITY OF BEAMS STRENGTHENED WITH FRP PLATES – ANALYSIS OF THE ADHESIVE LAYER

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**Keywords:** Composite reinforcement, adhesive stresses, peel and shear stresses, lap shear test

The CIRIA organisation is currently leading a project, RP 645, entitled 'Strengthening metallic structures using externally bonded fibre reinforced polymers' prepared by Faber Maunsell and University of Surrey. The final report is due to be published in May 2003. This guideline covers all aspects of the material, design and installation regarding the application of FRP strengthening systems to beam structures.

Within the design section of this report, an alternative approach to design and analysis of the adhesive layer is proposed. Rather than current design practice which considers average stresses within the adhesive layer, profiles of the peel and shear stresses along the adhesive layer are calculated. The designer then compares the maximum values of these stresses to inferred peak stress values from lap shear test data.

This paper summarises the derivation of the stress analysis for the adhesive layer. Both uniform and tapered reinforcements are considered. Included in the analysis are the effects of both pre-tensioning the FRP plate and thermally induced stresses.

The paper also addresses the practical design issues of what are the acceptable level of stresses within the adhesive layer and the corresponding issue of how to interpret results from lap shear test data.

## PREDICTION OF DELAMINATION FAILURE IN CONCRETE BEAMS STRENGTHENED WITH CFRP STRIPS

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**Keywords:** CFRP laminates, strengthening, anchor, end-peeling, FE-analysis

In recent years the development of the plate bonding repair technique has shown to be applicable to many existing strengthening problems in the building industry. This technique may be defined as one in which composite sheets or plates of relatively small thickness are bonded with an epoxy adhesive to, in most cases, a concrete structure to improve its structural behaviour and strength. The sheets or plates do not require much space and give a composite action between the adherents. The adhesive that is used to bond the fabric or the laminate to the concrete surface is normally a two-component epoxy adhesive. The old structure and the new bonded on material create a new structural element that has a higher strength and stiffness than the original. Advanced composites have received great attention as materials for choice for a variety of application in repair and strengthening projects. The area of composites in construction, and in particular for strengthening, has been one of the fastest growing new areas within civil engineering during the last 10 years. Much focus and effort has been placed on understanding the

behaviour of Fibre Reinforced Polymers (FRP) strengthen concrete structures. The most common way to strengthen structures has been for bending and retrofitting (confinement) but shear strengthening is also often needed. When strengthen a structure for bending generally laminates or sheets are bonded to the surface of the structure.

Even though strengthening for bending has been commonly used over a decade there are still topics related to this part of strengthening that are not fully mapped out. In particular end peeling. The end peeling failure modes are caused by interfacial shear and normal stress concentrations at the cut-off points and at flexural and or shear cracks along the beam. These failure modes are not only dangerous because of their often brittle nature, they are also undesirable because the laminates or sheets will no be fully utilized.

In this paper a non-linear FE-analysis, together with closed analytical formulations and laboratory tests are presented studying the end-peeling phenomenon. Here, focus has been placed on the shear stresses at the end of epoxy bonded CFRP laminates. The distance to the support and the young modulus of the laminates have been variables in the study. A comparison between theory, FE-analysis and tests are made.

## **DESTRUCTIVE EVALUATION OF PATCH REPAIRS OF COMPOSITE STRUCTURES**

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**Keywords:** Destructive evaluation, composite repairs, honeycomb and solid laminates

This paper presents the results of destructive evaluation of scarf repair of honeycomb and solid laminates composites. Evaluation of honeycomb repairs was performed on a section contains two repair patches that were circular interior and rectangular edge. The two repairs were performed by a leading repair company in according with approved industrial standards and are classified as good repairs. The destructive evaluation was focused on sectioning the panels into one-inch strips and performing microscopic analysis of the bond surface of the skin as well as performing flexural tests on the honeycomb strips and direct tensile tests on the skin only. Four point loading conditions were adopted for the flexural test. The load versus mid-span deflection was recorded and the mode of failure was monitored. For the direct tensile tests, load versus strain on both parent and patch materials were recorded. The tests results of the flexural and tensile tests of the sections contain patch were compared to those of the same test configurations on sections with parent material only.

The solid laminate repair evaluation is

still underway and is focused on a full-scale tensile test of repaired panels.

Based on the testing program and the available data, it appears that patch repair increases the overall stiffness of the panel. Also, the connection between the patch and the parent material may be a point of concern.

## **REHABILITATION OF LAP-SPLICES IN NON-DUCTILE REINFORCED CONCRETE COLUMNS USING CFRP JACKETS**

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**Keywords:** FRP composites, concrete retrofit, seismic retrofit, lap-splice, bond stress

Many reinforced concrete frame structures built prior to the 1970's were designed for gravity and wind loads only. 'Compression-only' reinforcing details used in the columns of these structures are often associated with non-ductile lap-splice failures when subject to lateral load. The objective of this study is to investigate the use of carbon fiber reinforced polymer (CFRP) jackets as a retrofit measure for deficient lap-splices.

Three full-scale building column specimens having lap-spliced longitudinal reinforcing bars were tested under combined axial and cyclic lateral load. The columns were intentionally designed such that the lap-splices would fail prior to achieving the flexural capacity of the column. One column was tested without

retrofit as a control and the others were retrofit with CFRP jackets. Comparisons are also drawn with results of tests of similar columns having no lap-splices.

It is shown that with a CFRP jacket retrofit, the nominal capacity of the column may be achieved. The ductility of the repaired column, however, is limited by slip of the spliced bars resulting in a splitting failure in the lap-splice region. Additionally, the behavior of the lap-splice is accurately modeled and predicted using existing lap-splice behavior models regardless of the presence of the retrofit jacket.

## **ICC EVALUATION SERVICE— FOSTERING NEW REPAIR AND STRENGTHENING TECHNOLOGIES IN BUILDING CONSTRUCTION**

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**Keywords:** Structural evaluation, acceptance criteria, FRP composites, strengthening, repair.

The paper presents the involvement of the International Code Council (ICC) in developing acceptance criteria for new construction materials and technologies, such as fiber reinforced polymer (FRP) composites. The focus of this paper is on two major criteria that have been developed by the ICC in the past few years related to the FRP technology for strengthening and repair of concrete and masonry structures.

## **STRUCTURAL BEHAVIOR OF REINFORCED CONCRETE BEAMS STRENGTHENED WITH CFRP SUBJECTED TO STATIC AND FATIGUE LOADING**

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**Keywords:** Carbon fiber reinforced polymers, concrete structures, wrapped, confinement reinforcement, fatigue, static, strength.

Externally bonded Carbon Fiber Reinforced Polymer (CFRP) sheets have been successfully applied to reinforced concrete beams and other structural elements to increase the load carrying capacity of such elements. The focus of this study is to investigate the structural behavior of reinforced concrete beams strengthened with CFRP subject to static and fatigue loading, reinforced concrete slabs, and compression cylinders strengthened with CFRP subject to static loading. The number of layers and the type of CFRP sheets are considered as study parameters.

## **A MODEL TO PREDICT THE STRUCTURAL BEHAVIOUR OF REINFORCED CONCRETE BEAMS STRENGTHENED WITH EXTERNALLY BONDED COMPOSITE SHEETS**

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**Keywords:** Concrete beams, FRP sheets, strengthening, structural analysis

The results of a study on the behaviour of reinforced concrete beams, strengthened for flexure with externally bonded composite (Fiber Reinforced polymers, FRP) sheets, are discussed in the paper. The structural behaviour of strengthened reinforced concrete beams has been analysed both at the serviceability (cracking and deflection) and at the ultimate condition, once the moment-curvature law was defined. The moment-curvature diagram, in the cracked stage, is determined by a non linear model that accounts for both the mechanical properties of constituent materials and the characteristics of the concrete-to-FRP interface, defined by means of the local bond-slip law. The model refers to a beam element between two contiguous cracks and, takes into account both the local bond-slip law at the concrete interface and the tension stiffening effects. The technique of discrete element analysis is used to solve the structural problem and to draw the moment-curvature diagram of the cracked beam element. All failure modes of strengthened beams (debonding, peeling, FRP failure, concrete crushing) have been considered in the model. Predictions of the utilized model have been compared with experimental results and with those of

models currently adopted in the analysis of concrete beams strengthened with externally bonded FRP sheets. Results of the comparison show as the model can be used to accurately predict the structural performances of strengthened reinforced concrete beams.

### **CHARACTERISATION OF ADHESIVELY BONDED COMPOSITE PLATES FOR UPGRADING STRUCTURAL STEELWORK**

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**Keywords:** Adhesive film, adhesive joints, bonded joints, carbon fibre composites, FRP strengthening, steel beams

The bonding characteristics of structural adhesives, including an adhesive film currently under development and conventional two-part epoxies, both compatible for use with an advanced carbon fibre prepreg composite material, specifically manufactured for the civil engineering industry, are compared in this paper. Tension experiments have been undertaken on a single strap joint in which two steel members in the same plane are joined, on one side of the discontinuity, to a carbon plate using the above bonding systems. The results of the single butt joint are contrasted with those of a double butt joint, where out-of-plane bending effects are significantly reduced.

Strains were measured to provide information on the longitudinal profiles over a chosen bond length on both the steel and composite material adherends and on the

load transfer mechanism across the two adherends; the overall extensions of the joints were also measured. The thickness of the two-part adhesives was varied between 0.1 mm and 1.0 mm, whereas for the adhesive film the application of one or two layers was investigated. In general, three nominally identical specimens were tested for each case.

Several failure mechanisms were observed, these were generally a mixture of cohesive failure within the adhesive, adhesive failure at the bondline with either the steel or CFRP adherend, and composite delamination; yielding of the steel also occurred in a few samples. The work is part of a research programme currently undertaken to support the upgrading of steel structures using advanced polymer composite material systems.

### **EFFICIENCY OF CFRP SHEETS IN UPGRADING AND/OR STRENGTHENING SQUARE REINFORCED CONCRETE COLUMNS**

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**Keywords:** Columns, strengthening, upgrading, CFRP, confinement, strength, ductility

Strengthening and/or upgrading reinforced concrete columns through utilization of composite sheets is now receiving wide acceptance worldwide. The technique is simple to use and has many advantages over other available methods. However, limited data is available about its efficiency in confining non-cylindrical shape columns. In this paper, the influence of using different

schemes of wrapping of carbon fibre reinforced polymer (CFRP) sheets on the behaviour of reinforced concrete columns with and without utilizing mechanical anchoring system is reported. The columns were 300 × 300 mm in cross section and 2005 mm in height and were subjected to incremental monotonic loading until complete failure.

Test results indicated that the horizontally aligned CFRP sheets had more contribution to enhancing the ductility of the columns than the strength whereas the vertically aligned sheets had more contribution to increasing the column's ultimate capacity. The results also showed that both ductility and strength of the wrapped columns can be significantly increased by utilizing mechanical anchoring system that reduces the distance between the unsupported nodal points for the sheets.

## **AN EXPERIMENTAL STUDY ON SHEAR WALLS CONSTRUCTED BY LAYING CONCRETE OR GFRP BLOCKS INTO EXISTING RIGID FRAME**

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**Keywords:** Retrofitting method, reinforced concrete, precast block, GFRP block

This paper describes the development of new retrofitting methods and the results of structural experiments on these methods.

Many Existing buildings in Japan have been designed in accordance with the old

Building Standard Law. These buildings must to be retrofitted to comply with the present law. Adding new shear walls can increase their ultimate capacity under seismic force. Most previous methods have disturbed residents' daily activities during construction.

The new retrofitting methods introduced in this paper are noiseless during construction. They comprise laying of concrete or GFRP blocks into the existing Rigid Frames. The concrete blocks are made of precast high-strength concrete, and they weigh about 18 kg. The GFRP blocks are made from a GFRP grating and a GFRP frame, and they are laid in the exactly same way as bricks. However, an adhesive bond is used instead of mortar. No post-installed bonded anchors are required, so their is no noise during construction.

Experiments have shown that the retrofitted strength is two or three times than that of the rigid frame's strength before retrofitting, which is the same as the strength of two columns.

## **DESIGN GUIDELINES ON FRP FOR SHEAR STRENGTHENING OF RC BEAMS**

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**Keywords:** Concrete, beams, FRP, strengthening

The technique of strengthening reinforced concrete (RC) structures by externally bonding fibre-reinforced polymer (FRP) composites has attracted extensive research in the last decade. FRP composites may be used for flexural strengthening, shear strengthening, strengthening of columns or for a combination of these purposes. The

technique has also been increasingly used in practice. Consequently, several design guidelines have been independently developed by different organisations recently to meet the requirement for practical design. This paper presents a comparison of shear provisions in some of these design guidelines with an experimental database collected from the literature.

## **HIGHLY DURABLE REINFORCED POLYMER CONCRETE: PHYSICAL AND MECHANICAL OVERVIEW**

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**Keywords:** Adherence, fatigue, FRP rebars, microscopy, polymer concrete, porosity

This paper provides a general overview of the fundamental properties of the polymer concrete (porosity, internal structure and interface resin/aggregates) taking into consideration its macroscopic response (static and dynamic behaviour) in the presence of the fibre reinforced plastic (FRP) rebars.

Based on experimental results from polyester polymer concrete, several discussions will be made in relation to its internal structure. The microstructure of the polymer concrete analysed in the paper will be studied by mean of two techniques: intrusion porosity and scanning electron microscopy. The fundamental macroscopic properties to be considered are compression and flexural strength, strains and Young's modulus.

On the other hand, the bond behaviour between the rebars and the polymer concrete is one of the structural key parameters for understanding its structural behaviour. With this purpose, the bond response of different kind of rebars (plain and sanded GFRP and steel) embedded in polymer concrete blocks has been tested under static and dynamic pull-out forces. In the bibliography, there is not fully agreement with the most adequate method of interpretation of the experimental data. Nevertheless, some interesting conclusions will be shown in order to propose future developments in this field; that is, anchorage development in the reinforced polymer concrete.



# **Theme 2: Concrete + Advanced Composites**

## **Day 2:**

### **Corrosion + Cathodic Protection**



## **CONDUCTIVE CEMENT-BASED COMPOSITE AS ANODE FOR THE CATHODIC PROTECTION OF RC STRUCTURES**

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**Keywords:** Impressed current cathodic protection, cementitious conductive anode, activated titanium mesh, ease of installation, adhesion tests/durability.

Steel reinforcement is passivated by the high alkaline environment of the concrete, and therefore does not corrode. Active corrosion of the reinforcement can however occur when chlorides penetrate through the concrete cover and destroy the passivation layer, or through carbonation of the concrete. The corrosion of the reinforcement, an electrochemical process, is successfully stopped, mitigated or prevented with the use of several electrochemical methods. Cathodic protection for reinforced concrete is such an electrochemical method, which is used with success for the last 50 years.

A durable, conductive, polymer modified, cementitious mortar has been developed which serves as a secondary anode for the cathodic protection of steel in concrete. The electrical conductivity of this composite is obtained through the incorporation of nickel coated carbon fibres. The addition of acrylic polymers to the cementitious components does not have a major negative influence on the electrical conductivity of the composite. The polymers enhance the adhesion of the mortar to the concrete substrate, and as such aid the functionality of the CP system. The composite provides a uniform current

distribution. The major benefits over an activated titanium mesh anode system, used for the cathodic protection of steel in atmospherically exposed concrete, are its ease of installation and cost reduction. Typical applications for this conductive cement-based anode system include car parks, jetties, bridges etc.

Galvanostatic tests have shown the excellent durability of the nickel coated carbon fibres in this cement-based mortar. This conductive material has been successfully tested in laboratory tests and in the field, and has been successfully used to protect more than 20,000 m<sup>2</sup> of reinforced concrete.

## **CRITICAL EVALUATION OF METHODS TO ASSESS THE CORROSION RATE IN REINFORCED CONCRETE STRUCTURES**

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**Keywords:** Concrete, reinforcement steel, corrosion, polarization resistance, galvanostatic pulse.

There is a growing tendency to use non-destructive techniques for testing of durability of steel reinforced concrete structures. Methods for predictions of the residual service life of existing structures can benefit from having such additional information available. For steel reinforced concrete in which corrosion is the limiting degradation process in situ measurement of

the corrosion rate may provide useful quantitative information as an input. In this paper two non-destructive techniques for corrosion rate measurements, i.e. the linear polarisation resistance technique and the galvanostatic pulse technique are described and compared. The practical relevance of corrosion rate measurements is discussed from an owner's point of view.

## **EFFECTS OF CATHODIC PROTECTION ON BOND STRENGTH OF REINFORCEMENT IN CONCRETE**

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**Keywords:** Reinforced concrete structures, cathodic protection, structural effects, bond

Reinforced concrete is commonly used in highway structures and if it is designed and constructed correctly it is generally a durable material. However, corrosion of reinforcement can (and frequently does) occur necessitating repair of the concrete and sometimes additional protection of the reinforcement. One such form of protection is cathodic protection. Currently there is little information regarding the effects of this technique on the structural performance of reinforced concrete.

During works to Dartford West Tunnel eighteen blocks of reinforced concrete were saw-cut from road deck units. These concrete blocks were taken from areas that had been repaired using sprayed concrete. Fifteen of the blocks had also been subjected to cathodic protection. The blocks

presented an opportunity to perform pullout tests on reinforcement bars embedded in concrete specimens that had been cathodically protected and unprotected control specimens. In total pullout tests were performed on 57 plain round reinforcement bars.

Analysis of the experimental results indicates that the use of cathodic protection has had no significant effect on the ultimate bond stress of the plain round reinforcement bars in either the parent concrete or the sprayed concrete.

## **CORROSION MONITORING IN CONCRETE STRUCTURES WITH FIBRE OPTICAL SENSORS**

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**Keywords:** Fibre optical sensors, concrete structures, monitoring, reinforcement corrosion

Corrosion of steel reinforcement in concrete is major factor, provoking deterioration of concrete structures, reducing their service life. Maintenance of reinforced concrete structures and planning of the work on their remediation requires effective monitoring techniques. These techniques should be accurate, cost effective, immune to

aggressive substances, and should provide long term measurement stability.

Corrosion of steel can be measured directly, or indirectly by measuring parameters correlated with corrosion such as moisture, pH value, Cl<sup>-</sup> ion content, and cracks in concrete due to the corrosion process. Many monitoring techniques have been developed for these purposes, of which most are the electrochemical ones. Chemical fibre optical sensors (FOSs) are an interesting approach for making measurements of parameters correlated with corrosion. The FOSs are advantageous compared with conventional measuring methods. They possess long-term stability, immunity to electromagnetic fields, and ability to make distributed measurements. The FOSs are in use for chemical analyses of solutions or gases, and application for making measurements in concrete structures needs further research and development. The FOSs can be extrinsic or intrinsic. The extrinsic sensors use an optical fibre for the transmission of light from the sensing element and back to the detector. The intrinsic sensors make use of the properties of fibre to measure a given parameter. Important measurement principles used in FOSs are based on evanescent wave absorption phenomenon and micro bending.

## **ASSESSMENT OF CORROSION DAMAGE IN PRESTRESSED RC BEAMS BY STATIC AND DYNAMIC EXPERIMENTAL TESTS**

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**Keywords:** Corrosion, damage, beam model, static and dynamic tests.

The damage effects due to corrosion on the behaviour of prestressed RC beams have received much attention in the last years because of its importance in the analysis of existing civil structures as highway/railway bridges. The aim of this paper is to present a method of analysis for prestressed reinforced concrete (PRC) beams damaged by corrosion.

The authors analyse experimental PRC beam models undamaged and damaged by an artificial electrochemical process of corrosion localised in a zone. The utilised experimental method is based on static and dynamic experimental tests regarding both undamaged and damaged beam models.

The analysis of data permits to assess the decrease of mechanic parameters of PRC beams subjected to corrosion of reinforcement before that the electrochemical process produces cracking on the surface of concrete with spalling of the cover.

## **A FUNDAMENTAL STUDY ON THE EFFECT OF DESALINATION APPLIED TO PRE-STRESSED CONCRETE BEAM**

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**Keywords:** Post-tensioned PC beam, desalination, chloride ion, bending performance

Desalination is the electro-chemical technique for reinforced concrete structures which based on the principle of ion migration thorough concrete. In Japan, this technique has been focused on as one of the effective repairing techniques for damaged concrete structures due to chloride attack. However, some researchers point out that the hydrogen, produced around the reinforcement in desalinating process, will make steel brittle condition. Especially, this problem, which called 'hydrogen embrittlement of steel in desalination process', can be more severe for the pre-stressing tendon. Additionally, quite few study cases relating to the effectiveness, or difficulties, of the desalination technique for pre-stressed concrete members have been reported.

From these viewpoints, the authors experimentally applied the desalination to post-tensioned concrete beams, which had been in service for almost 40 years in marine environment. The desalination level was prepared at 1 and 2 A/m<sup>2</sup>. Mainly, the chloride ion profile in concrete, before and

after desalination, were compared. In addition, chloride ion content in grout, tensile properties of pre-stressing cable were carried out.

This paper shows the results and discussion on the removal effect of chloride ion from PC beam, the damage level of pre-stressing steel due to desalination (or chloride attack).

## **THE INFLUENCE OF CURING REGIME ON THE PASSIVITY OF REINFORCING STEEL IN CONCRETE**

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**Keywords:** Steel corrosion, reinforced concrete, passivity, curing regime

Reinforcing steel in concrete is protected by the high alkalinity of its pore water, which, in the presence of oxygen, results in the formation of a tightly adhering oxide film that passivates the steel and protects it from corrosion. The common understanding is that the passive film is formed on the reinforcing steel soon after the placing of concrete around the reinforcing steel bars.

An experimental investigation has been carried out to evaluate the effect of curing conditions on the mechanism of the formation of the passive film on reinforcing steel bars embedded in concrete, and to estimate the time of formation as affected by the curing regime.

Different concrete mixes were prepared and subjected to various curing regimes. The corrosion activity was evaluated using the half-cell potential. The results indicate that as long as the concrete kept immersed in water, the passive film will not form. This may be due to the lack of oxygen at the interface of the steel and concrete. The

corrosion evaluation of concrete using the half – cell potential is misleading when testing concrete immersed all the time in water. High potential values have been obtained, although no corrosion activity was exit.



# **Theme 2: Concrete + Advanced Composites**

**Day 2:**

**NDT of Concrete**



## **IMPACT-ECHO TESTING FOR DELAMINATIONS IN THE WALLS OF A MARINE STRUCTURE**

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**Keywords:** Impact-echo, marine,  
reinforced concrete

The impact-echo test method is briefly outlined and a major testing program for detection of delaminations in a massive reinforced concrete structure is described. The case study includes detection of delaminations in 600 mm thick heavily reinforced concrete walls of a large marine structure.

## **DETECTING DEFECTS IN CONCRETE SLAB BY STACK IMAGING OF SPECTRAL AMPLITUDES BASED ON THE IMPACT-ECHO**

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**Keywords:** Impact-echo, frequency  
spectrum, scanning procedure, SIBIE,  
concrete slab

The impact-echo method is an advanced nondestructive evaluation (NDE) for defects in concrete structures by analyzing elastic waves due to a mechanical impact. In order to improve the impact echo, a new procedure to evaluate defects in concrete is investigated, applying a scanning procedure. Thus, stack imaging of spectral amplitudes based on the impact-echo (SIBIE) is developed. The impact-echo method and the SIBIE are applied to specimens of reinforced concrete slabs containing artificial voids. It is confirmed by impact-echo method that presence of a void near concrete surface is detected as a peak frequency due to flexural modes of vibration in a cover concrete over a void. Further, It is clarified that the location and presence of the void in reinforced concrete can be visually identified by SIBIE. However, in the case that spacing of steel bars becomes narrow, detecting of intense regions due to the void becomes difficult.

## **STUDY ON EVALUATION OF SETTLEMENT CRACKS OCCURRING ON THE CONCRETE SURFACE ABOVE STEEL BARS OF REINFORCED CONCRETE SLAB BY NONDESTRUCTIVE TESTING**

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**Keywords:** Reinforced concrete, settlement crack, fly ash of type IV, visual inspection, ultrasonic method

In order to clarify the extensibility of fresh concrete with fly ash of type IV that substitute for sea sand, visual inspection and ultrasonic method of nondestructive testing are performed to evaluate width and depth of settlement cracks of normal concrete and concrete with fly ash of type IV. As a result of this experimental study, it is observed by visual inspection that the average of settlement crack width of concrete with fly ash of type IV become as half as one of normal concrete in same covering. By ultrasonic method, it is clarified that the crack depth of normal concrete agree approximately with one of concrete with fly ash of type IV in the case of same crack width. In addition, it is confirmed that settlement cracks penetrate relatively nearer the reinforcement bar, as covering thickness become thinner.

## **ACOUSTIC EMISSION GENERATING SITUATION OF STEEL PLATE-CONCRETE COMPOSITE SLABS**

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**Keywords:** Acoustic emission, steel plate and concrete composite slab, non-destructive inspection

The steel plate and concrete composite floor system has come increasingly into use as bridge slab. However, it is impossible to inspect the concrete slab visually, since there is the steel plate that covers bottom face. Therefore, the new inspection method is desired. The final object of this research is development of practical non-destructive inspection method for health monitoring of steel plate and concrete composite slab using acoustic emission (AE) technique. AE monitoring in four kinds of bending tests were carried out and correlations between characteristics of AE wave and fatigue damage of steel plate and concrete composite beams and slab were considered. Consequently, AE about concrete crack was observed through the steel plate. The feature

of the generating situation of AE wave, although many AE waves are observed at the time of the maximum load at the time of crack generating of concrete, if load is repeated, AE wave will come to be observed at the time of the minimum load and in case the amount of generating of AE wave per one cycle increases gradually and the specimen fractured, much value per one cycle come to occur.

## **LOCATION OF STEEL REINFORCEMENT IN CONCRETE USING GROUND PENETRATING RADAR AND NEURAL NETWORKS**

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**Keywords:** Ground penetrating radar, neural network, pattern recognition, multi-layer perceptron, reinforcement, concrete, dielectric properties, horn antenna

Ground-penetrating radar is becoming increasingly popular for use as a non-destructive assessment method for investigating reinforced concrete structures. The amount of data collected however can be very large and take a significant level of subjective experience to interpret. This study focuses upon the use of a neural network approach to automate and facilitate the post-processing of ground penetrating

radar results. The radar data is reduced to a simplified data set by using an edge detection routine. Signal reflections from reinforcing bars displaying a hyperbolic image format are detected using a multi-layer perceptron (MLP) network with a single hidden layer containing 8 nodes to recognise a simplified hyperbolic shape. Training and testing of the network was carried out making use of an emulsion analogue tank, simulating the properties of concrete, and using real concrete specimens. The results showed that the use of a MLP neural network approach could be quite effective in automating the identification and location of embedded steel reinforcing bars from a radar investigation. Accurate estimation of depth, or cover, requires a reliable knowledge of the dielectric properties of the concrete, and recent work using a specially-developed wideband horn antenna for direct determination of in situ properties is also outlined.

## **EXPERIMENTAL STUDY ON MEASUREMENT OF CHLORIDE CONTENT USING ELECTROMAGNETIC WAVE IN REINFORCED CONCRETE STRUCTURES**

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**Keywords:** Electromagnetic wave, content of chloride ions, dielectric constant, amplitude

The possibility of using electromagnetic waves as one of non-destructive methods for estimating the chloride content in reinforced concrete structures has been explored. Experiments were carried out to confirm change of the electromagnetic waves using specimens cast with varying amounts of chloride ions. The amplitude and dielectric constant of reflected electromagnetic waves, and the effect of temperature and moisture in concrete was studied and efforts made to relate them to chloride content. Results from the study indicate clear possibility of using changes in electromagnetic waves to measure chloride content in concrete.

## **APPLICATION OF AET TO CONCRETE BRIDGES: PRACTICAL CONSIDERATIONS AND A CASE STUDY**

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**Keywords:** Bridge, concrete, acoustic emission, cracks

During the last decades, the understanding and use of the Acoustic Emission (AE) technique has been developed and progressed, posing the basis for its application to real civil engineering structures. Among the latter, bridges represent a fundamental category. Attempts to apply the AE method on bridges started in 1972, initially focusing on steel bridges. The successful results obtained on steel structures opened the way to further investigation on the feasibility of the AE technique to concrete bridges. Recently, several examples of AE study on concrete structures have been carried out, but the lack of an uniformed procedure has also been highlighted. In the light of these considerations, a draft of an experimental protocol on the use of the AE method to concrete bridges is herein proposed - each step is singularly described and discussed. The case study of the investigation of a concrete bridge in the Scottish Borders is therefore illustrated, following the suggested procedure. Conclusions are

finally achieved about: the feasibility of the AE method, the proposed protocol and the particular case study structure.

## **ESTIMATING DAMAGE AND LOAD CARRYING CAPACITY OF CONCRETE BRIDGE BEAMS BY AE**

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**Keywords:** Acoustic emission activity, ‘relaxation ratio’, concrete, beams, bridge

The Acoustic Emission (AE) technique has been widely used on several different fields, such as nuclear, petroleum and chemical industry, rock mechanics and studies of material properties. Its application to civil engineering structures has however been limited by the lack of standard procedures and ‘International Uniformed’ codes. This paper provides a summary overview of the actual situation of AE codes, from which the need of quantitative assessment methods emerged. A step towards this direction is therefore presented. An alternative method of analysis was developed and it is herein illustrated. This method is based on a new defined parameter, named ‘relaxation ratio’, which quantifies and compares the AE energy activity during the loading and unloading phases of an AE test. Results from different data sets (related to tests on varied RC beams) are described and discussed, showing that a relaxation ratio greater than one is generally an indication

of serious damage on the specimens. The results appeared however to be affected by the properties of the concrete and the loading rate applied during the experiments. These results were then validated against the NDIS-2421 assessment criterion proposed by the Japanese Society for Nondestructive Inspections (JSNDI). Based on the relaxation analysis a new procedure for evaluating bridge beam integrity and load carrying capacity by Acoustic Emission is finally suggested.

## **AN ALTERNATIVE METHOD OF AE DATA PROCESSING: B-VALUE ANALYSIS OF CONCRETE BEAMS**

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**Keywords:** Non-destructive testing, acoustic emission, *b*-value, concrete, beams, bridge

Non-destructive testing (NDT) techniques allow the evaluation, inspection, testing and characterisation of a structure. Since the spread of their application in civil engineering, one of their main disadvantages lies in the processing and interpretation of the data, which is often not trivial. This paper addresses the issue of the data analysis, with specific reference to the Acoustic Emission technique. An alternative way of processing the AE signals

is proposed, based on the seismologic concept of the '*b*-value'. The *b*-value is defined as the log-linear slope of the frequency-magnitude distribution of acoustic emission.

This paper presents the results of two case studies – a *b*-value analysis carried out on data recorded during a laboratory test on a reinforced concrete (RC) concrete beam designed as representative of a bridge beam – a *b*-value analysis undertaken on data recorded during the monitoring of a bridge beam in service. In both cases, the results showed a good agreement with the development of the fracture process of the concrete beam and with cracking visible on the bridge beam, respectively.

## **CHAOS AND FRACTAL PATTERN RECOGNITION AND BEHAVIOR IN STRUCTURAL CONCRETE BEAM SYSTEMS THROUGH IN-DEPTH ACOUSTIC EMISSION [AE] AND THREE-DIMENSIONAL [3-D] ELASTOSTATIC MODELING**

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**Keywords:** Acoustic Emission, concrete, chaos, fractal patterns

Acoustic emission (AE) behavior, in conjunction with the sciences of complexity of chaos and fractals, that offer new tools, and may be more appropriate than traditional methods at certain times, due to localized cracking and damage, was investigated in 200 reinforced concrete beam specimens. The load application was conducted by means of monotonically increasing three point loading conditions. The concrete beam specimens, as tested, were sized at 1.6510 m. (65.0 inches) in length, 0.1524 m. (6.0 inches) in width, and 0.2540 m. (10.0 inches) in height. The

material variables that were emphasized, consisted of: various concrete curing times (ages), amounts of tension and compression steel reinforcement, and significant glass-fiber additions to the concrete mix. A total of 1,200 concrete cylinder specimens, sized at 0.1524 m. (6.0 inches) by 0.3048 m. (12.0 inches) were tested to ascertain the range of material strength was minimal. Various compression steel and tension steel areas, induced variations in the gross failures (observed cracking and/or load decrease) although diagonal tension failure predominated. Further the Kaiser effect (KE) and Felicity ratio (FR), as applicable to homogeneous materials (steel in particular) were identified, and partially modified in order to represent heterogeneous materials (tested concrete beam specimens), with varying reinforcement conditions accurately and correctly. The actual behavior of heterogeneous materials (concrete beam specimens with different reinforcing conditions) was precisely monitored and recorded over a predefined time domain, as a function of AE parameters, and load respectively. In order to interpret the AE results and study their time responsive behavior more rigorously, chaos and fractal techniques have been incorporated and utilized to attempt to link this new approach, and study its effects upon the in-place structural system that has been monitored further than previously.

## PRO'S AND CON'S OF HALF-CELL POTENTIALS AND CORROSION RATE MEASUREMENTS

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**Keywords:** Half cell potential (HCP), corrosion rate ( $I_{\text{corr}}$ ), galvanostatic pulse measurements (GPM), concrete structures

Half-cell potentials and corrosion rate measurements are compared and evaluated. The paper presents four different on-site cases. The first example is from a bridge pillar exposed to de-icing salts. This example shows a good correlation between corrosion rate and half-cell potential mapping. The second is a dry structure where high half-cell potentials were measured and shown to be directly misleading, while the corrosion rate provided the reliable results.

In the third testing case very low half-cell potentials were measured in a wet structure, and shown not to be a reliable indicator of the corrosion activity, again indicated accurately by the determination of corrosion rate.

The last example is an underground parking with leaking water/ de-icing salts from the above street. In this case the half-cell potentials indicated high corrosion risk while the corrosion rate is rather low. In all cases the actual corrosion was documented by exposing the reinforcement during visual inspection.

## DETERMINATION OF CHLORIDE CONTENT IN CONCRETE STRUCTURES WITH LASER-INDUCED BREAKDOWN SPECTROSCOPY

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**Keywords:** Chloride content, laser induced breakdown spectroscopy (LIBS), on-line results, reinforced concrete

An important criterion for the evaluation of reinforced concrete structures is the measurement of the chloride content. This will normally be done by time consuming standard chemical methods. We propose the application of a spectroscopic technique, the Laser induced Breakdown spectroscopy (LIBS), which provides the advantages of a fast measurement, the potential for on-site application and the possibility to investigate a wide range of different measuring points.

The surface can be scanned, or depth profiles are available from cores. Measurements can be performed directly on the sample surface and the results are available on-line.

We present LIBS results measured on concrete cores as well as on grinded and pressed material in comparison with the results of standard chemical methods. The optimum LIBS set-up and the experimental conditions to detect and measure chlorine in building materials are reported. The limits of detection were determined and calibration curves were measured.

## **MEASUREMENT OF CRACK DEPTH IN CONCRETE BY ULTRASONIC METHODS**

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**Keywords:** Concrete, crack depth, ultrasonic, impact echo

This paper describes the results of crack depth measurement in concrete by ultrasonic methods. Pulse Transmission and Impact echo methods were used. The measurements were performed on concrete sample with dimension of 150mm × 150mm × 750mm and artificial surface notches of various depths ranging from about 5mm to 80mm were fabricated. The measurement results by the various methods mentioned are explained and discussed.

## **QUANTITATIVE IMPULSE-THERMOGRAPHY AS NON-DESTRUCTIVE TESTING METHOD IN CIVIL ENGINEERING – EXPERIMENTAL RESULTS AND NUMERICAL SIMULATIONS**

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**Keywords:** Impulse-thermography, numerical simulation, non-destructive testing, concrete, civil engineering

Impulse-thermography is an active method for quantitative investigation of the near surface region of various structures and elements. It is well known for material testing in other industry branches like aerospace industry (graphite-epoxy

structures) and aluminium industry (aluminium laminates). Within the scope of a national funded project the possible applications of impulse-thermography in civil engineering are analysed. The technique of heating up the surfaces and observing the cooling down process is intended to detect near surface inhomogeneities in building elements, normally defects, and to determine their geometrical and material parameters. Thus, impulse-thermography will be an addition of other non-destructive testing (NDT) methods for volumetric investigation like radar and ultrasonic having high sensitivity and resolution in the surface near region.

For quantitative analysis of experimental data, a computer program for numerical simulation of the heating up and cooling down processes was developed based on Finite Differences. With this program parameter studies have been performed for investigating the influence of environmental conditions, material parameters and geometry on the thermal behaviour. The comparison between experimental and simulated results enables the Inverse Solution.

In this paper, experimental and theoretical investigations of a concrete test specimen containing voids at different depth and with different sizes are presented.

# **CORRELATION BETWEEN PULL OUT BOND STRENGTH & NONDESTRUCTIVE TESTS FOR DIFFERENT CONCRETE REPAIR SYSTEMS**

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**Keywords:** Concrete repair, NDT, pulse velocity, Schmidt hammer, bond strength, pull-out strength, durability

As more repaired concrete systems are subjected to scrutiny and evaluation, the need to develop methods that can assess the integrity of a concrete repaired cheaply and quickly becomes more critical. For that end, traditional nondestructive tests were investigated as part of an overall research project aimed at evaluating the performance of various patch repair systems.

Five full size reinforced concrete solid slabs were pre-cast to be repaired. Each slab was 2m × 3m × 150 mm in size. Each slab had six recesses to accommodate 60 mm thick repair patch. Slabs were placed in an exposed position at an elevated position for easy access. Each repair system was applied by the manufacturer's crew to one slab. The slabs were left in their elevated position for one full year exposed to the elements. The repaired zones were monitored periodically over the year by performing visual inspection, PUNDIT and the rebound hammer test. A series of test cubes with different concrete strengths were used to calibrate the pulse velocity and the hammer.

This paper presents the results obtained from the periodic monitoring of the repaired zones and the correlation of the measurements against the pullout tests. The reading time history is reported and show little fluctuation. However, consistent readings were obtained from different locations within the same slab. No or little correlation was obtained between the measured pullout strength, the compressive strength, or density and the pulse velocity or the rebound hammer number. The measured pulse velocity and the rebound hammer number had no correlation.

## **MINIMUM DELAMINATION WIDTH FOR GPR**

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**Keywords:** GPR, simulation, minimum width, delamination, delamination

Traditionally the investigation of delamination in structures is carried out by thermal imaging and mechanical or sonic probing. The recent development of high frequency Ground Probing Radars (GPRs), gives the possibility of detecting structural features in the millimetre range. This paper describes a series of measurements carried out using a high frequency GPR which were then compared with simulations of similar conditions using GPRMAX2D software (A.Giannopoulos 2002). The radar used for the experiments was an Utsi Electronics' Groundvue 5 which has a pulse giving a centre frequency of 4GHz.

## **THE STRAIN RELIEF METHOD FOR MESURING THE STRESS IN CONCRETE**

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**Keywords:** Strain relief, stress, concrete, measurement

To ensure serviceability of structures, an accurate survey of the loss of prestress can be required so that appropriate remedial solutions can be engineered. Complex states of stress are difficult to estimate accurately through calculations and models. The exact state of stress can only be determined through direct measurements on the structure.

The strain relief method has been proven to be the only method available to measure stresses in concrete. Its principle is simple: the strain field is relieved by slotting the material; the change of the strain in the relieved area is measured and the stress is calculated taking into account the elastic properties of the material and the geometry of the cut.

However, in concrete, the modulus of elasticity varies with concrete mix, age, curing and environmental conditions. In order to eliminate the need to know the elastic properties of the concrete, a flat jack can be inserted into the slot and pressurized. As a result the initial strain field will be restored. The combination of the measured data on strain and pressure will give the value of the stress.

Extensive research and testing have

been conducted in order to achieve better performance and cost efficiency, resulting in several improvements of the original technique

The method can be used to estimate:

- the stress profile in any RC/PC structure (bridge girder, pier, building column, slab, tunnel, arch...),
- the residual prestress in a PC structure,
- the loss of prestress in PC structure

This paper will present the improved method and a case study of an application in Japan.

## **PERMIT – A NEW IN-SITU ION MIGRATION TEST TO DETERMINE THE CHLORIDE TRANSPORT THROUGH COVER CONCRETE**

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**Keywords:** Chloride diffusion, in-situ test, ion migration test, PERMIT

The ingress of chlorides into concrete is predominantly by the mechanism of diffusion and the resistance of concrete to the transport of chlorides is generally represented by its coefficient of diffusion. The determination of this coefficient normally requires long test duration (many months) and, hence, rapid test methods based on the electrical migration of ions have widely been used. The current procedure of chloride ion migration tests involves placing a concrete disc between an ion source solution and a neutral solution and accelerating the transport of ions from the source solution to the neutral solution by the application of a potential difference across the concrete disc. This means that,

in order to determine the chloride transport resistance of concrete cover, cores should be extracted from the structure and tested in laboratories. In an attempt to facilitate testing of the concrete cover on site, an *in-situ ion migration test* (PERMIT) was developed.

The PERMIT Ion Migration Test was validated in the lab by carrying out a comparative investigation and correlating the results with the migration coefficient from the one-dimensional chloride migration test, the effective diffusion coefficient from the normal diffusion test and the apparent diffusion coefficient determined from chloride profiles. A range of concrete mixes made with ordinary Portland cement was used for this purpose. In addition, the effects of preferential flow of ions close to the concrete surface and the proximity of reinforcement within the test area on the In-situ Migration Coefficients were investigated. It was observed that the In-situ Migration Index, found in one working day, correlated well with the chloride diffusion coefficients from other tests. The quality of the surface layer of the cover concrete and the location of the reinforcement within the test area were found to affect the flow of ions through the concrete during the test. Based on the data, a procedure to carry out the PERMIT Ion Migration Test was standardised.

## **NDT OF SPECTRUM ANALYSIS OF SURFACE WAVES (SASW) METHOD IN SINGLE AND MULTI-LAYER SLABS WITH FINITE THICKNESS USING NUMERICAL MODELING**

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**Keywords:** Spectral analysis, nondestructive testing, surface waves, numerical modeling, concrete slabs

The method of spectral analysis of surface waves (SASW), a nondestructive testing method, has mainly been developed and used for many years in the fields of civil and architectural engineering such as examining the material properties of pavement systems and soil media under an infinite half-space condition. This method consists of generation, measurement, and processing of dispersive surface waves. In an SASW test, the surface of the media under investigation is subject to an impact to generate surface wave energy at various frequencies. Two vertical accelerometer receivers are set up near the impact source to detect the energy transmitted through the testing media. By recording signals in digitized form using a data acquisition system and processing them, surface wave velocities can be obtained by constructing a dispersion curve. This paper presents the numerical modeling of SASW method to find the surface wave velocities and to investigate if the numerically modeled multi-layer slab system can show the dispersive characteristics. In the single-layer slab, average surface wave velocities obtained from finite element mode superposition analysis are reasonably close to the theoretical value. The refinement of

finite element meshes from  $2.54 \times 2.54$  cm to  $1.27 \times 1.27$  cm using mode superposition method improved the surface wave velocities from 1880 m/s to 2060 m/s. When each layer in the three-layer slab system was modeled with quite different material properties such as Young's modulus of 17573612, 30438395, 39295800 kpa, Poisson's ratio of 0.2, 0.23 and 0.26, and mass density of 1.9043, 2.0815, 2.2420 g/cm<sup>3</sup>, respectively, the average surface wave velocities were 1886 m/s in the top layer, 2225 m/s in the middle layer and 2627 m/s in the bottom layer. The distinguishable dispersive characteristics were found in the numerically processed compact dispersion curves. This study can be contributed in examining structural elements of general concrete structures and be applied in the integrity analysis of concrete structures with a finite thickness.

## **NEW CALIBRATION METHOD OF REBOUND HAMMER**

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**Keywords:** Rebound number, calibration anvil, non-destructive test

Rebound number method is one of the popular methods in Japan to evaluate qualities of concrete because of its easy application in situ. On the other hand, the accuracy of rebound number method is questioned. Though it has been recognized that there are many factors that can affect rebound number, this paper discuss the individual difference and calibration method of rebound hammers. We collected many rebound hammers and compared rebound numbers measured with them. Various calibration anvils including low

bounce anvils that are newly designed to give approximately 40 by rebound number were also collected to compare the status of rebound hammers. Test results show that there is considerable difference of performances between rebound hammers supplied by manufacturers and the others; the difference is apparent in case of concrete specimens and low bounce anvils, but not in conventional anvils. Authors recommend calibrating rebound hammers with low bounce anvils.

## **MODELLING GROUND PENETRATING RADAR USING GPRMAX**

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**Keywords:** Radar, modelling, software, GPRMAX

Ground penetrating radar is an important tool for the non-destructive testing of structures and transport systems. However, the interpretation of the data acquired using a GPR is often a complicated and error prone procedure mainly due to the complexity of the GPR signals and the variety of factors that influence and determine them. In order to successfully interpret GPR data a considerable amount of expertise is required by the system's user or the data analyst. This experience is usually obtained either by expensive experimentation or by referring to prior knowledge often obtained after costly mistakes in the field. This paper deals with the fundamentals of GPR operation and presents a software tool that can be used to simulate (i.e. model) GPR responses from arbitrarily complex targets. This software

tool called GprMax is available free of charge for both academic and commercial use and has been successfully employed in situations where a deeper understanding of the operation and detection mechanism of GPR was required. Examples from both 2D and 3D models are presented which demonstrate the use of GprMax. The tool can be downloaded from [www.gprmax.org](http://www.gprmax.org) or by contacting the author.



# **Theme 2: Concrete + Advanced Composites**

## **Day 3:**

### **Concrete + Advanced Composites**



## **CONCRETE BEAMS STRENGTHENED WITH CFRP A STUDY OF ANCHOR LENGTHS**

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**Keywords:** NSMR, CFRP, concrete, strengthening, anchorage, epoxy, composite

The need for concrete maintenance, repair and upgrading is extensive and almost every country in the world is carrying out research in this field. New methods and technical solutions that can make rehabilitation more effective and economical are very welcomed. CFRP (Carbon Fibre Reinforced Polymers) strengthening has shown to be such a method. This method implies that a thin carbon fibre laminate or fabric is bonded to the surface of a structure. This outer reinforcement layer act compositely with the structure and enhance its stiffness and strength. Also NSMR (Near Surface Mounted Reinforcement) of composites can be used where a composite rod is bonded in a pre-sawn slot in the concrete cover.

Essential for a good strengthening effect is anchorage of the CFRP material used. Without sufficient anchor lengths full utilization of the strengthening material can be difficult to achieve. This paper presents laboratory test for different cfrp strengthening techniques; laminates, fabrics and nsmr rods. Different anchor lengths have been investigated together with different surface treatment. The effect of the unevenness of the concrete surface has also been studied. in addition a comparison between theory and test is carried out.

## **USE OF FRP FABRIC FOR STRENGTHENING OF REINFORCED CONCRETE BEAM- COLUMN JOINTS**

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**Keywords:** Low engineered reinforced concrete, earthquake, fibro-reinforced polymeric fabric, strengthening

Devastating earthquakes in the last 3 years have shown that non-engineered concrete frames are particularly vulnerable to seismic action and are a major cause of loss of lives. This structural type constitutes a large share of the building stock, both in developed and developing countries, and hence represents a substantial exposure. Direct observation of damaged structures, following the Kocaeli, Turkey 1999 earthquake, has shown that damage occurs usually at the beam-column joints, with failure in bending or shear, depending on geometry and reinforcement distribution and type.

While substantial literature exist for the design of concrete frame joints to withstand this type of failure, after the earthquake many structures were classified as slightly damaged and, being uneconomic to replace them, at least in the short term, suitable means of repairs of the beam column joint area are being studied. Furthermore there exist a large number of buildings that need retrofitting of the joints before the next earthquake.

The paper reports the results of cyclic tests carried out on cruciform beam-column joint specimens, with two different

configurations of geometry and various configuration of strengthening by externally bonded FRP fabric. The specimens were designed to comply with gravity load design codes, but no seismic design was considered. In the design of the FRP wrapping, two different type of fabric were considered and three layout of the wrapping strips.

## **FLEXURAL STRENGTHENING OF RC BEAMS WITH SIDE-BONDED CFRP SHEETS**

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**Keywords:** Reinforced concrete beams, FRP, CFRP plates, flexural strengthening, side-bonding

Available research on the flexural strengthening of RC beams has been focused on the behavior of beams bonded with an FRP soffit plate. In practical applications, there are situations in which access to the soffit of the beam is obstructed by the presence of another structural member or non-structural installations. In such cases, bonding of soffit plates is no longer desirable, but the alternative of bonding FRP plates to the sides of the beam below the neutral axis of the section becomes an attractive alternative. This paper presents the results of the first study of this alternative strengthening method, in which a total of four concrete beams were elaborately devised and cast under laboratory conditions. Each specimen was pre-loaded under two symmetrically-positioned concentrated loads to the extent that one main crack was observed, and then unloaded and strengthened by bonding CFRP plates on its side faces within the

tensile region. After proper curing, the specimens were loaded again to ultimate failure. The experimental results show that this alternative strengthening method is effective in enhancing the flexural capacity, and in the meantime leads to a very ductile behavior compared to an RC beam bonded with a CFRP soffit plate. Based on the experimental results, a practical design method is proposed, which shows close agreement with the experimental results and provides conservative predictions.

## **STRENGTHENING OF HOLES IN TWO-WAY CONCRETE SLABS USING CFRP COMPOSITES**

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**Keywords:** Composite, concrete, CFRP, design, FRP, hole, reinforcement, repair, slab, strengthening

Strengthening with FRP composites has existed for over a decade, and the most common way to strengthen structures is in bending where the design is more or less straightforward. Another common application for FRP strengthening is to strengthen slabs or walls before holes are made. In these situations, FRP fabrics are very suitable and after coating the wall or slab, the hole is made whereafter the strengthening material takes up the additional loads. However, there has not been many studies reported on slabs with holes strengthen with CFRP and especially, not when a distributed load has been applied.

This paper presents laboratory tests of two-way full-scale concrete slabs with a made hole that have been strengthened or repaired with CFRP fabrics and loaded with a uniform load. The strengthened slabs are compared to an as-built homogeneous slab, slabs as-built with a hole and slabs weakened by a made hole, and the study shows that it is fully possible and quite effective to strengthen or repair holes in slabs with CFRP fabrics.

## **AN INVESTIGATION OF THE FIRE BEHAVIOUR OF FRP-STRENGTHENED REINFORCED CONCRETE BEAMS**

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**Keywords:** FRP, beams, fire resistance, reinforced concrete, numerical modelling, strengthening.

Fiber Reinforced Polymer (FRP) products are becoming increasingly accepted as a viable material alternative for both new construction and repairs to existing structures. However, much of this innovative technology has been centred on bridge structures – leaving the building repair market largely untapped. This lapse is mainly due to the lack of data concerning FRP performance under fire conditions. To address this gap in knowledge, a research project is currently underway to investigate the fire performance of concrete columns confined with FRP sheets, and beam-slabs strengthened with FRP sheets.

This paper presents a comprehensive background to the work performed in the area of FRP under fire, specifically related to beams and slabs. A numerical model has also been developed, which uses the finite difference method to predict the temperature distribution through the cross section of an FRP-strengthened member under fire conditions. Preliminary results from the model are presented here. The model is being validated against fire tests on FRP beams. The beam specimens are 250 mm deep and are topped with a 150 mm thick, 1220 mm wide slab. The beam-slab assemblies will be strengthened along the base of the web with CFRP sheets and provided with supplemental fire protection. Based on the experimental and analytical studies, design guidelines and fire protection schemes will be produced for the use of FRP in building repair.

## **INTERFACIAL STRESSES BETWEEN FRP PLATE AND CONCRETE IN A PEEL TEST: AN ANALYTICAL SOLUTION**

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**Keywords:** Peel test, interfacial stresses, strengthening, fibre reinforced polymer composites (FRP)

Strengthening of reinforced concrete (RC) structures using externally bonded fibre

reinforced polymer (FRP) composites has become a popular technique over the last decade. The success of the technique relies on the effective stress transfer between FRP and concrete through an adhesive layer. The bond behaviour between FRP and concrete is thus of critical importance. The so-called peel test, in which an inclined force is applied to an FRP plate bonded onto a concrete block in the present context, is widely used to characterise the bond behaviour of adhesives. This paper presents an analytical solution for the interfacial normal and shear stresses in such a peel test to provide an improved understanding of its underlying mechanism. The effect of the peel angle (i.e. the angle between the applied force and the substrate) on the interfacial stresses is discussed.

Apart from being a widely used test for quantifying adhesive characteristics, the debonding process in a peel test resembles that of intermediate flexural-shear crack induced debonding failure in flexurally strengthened RC members where a relative vertical displacement exists between the two sides of the crack, leading to an angle between the FRP plate and the concrete substrate. Therefore, results of this study shall also offer some insight into the latter failure mode which is very important in the flexural strengthening design of RC members.

## **FLEXURAL STRENGTHENING OF R.C. BEAMS UTILISING A SPECIFICALLY SHAPED WET LAY-UP GLASS FIBRE CHOPPED MAT COMPOSITE**

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**Keywords:** Carbon fibre composites, glass fibre composites, reinforced concrete beams, FRP strengthening of RC beams

The upgrading of bridge structures and buildings using fibre reinforced polymers (FRP) is a well researched topic and one where the technology has been transferred to the construction industry; the plate material would normally be carbon fibre reinforced polymer.

This paper suggests an application, for a wet lay-up technique of chopped strand glass fibre mat and vacuum assisted compaction, with a particular wrapping geometry, which can be utilised in certain cases; the matrix of the composite also acts as the adhesive material. The system differs from the traditional continuous fibre composite plate in two respects, firstly the 2D random orientation of the fibres means that its properties are quasi-isotropic in the plane of application and secondly the composites are shown to be tougher and more damage tolerant than continuous fibre composites which are brittle and fail in a catastrophic manner. Furthermore, the process of fabrication is a 'cleaner' system compared to the sprayed system which has been proposed in another recent study.

The paper discusses the experimental

results of this application relating to the stiffness of the system, the strain analysis at the mid-point of the span of small scale beams and compares these parameters with those of a carbon fibre reinforced polymer plate bonded to the soffit of nominally identical beams.

It is shown that the static load capacity of the particular U-shaped wrapping geometry used in the investigation for glass fibre reinforced polymer plated beams is increased by a factor of 2.2 and 2.9 for thicknesses of the composite of 1.8 mm and 3.0 mm respectively, compared to that of the control beams. It is also demonstrated that some of the geometries for GFRP upgraded beams have a greater stiffness than the control beams and fail in a more ductile manner compared with the CFRP plated beams.

## **EXPERIMENTAL STUDY OF RC COLUMNS CONFINED WITH FRP SHEETS**

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**Keywords:** FRP, columns, confinement, concrete

The paper aims to contribute to a better understanding of the behaviour of RC columns confined with FRP sheets. The study is based on an experimental program carried out on ten circular columns with and without transverse steel reinforcement

(stirrups) and with different amounts and types (Glass and Carbon) of Fiber Reinforced Polymers (FRPs) wraps. The test results provide some new insights into the complex failure mechanisms that characterize the ultimate capacity of RC columns with transverse steel reinforcement and FRP sheets.

## **FLEXURAL BEHAVIOR OF RC BEAMS STRENGTHENED WITH CARBON FIBER SHEETS BONDED WITH ORGANIC AND INORGANIC MATRICES**

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**Keywords:** Concrete, beams, strengthen, CFRP

The objective of this paper is to study and compare the performance of concrete beams strengthened with carbon fiber sheets bonded with inorganic and organic resin matrices. The experimental study comprised of testing two groups of steel RC beams. The first group of beams was strengthened with carbon fiber sheets bonded with an organic matrix and the second was strengthened with carbon fiber sheets bonded with inorganic matrix. Each group was strengthened with 2, 3, 4 and 5 layers of carbon fiber sheets. Strength, stiffness, ductility, deflection, failure pattern and cracking of beams strengthened with the two systems were compared. Results showed that the inorganic matrix system is as effective in increasing strength and stiffness of reinforced concrete beams as the organic matrix system. The failure mechanism of the inorganic system, however, seems more brittle. The failure of beams strengthened with an inorganic matrix showed crack

formation in the composite and a minimum build-up of strain along the interface of the composite and concrete. Analytical models were proposed to predict deflection of the strengthened beams. The experimental values compared well with those predicted by the analytical model.

## **IN PLANE DEBOND RESPONSE OF VACUUM ASSISTED RESIN TRANSFER MOLDED CARBON FIBER SHEETS ON CONCRETE SUBSTRATES**

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**Keywords:** VARTM, FRP reinforcement, RC beams

High quality and expedient processing repair methods are necessary for enhancing the service life of bridge structures. Deterioration of concrete can occur as a result of structural cracks, corrosion of reinforcement, and freeze-thaw cycles. Cost effective methods with potential for field implementation are necessary to address the issue of repair and vulnerability to bridge structures. Most infrastructure related applications of fiber-reinforced plastics (FRPs) use traditional hand lay-up technology. The hand lay-up is tedious, expensive, labor-intensive and prone to personnel skill level. An alternative to traditional hand lay-up of FRP for infrastructure applications is Vacuum Assisted Resin Transfer Molding (VARTM). VARTM uses single sided

molding technology to infuse resin over fabrics wrapping large structures, such as bridge girders spans and columns. There is no work available in understanding the interface developed, when VARTM processing is adopted to wrap fibers such as carbon and/or glass over concrete structures. A weak interface creates potential problems such as water seepage, fiber wrinkling, premature failure of beam caused by debonding at the interface and moisture induced delamination. This paper is aimed at understanding the interface formed by carbon fiber processed on to a concrete surface using the VARTM technique. Various surface treatments of the concrete including sandblasting were performed. Carbon fiber wrap Sikadur HEX 103C and low viscosity epoxy resin Sikadur 300 were considered in VARTM processing of concrete specimens.

## **RETROFITTING OF RC BEAMS WITH CARDIFRC®**

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**Keywords:** RC beams, retrofitting, high performance FRC, adhesive bonding, computational modelling, ultimate moment capacity

This paper will describe first the important steps necessary for the manufacture of the high performance fibre reinforced cementitious composite developed at

Cardiff University. These steps have been patented (GB 0109686.6) and the class of materials so produced registered under the trademark CARDIFRC®. It will then describe a new technique of retrofitting damaged and/or understrength RC beams. In this technique thin pre-cast strips of CARDIFRC® are adhesively bonded to the tension and, if necessary, other faces of the beams. This technique ensures that the ultimate failure of the retrofitted beams will occur in the gradual flexural mode. It therefore overcomes some of the problems encountered with the existing techniques, based on externally bonded steel plates and FRP laminates, which arise primarily due to the mismatch of their tensile strength and stiffness with that of concrete.

The paper will then describe two analytical/computational models for predicting the ultimate moment capacity and the complete load-deflection behaviour of retrofitted RC beams. The first model takes a classical approach involving the tensile contribution from the reinforcing steel and the compressive contribution from concrete, but it also includes the complete tensile contribution of concrete and of the retrofit CARDIFRC® strips. The second computational model takes a purely fracture mechanics approach and follows the initiation and growth of the dominant flexural crack that eventually leads to the failure of the retrofitted beams.

Both computational models predict ultimate moment capacity and load-deflection behaviour that are in excellent agreement with test results.

## **INTERFACE MODELLING BY FINITE ELEMENT & FRACTURE MECHANICS OF CARBON PLATES BONDING**

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**Keywords:** Composite materials, concrete, finite elements, theory of cracking, release rate, constitutive laws, repair, reinforcement.

This article concerns the repair and reinforcement of sewerage structures using composite plates. Tests were performed to characterise the interface, using prisms reinforced with pultruded carbon fibre-based plates in different environments (normal, water-saturated, submerged). The prisms were then subjected to four-point bending to study the behaviour of the concrete/adhesive/composite interface and to obtain the intrinsic properties of the materials.

A finite-element analysis was performed to reproduce the behaviour of the reinforced prisms. The results of these numerical calculations were then compared with the experimental tests.

## **CLASSIFICATION AND QUALIFICATION OF COMPOSITE MATERIALS SYSTEMS FOR USE IN THE CIVIL INFRASTRUCTURE**

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**Keywords:** Application, classification, composite materials, qualification, specification, test methods

The growth in the use of composite materials systems for very different applications has signalled the need for more generic guidance in the materials selection, design, application and approval processes. Materials selection can either be prescriptive or performance-based; in the latter case, the performance of the combined system is defined and the testing necessary to verify that performance is prescribed. This paper outlines a performance-based qualification scheme that will enable designers to select FRP materials systems based upon performance requirements. The concept of classification schemes that define the requirements of the individual components of a materials system are also introduced; these requirements are linked directly to quality control procedures for on-

site application, approvals and long-term assessment. The introduction of such qualification and classification schemes, together with new test methods, will provide engineers with greater confidence in the design and use of FRP materials systems.

## **REPAIR AND UPGRADE FOR SHEAR OF RC BEAMS USING FRP FABRICS**

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**Keywords:** FRP, concrete, rehabilitation, shear, beams

The use of Fiber Reinforced Polymers FRP in repair and rehabilitation of reinforced concrete structures is gaining a worldwide acceptance due to their numerous advantages over other repair materials. In this paper, the structural behavior of reinforced concrete beams repaired using Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP) fabrics, was investigated. Five beams of 300×100×1100 mm were designed to assure shear failure, cast, cured and then loaded to failure. Ultimate load, load- deflection relation and crack pattern were recorded for each beam. Beams were then repaired using either CFRP or GFRP. Wraps were epoxy bonded on both sides of beams, except for one beam where the bottom was also wrapped for comparison. Repaired beams were then loaded to failure. Ultimate load and ductility were compared.

It was concluded that the use of either GFRP or CFRP wraps restores and

improves both the load carrying capacity and the ductility of tested beams. GFRP repaired beams demonstrated better results than the CFRP repaired ones. The beam repaired on both sides and bottom showed better load carrying capacity than those where wraps were applied on sides only. Failure of rehabilitated beams was found to be due to debonding and peeling of FRP wraps. The repair method was found to be easy, efficient and less time consuming compared to other conventional repair methods.



# **Theme 2: Concrete + Advanced Composites**

## **Day 3: Concrete**



## MONITORING ALKALI SILICA REACTION IN HOLLOW PILES

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**Keywords:** Concrete, alkali silica reaction, instrumentation, precast piles

Specimens cut from hollow piles were monitored for alkali-silica reaction (ASR) progress. The hollow precast piles were prepared using four different concrete mixes. All mixes have a very low water/cement (w/c) ratio. The piles were prepared using the spin technique and were rapidly cured in a steam room at 70°C for four hours. The ASR progress was monitored by measuring the strain development in the concrete over time. This method is feasible given the recent development in instrumentation technology and the experience gained by many researchers in installing such instruments in real structures. A T-type thermocouple and a strain gauge (Measurement Group EGP-5-350) were installed inside the piles on both sides prior to casting the concrete. After curing, specimens were then cut from the piles and were immersed in a curing tank at 38°C (100°F). Strain and temperature measurements were taken weekly using a wide-range strain indicator device (model P-3500, manufactured by Measurements Group) and a microprocessor thermometer (model HH21, manufactured by Omega), respectively. After 52 weeks, no visible cracks had developed in any of the specimens. Strain in all specimens reached

a plateau at a value of less than 250 mstrain. This measured strain is less than the 550 mstrain measured by the authors on specimens with high alkali-content cement and active silica aggregates, which developed cracks due to ASR reaction after only 90 days of immersion.

## IN SITU MONITORING AND DAIGNOSIS OF REINFORCED CONCRETE MEMBERS IN AN EXPOSURE TEST AGAINST SALT ATTACK

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**Keywords:** Salt attack, chloride penetration, corrosion, acoustic emission, ultrasonoics.

To maintain concrete structures in good conditions and in safety, monitoring and diagnosis against deteriorations are key issues. To inspect environmental conditions and develop a monitoring procedure for the deterioration due to salt attack, an exposure test was conducted at a site constructing the viaduct of Shin-Kitakyushu Airport. Monitoring by acoustic emission (AE) and ultrasonic testing (UT) had been carried out routinely from 1993 to 1999. Results showed a great promise for an applicability of AE technique to monitor the corrosion in reinforced concrete (RC) members. In order to confirm these results and apply to practical monitoring, comparable tests are

performed in a laboratory. Based on diffusion analysis of chloride ions, quantitative nondestructive evaluation for the corrosion of rebars by AE is performed, and a promising procedure for monitoring and diagnosis on the salt damage is proposed.

## **AN ASSESSMENT OF ELECTRO-CHEMICAL CHLORIDE EXTRACTION AS A REMEDIATION TECHNIQUE FOR STEEL REINFORCED CONCRETE**

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**Keywords:** Desalination, electrochemical chloride extraction, corrosion control

Steel reinforced concrete blocks were subjected to chloride extraction after they were dosed with either NaCl or CaCl<sub>2</sub>. All the blocks were then exposed to the elements at the BRE exposure site for a total period of about 6 years. The steel reinforcement was regularly monitored electrochemically to determine its level of corrosion. Core samples were also analysed before and after treatment to determine the chloride concentration profiles. A selection of blocks were cut into smaller steel-containing prisms after 4½ years of exposure and were exposed to controlled laboratory conditions for 6 months while determining the level of corrosion electrochemically. At termination, each steel bar was removed and examined visually. The total weight loss was assessed gravimetrically. The final chloride concentration profile of each prism was also determined.

Results suggested that corrosion was

reduced significantly following chloride extraction but that the primary long-term controlling factor, both for the desalinated and control specimens, appeared to be the level of chloride present at the depth of the steel reinforcement. As, under normal procedures, a proportion of chloride remains after chloride extraction, a significant level of corrosion of the reinforcement, although greatly reduced, is still likely.

## **PROPERTIES OF CONCRETE CONTAINING FURNACE BOTTOM ASH AS A SAND REPLACEMENT MATERIAL**

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**Keywords:** Air permeability, compressive strength, furnace bottom ash, sorptivity, slump

This paper presents the results of an investigation carried out to evaluate the properties of concrete containing Furnace Bottom Ash (FBA) from a thermal power plant in Northern Ireland as fine aggregate. Two test series were used to study different approaches. Series A was designed at fixed water-cement ratios of 0.45 and 0.55, and Series B at fixed slump in the range of 0~10mm and 30~60mm. For both series, the natural sand was replaced with the FBA sand at 0, 30, 50, 70 and 100 percent by mass, and the cement content was fixed at 382 kg/m<sup>3</sup>. The workability, compressive strength, air permeability and water absorption properties were studied.

The results indicated that, at fixed water-cement ratios, with the increase of the FBA sand, the workability increased, the

compressive strength decreased up to 28 days and the permeability increased. However, at fixed slump, the free water needed for the same workability decreased resulting in an increase in long-term compressive strength, but also an increase in the permeability beyond 30% replacement level. The comparison of the results from these two series indicated that the FBA sand has a water reduction effect. Thus, in order to recycle FBA in concrete as a natural sand replacement material, the decreased water demand of the FBA concrete should be taken into account during the mix design phase. Nevertheless, due to the porous structure of the FBA particles, the introduction of FBA into concrete would cause detrimental effect on the permeation properties of concrete beyond 30% replacement.



**Theme 3:  
Buildings, Masonry  
& Civil Structures**

**Day 1:  
Dams + Civil Structures**



## NUMERICAL ANALYSIS OF MULTIPLE DISCRETE CRACKS IN CONCRETE DAMS

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**Keywords:** Concrete dams, multiple cracks, discrete crack approach, minimum load criterion, curvilinear crack propagation, hydraulic loads, uplift pressures

A rigorous analytical procedure for the crack analysis of concrete dams is established using a newly developed numerical technique for analyzing multiple discrete cracks in concrete. A well-quoted scale model of a concrete gravity dam is used to study the cracking behaviors in concrete dams; the numerical modeling involves not only the original single-crack problems but also multiple-crack problems. Employing two different types of numerical models and assuming multiple initial notches of different sizes at different locations along the upstream face of the model dams, various kinds of cracking behaviors are obtained and discussed, focusing on the crack interactions.

## INVESTIGATION OF UNKNOWN TRANSMISSION TOWER FOUNDATION USING NDT

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**Keywords:** Steel tower, foundation, shape identification, nondestructive, elastic shock wave surveying, ultrasonic testing, elastic shock wave surveying in simple exploratory drillholes

There has been a growing need of identifying the shape of a steel tower foundation during construction work in the vicinity of the tower or tower renovation to accommodate increased capacity of power transmission facilities. The authors assessed methods for easily identifying the shape of a steel tower foundation without carrying out any construction work such as the drilling of boreholes. Then, the applicability was determined for the methods for measuring the embedded depth of a concrete foundation by examining an elastic shock wave, measuring the length of the main leg in the footing by ultrasonic testing, and measuring the width of a concrete footing by sensing an elastic shock wave in simple exploratory drillholes (elastic shock wave surveying in simple exploratory drillholes).

## **DEFORMATION ANALYSIS OF BURIED PIPELINE SUBJECTED TO FAULT MOVEMENT**

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**Keywords:** Earthquake pipeline fault beam-shell modelo

Turkey earthquake in 1999 brought severe damage to lifeline engineering, especially water supply. Relative motion of seismic fault resulted to permanent ground displacement, and permanent ground displacement brought large deformation of pipeline crossing the fault for water supply, and pipeline ruptured near fault. The beam-shell model was used to simulate the deformation of pipeline in this paper, and reasonable results were provided.

## **SIMPLIFIED NON-LINEAR ANALYSIS IN RENOVATION DESIGN OF AGING SEWERS: APPLICATION IN SOFTWARE**

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**Keywords:** Sewer, renovation design, separate method, design-oriented software

The current design practice for the renewal of aging RC sewers using the Sewage Pipe Renewal (SPR) method is based on the limit state design concept. For evaluating the load-carrying capacity of aging and

renovated RC sewers, the non-linear FE structural analysis, taking crack behavior into account, is required. Although these solutions obtained could be accurate, the computational procedure is both time-consuming and costly in practice. In this paper, to simplify the solution procedure, a separate method is introduced, which evaluates the individual contribution of reinforcement and that of plain concrete to the ultimate load-carrying capacity of a sewer. The maximum load is then obtained from summing up their respective contributions. Numerical studies with full-scale loading tests on eight aging and renovated test specimens are carried out. The studies show the effectiveness and accuracy of the method in predicting the maximum loads of RC structures. Based on this separate evaluation concept, a design-oriented computing software has been developed. This software contains an automatic mesh-generation function for various types of the cross-sections of sewers. It also has a windows-type input-output feature to facilitate its operation. The software is easy to use and the computational time and cost are greatly reduced.

## **INSPECTION, TESTING AND APPRAISAL OF MISURATA OIL JETTY, A CASE STUDY OF REINFORCEMENT CORROSION**

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**Keywords:** Chloride, corrosion, cover, cracking, delamination, NDT, durability, repair, sounding, structural analysis

Reinforcement corrosion deterioration as well as structural damages due to a ship accident of Misurata Oil Jetty (MOJ) are being investigated.

The executed NDT program included a sounding survey, a rebar cover thickness survey, half cell potential measurements, in addition to core & dust extractions, followed by carbonation and chloride analyses. Two dimensional elastic structural analysis was also performed on the various elements for the purpose of assessing MOJ structural integrity.

A summary of the results of the above works is presented, based on which some conclusions are made and consequent remedial measures are proposed.

## **REPAIRING OF THE ROAD IN LAKE SEDIMENTS SUBSIDENCE ZONE**

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**Keywords:** Culvert, sediments, road

The problem of culvert sinking on the Road M 5 at Bosnia and Herzegovina was the subject of investigation and reparatory design. Two variant solution were elaborate: solution 'a' was based on the rather delicate repair of the existing culvert structures with prefabricated piles introduction, while solution 'b' is a radical one and consisted in the establishing a 12 meters long new bridge. The Investor decided to realise solution 'b' specific in sense drilling piles length in comparison with structural dimensions.

## **REPAIR OF DAMAGED STRUCTURE OF BLENDING BUILDING IN NOVI SAD OIL RAFINERY**

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**Keywords:** Concrete, blast damage, bomb damage, repair, case study

The structure of Blending building in Novi Sad Refinery is a reinforced concrete one-storey skeleton structure, which consists of a system of transverse and longitudinal frames. It has about 3000 m<sup>2</sup> in plan.

It was heavily damaged during bombardment. The direct hits were located in the central part of the building and were followed by intensive fires lasting for hours. Almost all structural elements were damaged.

The repair was conducted according to the damage degree in the structural elements, and the investor's requirements referring to the future production process. It is based on a slightly changed structural solution. Concrete roof structure is replaced with a system of steel trusses and purlins in order to relieve lower structure. As the central truss roof elements span two fields of the original raster, it made the rebuilding of some inner columns destroyed in the bombardment unnecessary. Thus, few columns along the whole height and three columns in the upper floor section were omitted. Due to reduced mechanical properties of reinforced concrete, some of original elements (slabs, beams and columns) had to be strengthened in the floor level.

The adopted repair concept implied the demolition of some structural elements. In order to decrease costs of repair, the number of such elements was reduced to minimum. Still, the amount of demolition work remained large

The paper presents the structural repair design of the Blending building, as well as the demolition design of the part of the structure that was not worth repairing. It describes the procedures of demolition and securing of the part of the structure meant for rehabilitation. Requirements and conditions that determine demolition process are especially stated and discussed. Global repair design of the structure is based on changed structural solutions, which provides relatively low costs of works.

Some characteristic details and structural repair procedures are shown, which are still in progress and they have been completed up to 90% of the schedule.

## **ABANDONED MINESHAFTS AND THE PROBLEM OF DEFINING A REASONABLE 'SEARCH' DISTANCE FOR CONVEYANCING PURPOSES**

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**Keywords:** Mineshafts, geohazard, conveyancing, buildings,

In 1991, an Expert Committee, which included representatives from the British Coal Corporation (now The Coal Authority), the Law Society, and the Royal Institution of Chartered Surveyors, altered the mine search radius (the perceived safe limit around an abandoned mineshaft) from 5 m to 20 m. This radius was selected on the basis of observations in mining areas but is an arbitrary value rather than one based on scientific research. This has increased blight in relation to some houses in mining areas, which, prior to 1991, were not considered to be located 'in the vicinity of' abandoned mineshafts. The problems were mainly related to the perceived hazards and risks associated with shafts. As a direct

result, the owners of some houses experienced increases in insurance premiums, potential house purchasers were dissuaded from buying some properties, and home sellers not only had difficulty in selling their property, but also experienced a fall in value.

In this paper the problems associated with the presence of mineshafts and adits in urban areas are considered and illustrated by a case history showing the effects of mineshaft collapse on one house owner. The paper identifies the mining, geological and environmental factors that influence the style of mineshaft collapses and suggests that new research is needed if the problems caused by the presence of mineshafts are to be managed better in the future.



**Theme 3:  
Buildings, Masonry  
& Civil Structures**

**Day 1:  
Seismic + Blast Strengthening**



## **ADVANCES IN RAPID CONSTRUCTION OF TALL EARTHQUAKE RESISTANT BUILDINGS IN CALIFORNIA**

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**Keywords:** Welded reinforcement grids, BauGrids, concrete reinforcement, automation

Three tall earthquake resistant buildings under construction in California have a new type of reinforcement specified which replaces 1,000 tons of conventional transverse reinforcement. The new reinforcement for ductile concrete shearwalls, and other structural members is called Welded Reinforcement Grid (WRG). One WRG replace many individual hoops and crossties, resulting in saving in labor, materials and construction time. Testing of WRG at five universities and two national laboratories since 1987 has shown that for both normal strength concrete and high strength concrete elements, ductility is improved when WRG is used as transverse reinforcement. Results of this testing and new building systems developed with WRG is reported.

## **DEVELOPMENT OF A MULTIHAZARD RESISTANT PANELIZED BRICK VENEER WALL SYSTEM**

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**Keywords:** Brick veneer, seismic & impact resistance, masonry wall panel

Two types of backup wall are commonly used with masonry veneer wall systems: concrete block masonry and light gauge steel stud. Steel stud backup walls have inherent out-of-plane flexibility compared to masonry backup walls, and this can lead to cracking of the brick veneer wythe under wind loads. As a consequence of brick veneer cracking, additional moisture can seep through the cracks (moisture can get behind the walls by means other than wind induced cracks as well), and result in rusting and deterioration of masonry ties. On the other hand, the performance of older brick veneer walls in some of the past recent earthquakes has been poor primarily due to lack of horizontal and/or vertical movement joints or their deficiency because of the closure of the gaps under shelf angles with mortar.

This paper introduces a panelized brick veneer wall system that is designed with seismic isolation connections to avoid the participation of brick veneer wall in the in-plane lateral load resistance and thus prevent its failure. Moreover, the proposed system is designed with the use of heavy gauge steel studs to stiffen the backup wall for out-of-plane performance under wind loading conditions and out-of-plane seismic loads. Preliminary design of the proposed system, including the optional strengthening

for impact resistance is discussed in the paper. Results of the finite element modeling and analysis of the wall system are also presented. The proposed wall system is suitable for quick erection as it is prefabricated, and it can be used for new designs as well as retrofit and replacement situations.

## **BLAST RESISTANT MASONRY WALLS – RETROFITTING WITH ADVANCED COMPOSITE MATERIALS**

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**Keywords:** Masonry wall panels, blast loading, dynamic analysis, single degree-of-freedom, advanced composites, multi-linear resistance function

A mathematical modelling technique is presented that can be used to predict the load carrying capacity of a masonry wall panel either with or without advanced composite materials attached to its front and rear faces.

The development of a multi-linear resistance function is outlined in detail. This demonstrates the massive potential increase in strength of a masonry wall that can be produced by attaching FRP materials to it. Without FRP, the response of a masonry wall can be characterised by a small elastic deformation followed by a relatively large deformation created during the formation of a collapse mechanism.

With FRP, the response of the wall is characterised by several distinct phases. The first phase involves a small wholly elastic deformation. The second phase is a relatively large pseudo-elastic response in which the depth of tension cracks progressively spreads through the depth of

the masonry. The third is a non-linear response in which the wall thins due to compressive failures of the masonry and buckling of the FRP on the compression face.

The dynamic response of the masonry wall is analysed using the Central Difference time-integration scheme; idealising it as a one degree-of-freedom system. To enable it to be validated, an analysis of the equivalent MDOF system is carried out using the Mode Superposition Method.

## **FUZZY LOGIC ASSESSMENT OF SEISMIC CAPACITY OF EXISTING BUILDINGS**

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**Keywords:** Seismic, capacity, existing buildings, fuzzy logic

Damage assessment involves the difficulties of defining, assessing and modeling the variables involved, as well as handling uncertainty. This paper presents a methodology for the damage assessment of RC structures based on fuzzy logic, which is utilized to handle linguistically vague information and the imprecision involved. In the proposed system, the variables are defined in five stages up to the final assessment of the damage factor. The first level defines the three fundamental variables of a structure, the 'behaviour factor', the 'regularity' and the 'deterioration' of the structure based on variables that define, as precise as possible, its characteristics. At the next level, these three variables are used as input data in a

new rule-based system with other structure and soil parameters; in order to define four generalized variables. These are: 'Earthquake hazard', 'Structural strength', 'Structural form' and 'Construction characteristics'. Finally, from these four variables we assess a damage rate for any structure. The system is tested by comparing the damage value obtained by the program, to the one diagnosed by the experts in real life buildings. A case study is provided to illustrate the efficiency of the objective of the study.

### **COMPOSITE SEISMIC RETROFIT AND ADVANCED DISTRIBUTED FIBER OPTIC MONITORING OF AN HISTORICAL BUILDING IN FOLIGNO (ITALY)**

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**Keywords:** FRP, seismic, retrofit, monitoring, masonry

Fibre reinforced polymers (FRP) are gaining increasing popularity for upgrading, repairing and rehabilitation of existing structures thanks to many interesting advantages against traditional structural materials. Composite applications in civil engineering, that range from embedded non-metallic reinforcements to externally bonded strengthenings, are generally much more recent than other FRP applications, for this reason several questions regarding the assessment of the strengthening effectiveness as well as long term behaviour

and durability of the application remain still unsolved. Elmi-Pandolfi building, an historical structure dated 1600 that was seriously damaged in the earthquake of 1997, has been repaired and retrofitted including carbon FRP (CFRP) strengthenings externally bonded to some vaults and walls. Since an innovative strengthening technique intended to lock-out the possible failure mechanisms with CFRP tapes was used for the vaults, its effectiveness has been experimentally proved through dynamic testing. Furthermore a fibre optic monitoring network based on distributed Brillouin strain sensing was embedded in the CFRP strengthenings in order to evaluate the durability of the application especially in case of further seismic shocks. In this paper the dynamic tests carried out on the biggest of the repaired vaults and preliminary experimental tests characterizing the Brillouin distributed sensing performances are presented.

### **PREDICTION OF DAMAGE AND SEISMIC BEHAVIOUR OF RC BUILDINGS USING PUSHOVER ANALYSIS**

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**Keywords:** Assesment, damage, earthquake, pushover analysis, seismic

The prediction of damage to, and the seismic behaviour of, an existing reinforced concrete four-storey building had been investigated in the past at the ELSA in ISPRA using a pushover analysis. The building was designed and built in accordance to the design and practice that prevailed 40 to 50 years ago in the countries

of Southern Europe. Several experimental tests have been applied to this building. The tests represented earthquakes with an increasing return period and intensity and were similar to those experienced in South European countries. These experiments resulted in the collection of data regarding the type and mode of the development of the expected damage due to the input of seismic excitations. The aforementioned results are compared to the equivalent results of the inelastic static pushover analysis and discussed with reference to the damage that the building experienced following the experiments. The extent of the building's damage and its structural weaknesses were confirmed by the pushover analysis. This revealed the development sequence of plastic hinges that indicated the inelastic behaviour of the building.

## **METHODOLOGY FOR SEISMIC DESIGN OF ENVIRONMENTALLY-SENSITIVE REINFORCED CONCRETE STORAGE TANKS**

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**Keywords:** Concrete, seismic design, environmentally sensitive

The safety of storage tanks containing environmentally hazardous liquids during earthquakes far exceeds their mere economic values. For reinforced concrete tanks, in particular, serviceability (crack and leakage control) becomes the prime design consideration. Available design methods for such tanks are based on simplified approaches for the evaluation of both the hydrodynamic loads exerted on the tanks

due to the seismic event, and the stresses induced in the tank shell which is often assumed to be rigid. It should be noted that large hydrodynamic forces may result in highly stressed regions of the tank leading to severe cracking and leakage.

The first part of this study provides a realistic assessment of the induced hydrodynamic loads. Pressures resulting from all three components of an earthquake motion (two horizontal components plus a vertical component) are taken into consideration. These are super-imposed on the hydrostatic pressure to evaluate the spatial distribution of the overall pressure. For design purposes, these pressures are presented in the form of mechanical models that can be easily adopted in practice.

The effects of the seismically-induced hydrodynamic loading on reinforced concrete tanks were further evaluated by the finite element method. The finite element package (ABAQUS) was used to perform a parametric study. An axi-symmetric shell element model with asymmetric deformation was employed. Stresses and displacements were computed for a variety of parameters such as the tank radius, liquid height, shell thickness, and boundary conditions, under different earthquake loads characterized by peak ground accelerations and frequency contents.

Finally, design aids based on the results of the parametric study were devised for a systematic and efficient processing of the seismic design of reinforced concrete tanks by practicing engineers.

**Theme 3:  
Buildings, Masonry  
& Civil Structures**

**Day 2:  
Masonry Structures**



## **CORROSION: ASSESSMENT AND REPAIR – THE USE OF METAL WITHIN MASONRY WALL SYSTEMS OF EARLY SKYSCRAPERS**

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**Keywords:** Corrosion, masonry, metal

Early skeletal frame buildings utilized numerous exterior cladding materials. Brick, terra cotta, and stone were all used, with economics frequently dictating both the location and quantity of each material. Lateral and gravity anchorage of these masonry cladding materials typically utilized metal elements. As the building envelope aged, the embedded steel components were increasingly exposed to moisture resulting in corrosion. The distress resulting from the corrosion of embedded steel components led to the demise of many of the early skyscrapers.

This paper will review the types of metal used in skeletal frame construction over the past 125 years. A review of life-cycle issues of embedded metal components will be presented. This will include a discussion of corrosion potential and corrosion related distress as well as a review of methods of corrosion remediation and prevention within the construction industry.

## **SEISMIC STRENGTHENING OF UNREINFORCED THICK MASONRY WALLS USING POLYMER COMPOSITES**

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**Keywords:** FRP, construction, cyclic shear tests, unreinforced masonry walls

The paper presents the results of an experimental investigation on the cyclic shear behavior of thick brick walls reinforced with unidirectional E-glass/epoxy laminates. In this study, three large-scale tests were conducted. The wall specimens were fabricated from recycled bricks obtained from old buildings, to simulate the actual material properties of existing walls in historical masonry structures. For the same reason, mortar used in building the walls was Type-O mortar with low strength properties. Testing protocols were based on procedures specified in the Acceptance Criteria for Concrete and Reinforced and Unreinforced Masonry Strengthening Using Fiber-reinforced, Composite Systems (AC125-2001) by the International Conference of Building Officials Evaluation Services (ICBO-ES). Initially, the control specimens were subjected to a series of full-reversed cyclic loads until failure. Same loading history was used in evaluating the retrofitted wall specimen. The wall specimen was reinforced with a single ply of unidirectional E-glass/epoxy composites parallel to the applied shear load at one side of the wall. Strain gages and electronic string potentiometers were used to capture the critical strain and deflection information,

respectively. Test results indicated that the use of a single laminate applied on only one side of the wall has resulted in an appreciable increase to both stiffness and strength of the retrofitted wall. Plots between loads and displacements for the tests are provided, in addition to tables highlighting peak loads, and displacements corresponding to peak loads.

## **STRUCTURAL RESTORATION OF A VERY OLD MASONRY LIGHTHOUSE**

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**Keywords:** Masonry, restoration design, FEM model

In this work a restoration design of very old lighthouse is shown, it has been drawn on modelling masonry as a continuum with a commercial FEM software.

Through the visual analysis it is clear that four of nine brickwork barrel vaults were very warped on a side. The bricks were injured and showed any slip between them. This static damage of vaults caused a loss of vertical alignment beginning from the second level of the West and East façades.

## **RECONSTRUCTION AND REINFORCEMENT OF 'SI KU MEN' BUILDINGS**

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**Keywords:** 'SI KU MEN' building, reconstruction, brick-timber, concrete, structure

It is a new task for the architects and structural engineers that preservation of the richness in historic architecture and the new development of a city. The reconstruction project is even more complicated than a project for new building as the original layout and the joint function have to be taken into consideration. In the text, a representative example of 'Shi Ku Men' building reconstruction is selected to introduce how architecture and structure were coordinated and how preservation of the old buildings was achieved, along with the new innovative concept.

## **OUT-OF-PLANE BEHAVIOR OF URM WALLS STRENGTHENED WITH FRP BARS**

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**Keywords:** Cracking, glass fiber, flexural strength, reinforced polymer laminates, unreinforced masonry

For the retrofitting of the civil infrastructure, an alternative to Fiber Reinforced Polymer (FRP) externally-bonded laminates is the use near surface mounted (NSM) FRP bars. This technique consists of placing a bar in a groove cut into the surface of the member being strengthened. The FRP bar may be embedded in an epoxy- or cementitious-based paste, which transfers stresses between the substrate and the bar. The successful use of NSM FRP bars in the strengthening of concrete members has been extended to unreinforced masonry (URM) walls, one of the building components most prone to failure during a seismic event. This paper presents the results of an experimental program on the flexural behaviour of URM walls strengthened with (NSM) FRP bars. A total of fifteen URM walls reinforced with NSM FRP bars were tested. The specimens were strengthened with different amounts of reinforcement to observe their improved performance and the mode of failure. The influence of the bar shape (i.e. circular vs. rectangular), dimension of the groove and type of embedding material (i.e. epoxy or cementitious-based paste), were studied.

Two types of FRP fabrics, glass (GFRP) and carbon (CFRP), were used as externally bonded reinforcement to provide the benchmark. Strength and pseudo-ductility of URM walls were significantly increased by strengthening with FRP bars. Based on experimental evidence, the paper provides criteria that can be used in the development of design guidelines.

## **NDT ULTRASONIC METHOD FOR ANCIENT STONE MASONRY DIAGNOSIS IN CAGLIARI (ITALY)**

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**Keywords:** NDT, ultrasonic testing, masonry

The need to keep in good health buildings of any historical relevance, as well as their recovery from injuries, strongly supports the development of non destructive methods for strength evaluation and decay degree measurement in ancient stone masonry. Thus the aim of this study was to evaluate an ultrasonic method as a technique for masonry diagnosis. We focused our attention on limestone masonry, quite diffused in the ancient centre of Cagliari (Italy).

We studied how signal travel time (TT) and signal amplitude attenuation (AA) correlate with mechanical characteristics of the material.

With the aim to calibrate acoustic parameters with strength and quality we tested limestone specimens of variable size and quality. Then we applied the method to a full scale masonry model with various known anomalies inside.

Results show that integrate analysis of ultrasonic signals TT and AA is a reliable and suitable technique in determination of mechanical characteristics and anomalies of limestone masonry.

## THE SHEAR STRENGTH OF FIBER REINFORCED MASONRY WALLS

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**Keywords:** Out-of-plane masonry walls, fiber reinforced composites, shear strength

This paper investigates the shear strength of masonry wall panels reinforced with fiber-reinforced polymer overlay (FRP) composite systems under out-of-plane loading conditions. An experimental study coupled with analytical model was developed to evaluate the out-of-plane shear strength of the FRP reinforced masonry walls. The experimental study involved eighteen 2'x3'x8' (900x600x200 mm) walls reinforced with FRP on one side. The analytical model is based on the theories of elasticity and fracture mechanics. The presented analytical study accounts for the shear contribution of the masonry units and the fiber overlays.

The results indicated that the shear capacity of the retrofitted system increased with the thickness of the FRP used. Based on the analytical study, guidelines are presented for selecting the cross sectional area of an FRP retrofitting system for any specified shear strength.

## EXPERIMENTAL STUDY OF THE STRUCTURAL BEHAVIOUR OF DAMAGED MASONRY WALLS CONSOLIDATED BY DIFFERENT REPAIR TECHNIQUES

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**Keywords:** Masonry, walls, seismic, damage, repair

The paper describes the experimental study carried out at Cedros, in Faial Island, Azores, aiming the characterization of the behaviour of masonry buildings damaged by the Faial earthquake of July 98.

The experimental program consisted in *in situ* dynamic and static loading tests carried out on building walls with different typology and different repair techniques. Two techniques were considered: grout pouring filling in the existing empty spaces and steel mesh, covered with mortar, applied to both sides of the walls. The tests were performed on the original and the consolidate walls aiming the evaluating of the efficiency of the repair techniques on the seismic response.

Physical and mechanical properties of the masonry walls, as well as of stone and mortar constitutive materials and cement grout used in repair, were determined by *on situ* and laboratory testing.

Testing methodology, loading setup and instrumentation, adjusted to the limited technical means locally available, and deflection measurements are included.

The work undertaken meant to assess capabilities in predicting structure ductility as well as guidelines for the definition of well-adjusted rehabilitation and strengthening criteria of Faial buildings.

## **OUT-OF-PLANE BEHAVIOR OF URM WALLS STRENGTHENED WITH NSM GFRP BARS**

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**Keywords:** GFRP bars, infill masonry walls, masonry rehabilitation, flexural strengthening, embedding materials

Unreinforced masonry (URM) walls are prone to failure when subjected to out-of-plane loads caused by earthquakes or high wind pressures. In this context, fiber reinforced polymer (FRP) materials may be a solution to solve or lessen the effects of this overloading. This paper describes an experimental program dealing with the flexural behavior of nine concrete URM walls strengthened with glass FRP (GFRP) twisted sand-coated bars and subjected to out-of-plane loads. The reinforcement was placed vertically in different amounts and spacing. Two different embedding materials (epoxy-based paste and latex modified cementitious paste) were used to encapsulate the bars. This research allowed to compare different behaviours and failure modes of strengthened URM walls by changing the parameters described above. Design guidelines are also provided.

## **EXPERIMENTAL INVESTIGATION ON BOND BETWEEN FRP SHEETS AND NATURAL MASONRY BLOCKS**

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**Keywords:** FRP sheets, masonry, bond, stones

The use of FRP (Fiber Reinforcing Plastic) plates or sheets for strengthening masonry structures is gaining an increasing success due to many advantages with respect to the use of traditional steel plates. In particular, the low weight, the absence of electrochemical corrosion, the easier placing in cast, make composite reinforcements more attractive.

One of the most important aspects when FRP plates or sheets are glued to masonry elements is the bond between the reinforcement and the support that influence in great extent the effectiveness of the technique. In fact, a premature and brittle failure at the interface, known as delamination, can occur compromising the global structural response.

Bond performance between FRP sheets and concrete has been widely studied in the last decades, but few researches have been still carried out on the use of composite materials in masonry structures. Further investigations should be addressed on this topic considering the increasing need of strengthening masonry structures that in many cases represent a monumental and historical heritage.

The paper is devoted to the experimental analysis of bond performance between FRP sheets and masonry varying some significant parameters, as the bonded length, the reinforcement system, and the kind of masonry. Obtained results are presented and discussed. Finally the calibration of a bond-slip law has been addressed on the basis of obtained experimental results.

### **A NOVEL COMBINATION OF NDT-METHODS FOR ASSESSMENT OF MOISTURE CONDITIONS OF MASONRY – A CASE STUDY OF THE BERLIN ZEUGHAUS**

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**Keywords:** Microwave method, endoscopy, non-destructive technique (NDT), numerical hygrothermic simulations, masonry

The moisture condition of solid brick and sandstone walls of historic buildings may be examined and monitored non-destructively and effectively by means of a novel combination of test methods which provide useful information on planning and monitoring rehabilitation and maintenance measures.

Results are detailed of an interdisciplinary research project of BAM on the moisture balance in the main cornice area of the Berlin Zeughaus. The main part of the investigations was carried out in 1994 and 1995. The quality of the prognosticated drying out process has been verified annually by means of measurements up to now. The depth-resolved local moisture determinations were accomplished with a microwave method developed by BAM.

The moisture profiles revealed excessive moisture in the building element and reflected the slow drying process. Additionally, endoscopic examinations and chemical and physical analyses of miniature samples were carried out as well to help interpret the results. Hygrothermal data could be calculated from the quasi non-destructive tests and the parameters determined by the laboratory tests. Based on the 1995 measured moisture profile in the building element, the predicted simulation calculation indicated that a relatively long drying process must be anticipated. Therefore the planned waterproofing sealing can at the earliest be applied to the surface of the building element in 2005. The good correlation of predicted and measured moisture profiles of the past years (including 2002) demonstrates the high quality of the new combination of test methods.

### **FRP STRENGTHENING AND REPAIRING OF MASONRY UNDER COMPRESSIVE LOAD**

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**Keywords:** FRP, brick masonry, load bearing members, confinement

Strengthening of masonry structures with FRP rods embedded into bed joints is an innovative technique investigated up to now only in few research works, where the

objective was shear or flexural improvement (Tinazzi & al., 2000).

As most of the masonry structures are load bearing and their static problems are hence related to high compressive stresses, the present work focuses on confinement of masonry members.

Depending on the actual condition of the structural member, the FRP confinement can be either a strengthening or a repairing technique. After seismic events or when dealing with historical masonry structures, the application of confining reinforcement is usually a balance of the two approaches, which aims to re-establish safe conditions under new actions. In order to simulate those different cases, in the present research the evaluation of the technique involved also pre-damaged masonry walls subjected, after reparation, to monotonic and cyclic axial compressive loads.

An extensive selection of materials and reinforcement configurations was preventively performed, pointing out the mechanical parameters affecting the anchoring strength and effective length. Particularly, studies on bond were carried out considering the different stress conditions under which a masonry member can stand, for example, at the time of the application and under severe actions.

Further research could be developed to validate the repairing effectiveness of masonry assemblages under long-term sustained load, which is the typical condition of bearing members of historical masonry structures as towers, bridges and pillars.



**Theme 3:  
Buildings, Masonry  
& Civil Structures**

**Day 2:**

**Timber**



## **FRP REINFORCEMENT OF WOOD ELEMENTS UNDER BENDING LOADS**

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**Keywords:** FRP, wood, bending loads

This paper presents a study on the reinforcement of existing wood elements under bending loads through the use of FRP materials. First, an analytical investigation was conducted on the behavior of a generic FRP-reinforced wood section. This study, in turn, led to a numerical procedure based on non-linear wood properties, suitable for application in the design of FRP reinforcement of old, pre-existing wood beams under differing configurations of intervention layout and materials applied. At the end of this paper results of an experimental campaign are presented and used for comparison with the numerical procedure.

## **TROPICAL TIMBER ROOF STRUCTURE IN AMAZONIA**

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**Keywords:** Timber, roof, tropical, timber

In Brazil, excluding conventional structures for residential roofs, wood is very little used as an engineered structural element, in spite of the availability of over 2500 different

species catalogued in the Brazilian Amazon alone. In the developed countries, engineered wood structures are largely used in diversified constructions, such as, schools, churches, commercial and industrial buildings, residences, pavilions, highway and railway bridges, towers, theater screens, ships, military and marine installations.

The concept of a large span wooden roof structure with an attached ceiling is idealized for construction in tropical climates. A glued-laminated (glulam) beam system with mixed tropical hardwoods is used for roof structure dictated by architectural and engineering considerations. This roof structure is part of a project for the construction of a 500-seat auditorium in Manaus, Amazonas, Brazil. The roof structure was developed using computer-aided design in order to achieve an optimized construction system. The project uses two 19.50 m and two 16.85 m long rectangular glulam beams around the perimeter supporting the roof structure. It is a 4-bay roof structure with a 22° slope, spaced glulam beams converging to two mid points, and a 1 m overhang. The roofing material is composed of regularly spaced glulam joists; T&G wood panel ceiling; asphalt sheet; and clay roofing tiles. The complete roof structure and its metal connections are modeled, analyzed, and designed with a finite element program.

## **REHABILITATION OF TIMBER STRUCTURES BY NEW MATERIALS AND CONNECTORS**

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**Keywords:** Timber structures,  
rehabilitation, mixed structures,  
connectors, innovative materials

Among the various techniques for strengthening the existing timber structures, the execution of 'composite' or 'mixed' structures is usually proposed as an effective restoration method to make up for various static deficiencies, such as material decay from biological attack, damage, and poor resistance and stiffness of elements, or to adapt the existing structural characteristics to new functional needs. Such interventions are also in optimal accordance with the current state of the art of the research and with the normative requirements for the design and the execution of works on ancient load bearing timber structures.

**Theme 3:  
Buildings, Masonry  
& Civil Structures**

**Day 3:  
Building Inspection + Repair**



# DIGITAL DATA CAPTURE AND AUTOMATIC REPORT GENERATION FOR STRUCTURE INSPECTIONS

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**Keywords:** Electronic data capture,  
structure inspection

The potential benefits which may be obtained by using digital data capture techniques for structure inspections are well recognised by many structure managers. The immediate benefits include a reduction in reporting time and hence cost without loss of quality, whilst added value can be obtained from the generation of useable data, derivation of management-level information and the capability for inspection teams to work remotely from the office.

Similar technologies have been used for a number of years in the highways sector and in other industries. However the difficulties of successfully implementing a system for structures inspection has until now prevented its widespread adoption, although a number of organisations have undertaken trials of various systems.

This paper provides a case study of a contract carried out for Infracore BCV Ltd. It examines the perceived difficulties and the techniques used to overcome them, and provides a critical review of the factors which contributed to the success of the system.

# RELIABLE MONITORING METHODS; ASSESSMENT CRITERIA AND RESULTS

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**Keywords:** monitoring; reliability; work  
process

Various methodologies are available in order to implement risk based maintenance of civil structures. In all methods, a prediction of the condition with time needs to be realized. The reliability criteria for predictions that need to be met apply to both technical and organizational aspects:

- Organizational: a reliable overview of the actual use (like type of traffic, axle load distribution etc) needs to be established in order to determine the possible deterioration mechanisms. Furthermore, the deterioration rate to be expected needs to be matched with the intensity of investigations.
- Technical: the adequacy of the NDT methods used for the deterioration mechanisms needs to be assessed prior to the actual investigation of the situation.

The paper discusses the questions that need to be answered in order to establish an adequate and reliable monitoring method. These effectivity checks are based on the HERMES study (a Dutch acronym for 'the rational monitoring and evaluation system), a Delft Cluster initiative dedicated to the rational approach of a monitoring method within a maintenance or research organization.

Characteristic features of monitoring methods such as the probability of detection and the accuracy need to be determined prior to the actual application. The

properties of a database tool incorporating these performance characteristics will be discussed and illustrated by means of cases from practice.

## **ZONING DETERIORATION AND PINPOINTING DEFECT OF RC STRUCTURE BY COMPOUND METHOD OF NATURAL POTENTIAL AND IMPACT-ACOUSTIC TECHNICIS**

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**Keywords:** RC structure, reinforcement, corrosion, half-cell potential, zoning, external impact-acoustic method, non-destructive testing, pinpointing area, normal distribution

It is a worldwide problem to build safer reinforced concrete (under-mentioned RC) structures on reflection of the great Hanshin earthquake disaster in 1995, Japan. The researches on the durability and the earthquake proof have advanced and the various countermeasures for these have been proposed. This paper deals with the

specification of deterioration zones and its reliance, by using an external impact-acoustic detector, newly developed, which enables us to examine nondestructively the corrosive state of the inside of a concrete structure, and furthermore the verification with the natural potential method. The main experimental results concerning the building used in common are as follows:

(1) The macroscopical corrosive degree of the RC structure can be evaluated by measuring the natural potential by means of the  $\text{CuCuSO}_4$  half cell and the effectiveness of the corrosion map. (2) 'The external impact-acoustic method' can specify precisely the corrosive parts of reinforcement without the least damage on the RC structure, although the judgment of the corrosive grade is difficult; so, this disadvantage must be covered by using the natural potential method at the same time. (3) The relationship between the natural potential method and the external impact-acoustic one is quantitatively analyzed concerning an existing building.

## **COMMUTED SUM FOR STRUCTURES**

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**Keywords:** Structures, life cycle costing, refurbishment

During the life of a structure, maintenance costs are usually incurred. Furthermore if the structure is required to be rebuilt then renewal costs will be required also. The basis for calculating these costs is derived from the theory of *life cycle costing*. This is also sometimes referred to as *whole life costing*.

This paper is specifically concerned with the cost required to be calculated when a new or old structure is handed over to a respective authority or company for adoption.

**TISBO: AN INFRASTRUCTURE MAINTENANCE MANAGEMENT SYSTEM, INTERGRATING INSPECTION REGISTRATION & MAINTENANCE MANAGEMENT**

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**Keywords:** Infrastructure, bridges, roads, management, inspection, integration, registration

In order to practice ‘output management’, a more transparent and balanced determination process and a higher quality of justification for nationally desired maintenance budgets was required by government. Output management aims at allocating and justifying resources in relation with social demands or desired performance. Integrating functional, economical and technical considerations into a standardised and transparent management process, the Dutch Ministry of Transport, Public Works and Water Management (Rijkswaterstaat) is in the last stages of developing an Infrastructure Maintenance Management System (IMMS), named TISBO. This computer program integrates inspection registration and maintenance management, producing rationalized and justified short and long term maintenance programs and required maintenance budgets on a local, regional and national level in a controlled and transparent fashion.

**CON REP NET – A THEMATIC NETWORK ON PERFORMANCE BASED REHABILITATION OF REINFORCED CONCRETE STRUCTURES**

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**Keywords:** CON REP NET, thematic network, rehabilitation, reinforced concrete, structures

With over 50% of Europe’s annual construction budget being spent on rehabilitating existing structures, the owners of buildings and infrastructure now require greater certainty in the performance of rehabilitated concrete structures in order to manage their assets more effectively. This has generated a requirement for industry to deliver more durable and effective repairs to concrete structures.

To help address these issues, a thematic network on the performance based rehabilitation of reinforced concrete structures has been established, known as CON REP NET. This European-funded network was launched in Madrid in February 2003. It aims to improve the performance of rehabilitated concrete structures by looking at past, present and future circumstances.

Information about concrete durability and rehabilitation issues will be collected from industry and research. Problems and barriers to achieving durable rehabilitated concrete structures can then be identified and new avenues for industry and researchers to pursue can be proposed.

This paper describes the objectives of the network, how it will be delivered, and how members will participate.

## **STRUCTURAL ASSESSMENT AND REPAIRS OF A 34-YEAR OLD FOOTBALL STADIUM**

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**Keywords:** Stadium, condition survey, assessment, field observation, destructive assessment, sampling, dynamic vibration, spectral dynamic analysis, rehabilitation

This paper describes the assessment of a 34-year old football stadium prior to rehabilitation. The results from stadium's initial visual inspection showed that overall main structure members had signs of distress from reinforcement corrosion. A detailed investigation was performed and it was divided into five major tasks: documents review; field inspection and condition survey; sampling and material testing; structural evaluation; and finally identification and assessment of rehabilitation alternatives.

## **PRELIMINARY STUDY OF THE CARDINGTON CONCRETE BUILDING UNDER A COMPARTMENT FIRE**

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**Keywords:** Structural assessment, concrete building, fire test, numerical modelling

Recently a fire test was conducted in a ground floor compartment of the statically loaded, seven storeys- high European Concrete Building (ECB) at Cardington. The fire compartment contained a fully

exposed high strength concrete column in the centre, with similar but partially exposed columns on the periphery. The first floor slab, which formed the ceiling of the fire compartment, was of 'normal' strength concrete. The post-fire assessment of the building was carried out using visual observation and selected non-destructive test methods. Also a preliminary study of the whole-building behaviour under fire conditions was carried out using non-linear finite element analysis. The analyses included the behaviour of the building in case of central column failure and the behaviour of this column with the progress of the fire. This paper presents an overview of the ECB, the fire test, and some results from the preliminary non-linear finite element analyses.

## **REPAIR OF STRUCTURES USING PRESTRESSING CABLES ROUTING IN FUNCTIONAL DIRECTIONS**

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**Keywords:** Post-tensioning, masonry, arches, transversal and vertical cables, drilled substituted cable ducts

By post-tensioning we can achieve improvement of damaged structures, particularly their stability and efficient redistribution of the internal forces. There are described vertical and transversal cables repairing damaged historical constructions. Cables are made of monostrands positioned into substituted cable ducts.

## IMPROVEMENT OF STABILITY OF AXIALLY LOADED STEEL MEMBERS

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**Keywords:** FRP, axially loaded, steel, members, strengthening

The need for strengthening and retrofiting is well known and extensive research is going on in this field. The reasons for strengthening and retrofiting are numerous: increased loads, changes in use, deterioration, and so on. In recent years, the use of Fibre Reinforced Polymer (FRP) for strengthening has shown to be a competitive method, both regarding structural performance, and from economical aspects. Extensive research has been carried out in this field. However, most of the research has been undertaken on concrete structures and for confinement, flexural, and shear strengthening. Limited research has been carried out on steel structures strengthen with FRP, and to the authors knowledge, no research on axially loaded steel members has been presented. However, this paper presents axially loaded steel members strengthened for increased load and improved stability. The topic is studied theoretically and through laboratory tests. The theory is based on a numerical FE-analysis. Carbon and Aramid fibre reinforced polymers have been used to strengthen the members. The tests have been undertaken on full-scale specimens, non-strengthened, for reference, partially strengthened and fully strengthened.

## APPROACH TO REPAIR STRATEGY OF REINFORCED CONCRETE STRUCTURE

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**Keywords:** Concrete, corrosion, damage, inhibitor, reinforcement, repair system, quality control

Reinforced concrete structures damaged by reinforcement corrosion could be repaired with inadequate materials and procedures, despite great expense. Therefore, the decision for a repair strategy of reinforced concrete structures is of huge economic and technical significance.

In this paper the systematic approach to the repair of the reinforced concrete structure damaged by reinforcement corrosion is proposed. The approach consists of a number of separate activities such as diagnosis, repair project, realization, quality control, and maintenance. The steps in the application of repair system with migrating corrosion inhibitors are described in the detail. The requirements for the each step are suggested. The quality control in three stages is also proposed.

## **STRENGTHENING OF HIGH-RISE BUILDING, BEACH RESORT, & DOMES USING FRP**

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**Keywords:** Repair, FRP, concrete, domes, buildings

The objective of this paper is to present some of the real life applications of fiber reinforced polymers (FRP) in Egypt. The authors of the paper have recently used carbon fiber reinforced polymers (CFRP) with great success to repair several types of structures, which include hotels, administrative buildings, and historical structures. This paper will provide a brief summary of some of the projects repaired or strengthened using CFRP.

## **PROBLEMS IN ECCLESIASTICAL BUILDINGS RESULTING FROM MEDIEVAL BURIAL PRACTICES**

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**Keywords:** Human burials, medieval churches, masonry construction, foundation problems

Burial of human bodies within English churches was accepted practice until sometime in the 14th Century when it was realised that the smell of naturally degrading

human flesh was creating a nuisance and a health hazard. For religious reasons, bodies were stacked as tightly as possible to fill every available space inside churches, sometimes at depths up to about 3 metres below ground level. Walls and columns were frequently undermined from the inside and it is not surprising in modern times, that close proximity to burials sometimes creates problems of overall stability for medieval masonry construction forming ecclesiastical buildings. This cause and effect has been identified in two case studies: Brancepeth Church and Lamesly Church, both in County Durham in North East England.

This paper describes the practice of medieval burials, the effects of these on masonry walls, modern methods of identifying the presence of human remains, and solutions to such problems when they are encountered. It will be of interest to those involved with construction at or below ground level in ecclesiastic buildings or investigating the unexpected movement of walls within old churches and cathedrals.

## **HIO-TECHNOLOGY AS A PROTECTION FROM CAPILLARY MOISTURE OF BUILT HERITAGE OF VOJVODINA**

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**Keywords:** Capillary moisture, repair, horizontal hydro isolation, settlement, wall mass stabilisation

The aim of the work is to present the experience in the work with HIO technology by means of which many monuments of culture are saved from destruction with capillary moisture. Due to this fact in this work the technical solution of HIO technology is described as well as the reasons because of which it was developed. The experimental results, which followed its development, will be shown too. The analysis of the shown examples which are followed in the longer time period presents the effectiveness of this method in protection of the construction heritage, regardless of the sort of material of which the object was built.

Hio-technology was chosen in reconstructive curing and conservation of structures with massive walls, primarily stone walls, but also walls made in varied building materials. It presumes the application of two different methods: the classic and the new method. The new method uses a high performance machine

with diamond tools. The cuts are injected with a special liquid filling developed specially for the purposes of Hio-technology. Through this liquid filling, HIO/Master Barriers are inserted one after another, to form the waterproof barrier and achieve horizontal hydro isolation, and their vertical fins take on themselves the complete load of the superstructure.

The whole process and the results of HIO-technology are presented on the several examples, cultural monuments made in different building materials.

## **REPAIR OF INCREASED VIBRATION LEVEL OF POWER SAW FOUNDATION IN INDUSTRIAL ZONE IN PANCEVO**

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**Keywords:** Vibrations, repair, frequency, stiffness, mass, anchor

The foundation of the power saw (ESTERER type SS 710 S) has dimensions in the base 6x4m and the deck is 2.0m thick. The upper edge of the footing is lowered by 1.95m in relation to the neighbouring ground, and it is surrounded by reinforced concrete walls leaning on the strip foundation so that the space between the walls and the footing is narrow.

Due to an increased level of vibrations in the building of Gran Export which is 335m away from the power saw, the vibration regimen of the power saw and its influence on environment was investigated according to ISO 10816-3&6:1995 for both power and operational part, while the dynamic state of the footing was examined in accord with the requirements of DIN 4150-3:1995. As boundary vibration values were obtained through the measurements, the Employer decided to carry out a repair to reduce these vibrations.

Two solutions of the repair were considered. The first was the cutting of vibration waves by placing an obstacle in the form of a diaphragm wall between the vibration source and the Gran Export Building. The second solution, the vibration reduction on the very foundation, was cheaper and it was realized.

For the analysis of the current condition, the mathematical model of the foundation was used and processed through the SAP software package with solid elements and the frequency of the horizontal oscillations was compared to the measured values. The repair method was conditioned with a possibility to execute works in such narrow site. For improving the foundation behaviour, it was possible to add another 55.4 t to the existing foundation mass of 115.2 t. The analysis of oscillation mode through the value of displacement vector has shown that this solution was effective, providing the contact of the additional concrete mass in the foundation base was excluded. Therefore, in the executed solution the added mass was hanged to the existing foundation. The paper gives the technical solution for the repair works, way of modelling and measuring results of vibrations before repairing, which is used for constituting the dynamic model.

## **THE STRUCTURAL UPGRADING OF SLABS INCLUDING LOAD BEARING STEEL BEAMS**

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**Keywords:** Slab upgrading, steel beams, props, structural continuity, creep, shrinkage

The state of stress and deformation arising in slabs including steel beams upgraded by means of collaborating concrete layers is investigated. Two operational techniques are taken into consideration. The first based on the introduction of provisional props during the upgrading phase, the other involving structural continuity. The two techniques are sensitive to structural effects of concrete delayed deformations, which are studied in the paper in a refined way according to the suggestions of Eurocode 2. A case study is presented, in order to point out the most outstanding design aspects of the upgrading of slabs involving steel beams as bearing elements.

# STRUCTURAL DAMAGE, REPAIR AND RECONSTRUCTION OF THE VOJLOVICA MONASTERY CHURCH NEAR PANCEVO

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**Keywords:** Church, altar, vaults, dome, seismic resistance, settlement, cracks, repair work, reconstruction

The church was built in three phases. The first covered the end of the 14th and the beginning of the 15th century (the altar space, two choirs, the crossing with the eight-sided dome above, and the blind dome over the narthex). In 1752 another narthex was built, 6.65 m long. The baroque belfry was erected in 1836, in the third phase. There were other changes in the meantime. Some parts of the church were demolished, and at the end of the 18th century two angle columns with semi circular arcades were constructed next to each of the choirs.

A lack of isolation between the foundations and the walls, as well as the earth embanked around the structure caused abundant dampening of the walls with the crumbling of the plaster. The soil where the structure has been founded is heterogeneous containing organic matter and loam.

Control calculations for some parts of the structure that showed the contact stresses at the bottom of the foundations were uniform unlike the settling. The results of that analysis coincided with the actually recorded cracks. The damage was registered at the joints of the walls and the pillars, and of the longitudinal and transversal walls, too. The walls were the least compact in the middle part. The control seismic calculation revealed there was a small number of elements accepting transversal forces.

The damage and the structure's state determined the sequence of the repair works, and some measures were taken simultaneously with the research. The paper describes the rehabilitation measures concerning the drying of the walls, the isolation placement and the arrangement of the church's environment with drain trenches taking the surface waters away from the structure. Also, the rehabilitation of the foundations is described and the strengthening of the walls and columns to eliminate the damage and enlarge the stiffness in case of seismic influences. The structure of the church was strengthened with vertical and horizontal reinforced joints. The activities on the reconstruction are also presented, i.e. the returning of the original appearance of the church by rebuilding the cylindrical vault, the drum and the dome, and the reconstruction of the roof.

The original appearance was achieved through the reconstruction of the structure, while the rehabilitation measures stiffened the old parts of the church by rebuilding the necessary transversal walls, protecting thus this valuable cultural monument from further deterioration and possible seismic disturbances.

# **A QUEST FOR SIMPLIFIED METHODS IN THE ANALYSIS OF DETERIORATING STRUCTURES**

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**Keywords:** Assessment, structural analysis, reinforced concrete, corrosion, bond

The assessment of existing R/C structures is carried out at the Ultimate Limit State, considering the effects of the damage caused by bar corrosion, in the evaluation of both the design strength and actions.

Deterioration is introduced by considering the cross-section reduction, and modified material models including steel-concrete bond, within a non-linear analysis code. This allows some modifications to the traditional elastic analysis methods with bending-moment redistribution, and to the equations for the evaluation of the ultimate bending capacity.

An example is proposed, to show the application of the procedure to the ultimate state of continuous beams. This rather general solution allows the drawing of interesting conclusions regarding safety assessment and failure modes of existing structures.

**Theme 3:  
Buildings, Masonry  
& Civil Structures**

**Day 3:  
Car Parking Structures**



## **CAR PARK REFURBISHMENT IN USA**

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**Keywords:** Concrete, car park, refurbishment, USA

Although concrete is a relatively durable construction material, corrective measures are constantly required to realize the design service life of car parks. Car parks are directly exposed to the aggressive elements and experience very harsh conditions that contribute to accelerated deterioration and premature failure of the concrete structure.

## **WRAPPING THE HARBOUR CITY CAR PARK AND OTHER PROJECTS**

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**Keywords:** FRP, concrete, wrapping, car parks, repair, strengthening

The use of FRPs was a technology initially developed for the aerospace, ballistics and manufacturing industries. However it has fast become an accepted and respected technique used by civil engineers for structural strengthening. It is a technique which is not just limited to concrete, at the moment we are using these systems on other types of construction materials such as masonry, timber and cast iron.

## **STRENGTHENING OF A FLAT SLAB – EFFECTS OF CONTRACTION IN THE ADDED TOPPING**

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**Keywords:** Strengthening, concrete, slab, contraction, topping

A reinforced concrete flat slab constructed about 10 years ago for a car park has been strengthened for retail use. Headroom was restricted, so the original slab, which varied in thickness from 250 to 300 mm on a (typically) 7.8 m square grid, had to be strengthened with only minimal increase in thickness. After being propped, concrete was removed to reduce the thickness to 210 mm and a reinforced topping 115 mm thick was then added, bringing the total thickness to 325 mm. Full composite action was ensured by applying a bonding agent at the interface, so that mechanical connectors were not required.

Ultimate strength was assured by additional reinforcement provided in the topping over the supports (with a lesser amount continued across the span). However, there was some concern over the increased stress in the bottom reinforcement and over the final deflection.



**Theme 3:  
Buildings, Masonry  
& Civil Structures**

**Day 3:**

**NDT of Structures + Underground  
Service Mapping**



## **NDT AT PUBLIC WORKS, THE NETHERLANDS: POINT OF VIEW OF A PRINCIPAL**

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**Keywords:** NDT, bridges, concrete, steel, deck

The ministry of Public Works and Water Management is responsible for more than 4000 bridges. Most of these structures are a part of our highway network. These structures have, therefore, an important function in the infrastructure of the Netherlands.

To determine their condition these structures are inspected on a regular basis. This is mostly a visual inspection which determines if there is a problem. Once a problem, or a suspicion of a problem, is detected a detailed inspections will be arranged to obtain more information.

These detailed inspections are often focussed on technical aspects of the structure, for example cracks in concrete or steel. The techniques that are used to obtain the information during the analysis of the structure, are often destructive. Often cores are taken from concrete structures and tested in a laboratory to determine the actual strength. If we want to inspect the condition of a steel plate in a bridge deck, the top layer has to be removed. In both examples the methods used are destructive for the construction. Better ways to determine the concrete strength or the conditions of steel decks are therefore welcome.

Public Works often asks to do inspections in a non-destructive way to determine the condition of structures. The results of these inspections do not always

meet the expectations. Some problems with NDT projects are:

- The actual target of the inspection is not mentioned to the NDT company.
- Sometimes the principal has problems in understanding the results due to the used presentation method, which is often very technical.
- The definition of accuracy (the demanded reliability and probability of detection) is not always clear at forehand.

Most of these problems are related to communication.

Special interest within Public Works is the knowledge of NDT projects. NDT is not frequently used. Knowledge about dealing with NDT is therefore not available for everyone within Public Works. Public work has an intranet-site with information about used techniques for its employees. With this information it is easier to choose between the techniques available.

In this paper we will present NDT from a principal point of view. Some NDT projects will be outlined to show the process from inspection to NDT technique and dealing with the results. This paper will present the problems Public Works faces while working with NDT and how Public Works tries to improve to use of NDT within its organisation.

## **EXPERIMENTAL STUDY OF ATTENUATION OF ACOUSTIC EMISSION SIGNALS IN WELDED STEEL PLATE GIRDERS**

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**Keywords:** Acoustic emission, steel, plate girders, monitoring

This research focuses on the use of the acoustic emission method as a monitoring technique in welded steel structures that are subject to fatigue cracking. Specifically, this research studies the attenuation of acoustic emission signals in welded steel plate girders. The study is conducted by introducing stress waves to a steel plate and evaluating the attenuation of the stress waves as they cross typical welded details commonly found in welded plate girders. An understanding of the attenuation of the stress waves by these welded details may aid in the selection of the number and placement of transducers for a particular test. Complete details of the study presented in this paper are given in Mayrosh and Pessiki (2001).

## **EFFICIENT MANAGEMENT OF INSPECTION AND MONITORING DATA FOR A BETTER MAINTENANCE OF INFRASTRUCTURE**

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In North America, Europe and Japan, government agencies and large private owners are now facing the challenge of maintaining, with limited resources, large stocks of vital structures like highways, railways, bridges, dams, harbors, industrial facilities etc... These structures are representing a large amount of money, have not been designed to be easily repaired or replaced, and are getting older and more vulnerable.

People involved in structure management have developed extensive technical methods and tools to monitor the condition of the structure and establish the diagnosis. Each authority has been developing its own inspection maintenance procedures, taking into account their specificity, their different priorities, safety requirements, resources and range of competence.

In most cases visual inspections are used to detect deteriorations, to rank structures, define priorities, estimate repair costs, etc... These visual inspections require to record, report, analyze and store for years large quantities of data (inspection records, drawings, photos...) and it is easy to get

lost in the clerical work. Moreover a number of decision steps (inspection record, ranking of defects, long-term analysis) are still highly subjective and can greatly affect the quality of the final diagnosis.

An inspection-based management software system has been developed to optimize this process and provide decision-makers with objective information on the condition of the infrastructure. The system is a comprehensive management system which integrates: database of structural defects, on-site computerized record, analysis, maintenance, diagnosis, repair and budgetary functionalities.

This paper describes the basic functions and benefits of the system through a case study of a highway bridge in France.

## **COMPLEMENTARITY OF NON DESTRUCTIVE TECHNIQUES IN THE DIAGNOSIS OF DAMAGED HISTORIC STRUCTURES**

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**Keywords:** Masonry structure, non destructive techniques, inclusions, delamination, hidden elements

Frequently the application of NDT to historic buildings is needed in order to search for hidden part of the structure or for structural faults. The designer who requires the investigation is always facing the difficult situation of accepting the interpretation of the results given by the NDT experts, who on turn are usually non expert in material and structures. Only a strict collaboration between the designer and the experts and the use of different investigation techniques, from simplest to

more sophisticated can help in the interpretation of the results.

The application of georadar to the detection of three main structural problems for the Bell-tower (Torrazzo) of Cremona is presented, together with the description of the difficulties in acquisition, data elaboration and the description of auxiliary investigations used to validate interpretation of the results.

## **DETECTION OF WATER MOVEMENT BELOW A CONCRETE ROAD USING GROUND PENETRATING RADAR**

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**Keywords:** GPR, water, concrete, highway, pavement

The presence of water within the sub-base below a pavement can lead to deterioration in the performance of the pavement under trafficking. This paper describes an investigation of the use of ground penetrating radar to determine the moisture content of the sub-base.

## **SUB SURFACE RADAR FLOOR SLAB ASSESSMENT**

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**Keywords:** Sub surface radar, floor slab, finite difference time domain modelling

As part of a larger project to establish the characteristics of a distressed floor slab, and the nature and extent of the defects affecting the floor slab, a sub surface radar survey was undertaken using a relatively new high

frequency (4GHz) horn antenna in conjunction with finite difference time domain modelling. The information from the survey was used by engineers assessing the condition of the slab and designing the remedial solution.

The sub surface radar survey was used to:

- Assess the characteristics of the slab, essentially the depth
- The extent of any lifting of the floor slab from the underlying substrate
- The presence and extent of any poor compaction – honeycombing of the slab
- Confirm that the cracks penetrated the full depth of the slab

The paper presents the approach to the survey, the survey data and the results of the modelling. Findings from other parts of the project are introduced to illustrate the overall engineering context for the sub surface radar survey.

## **RADAR EXAMINATION OF UNDERGROUND GARAGE CONSTRUCTIONS**

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**Keywords:** Nondestructive testing, holographic subsurface radar, microwave image, crack, water infiltration

The paper reports the results of an underground garage investigation to search the cracks in reinforce concrete. The goal of investigation was to prevent ground water leakage in the garage. Holographic subsurface radar, which has the high resolution in plan of search, was used in the investigation. A number of microwave images were got at different radar

frequencies. The results of the survey indicate that the radar images can be an effective means of nondestructive testing in the building constructions.

## **APPLICATION OF DRILLHOLE VECTOR MAGNETIC MEASUREMENTS TO RESOLVE THE POSITION OF EXISTING UNDERGROUND STRUCTURES**

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**Keywords:** NDT, vector magnetic, measurements, underground, structures

Total field magnetic surveys are commonly utilized for mapping geological structure and the detection of underground ferrous metal objects such as ordnance, pipes and services. The method is directionally insensitive, especially in locally strong magnetic fields, introducing an unquantified component of error to detailed dimensional analysis of the source. For a number of years the potential advantages of employing vector or 3 component downhole magnetic measurements to calculate the full vector orientation of the magnetic field, and hence locate the 3-dimensional location of a buried magnetic ore body, has been recognized by the mining exploration industry. This paper presents the application of this vector magnetic downhole technique to the 3D mapping of ferrous metal in underground structures, such as reinforcing bar, pipes, foundations and also soil nails. The technique is discussed and a brief case history relating to the proposed alignment of a small bore tunnel is given.

## FULL-SCALE TESTS OF STEEL PILES SUPPORTING INTEGRAL ABUTMENTS

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**Keywords:** Integral abutments, steel piles, full-scale tests

The use of pile supported integral abutments for bridges of short to medium length has become accepted practice in a number of states in the USA. While not a pioneer in the move toward jointless bridges, Tennessee is currently the recognized leader in applying this concept in the design of highway bridges. Steel bridge lengths up to 122 m and concrete bridges up to 244 m are routinely designed and constructed with integral abutments and no intermediate joints. Pushing the envelope, the Tennessee Department of Transportation (TDOT) has designed a steel bridge 160 m long and a concrete bridge 358 m long; both of these bridges are currently in service.

## THE RAPID, NON-DESTRUCTIVE ASSESSMENT OF 'CRITICAL DEFECTS' IN COMPOSITE STRUCTURAL STRENGTHENING SYSTEMS USING TRANSIENT PULSED THERMOGRAPHY

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**Keywords:** Transient pulse thermography, critical defects, carbon fibre reinforced plates (CFRP)

Carbon fibre composites have been widely used for structural strengthening applications including the repair of slab, beam and column elements of concrete structures. Nevertheless, the ability to monitor the long-term durability and performance of composite strengthening systems in-situ is still a major concern to the civil engineering community since defects such as localised debonding of carbon fibre reinforced plates (CFRP) can adversely affect the overall structural integrity of the system. Poor performance of CFRP on-site is sometimes attributed to poor workmanship and inappropriate weather conditions (e.g. wet-dry cycles) during installation. However, long term exposure to harsh and changing environmental conditions under load also presents potential problems for CFRP strengthening systems.

Conventional non-destructive assessment techniques used in the construction industry such as ultrasonic scans, x-ray analysis and various mechanical 'tapping' methods have traditionally been used to investigate the properties of CFRP in-situ. However, there are a number of issues that have been highlighted whilst using these techniques on-site, the most important of these being

their poor cost-effectiveness, slow speed of assessment and limited access mode of operation.

In this present study Transient Pulsed Thermography (TPT) has been successfully adapted to rapidly detect 'critical defects' introduced during the application of CFRP strengthening systems to concrete substrates. In this study a 'critical defect' was defined as area of debonding between the concrete substrate and the CFRP strengthening sheets.

The results of the study have been compared to a conventional ultrasonic method of assessment in order to highlight the benefits of TPT. In comparison with existing non-destructive methods/techniques, TPT systems have the following potential advantages:

- Non-contact method.
- Fast scanning rates (for imaging purposes) over large areas (dependent upon the size of defects being assessed).
- Detailed 'image' information (requires minimal processing to interpret presence of defects).
- Ease of deployment (access normally required to only one side of the component).
- Impact during installation process (provide positive feedback system to enable enhanced quality control procedures).

## **NDT MONITORING OF STRUCTURES DAMAGED BY FIRE**

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**Keywords:** Fire damage, dynamic measurements, natural frequency, mode shape, structural health monitoring

During a fire rescue mission, firefighters are put at a great risk because they have no knowledge about when a structure component might collapse. Single-story steel or wood truss-roof buildings have been identified as the most critical structure type in firefighter casualties. The goal of this study is to develop a structural integrity monitoring system which is capable of detecting an upcoming structure collapse caused by fire. In this paper, the mechanical, thermal, and dynamic behavior of simply supported wood and aluminum beams subject to both static and thermal loads until failure is presented. Four Douglas Fir wood beams and four 6061-T6 aluminum beams were tested. The test plan was motivated by firefighters' experiences that a noticeable level of wall, floor, or roof displacement and vibration happened before a structural collapse. This implies that an upcoming structural collapse caused by fire could be detected by monitoring the dynamic characteristics of the structural system. The test results from real-time dynamic measurements presented in this paper verify the observation.

## **NDT APPLIED TO THE DIAGNOSIS OF HISTORIC BUILDINGS: A CASE HISTORY**

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**Keywords:** Masonry, diagnosis, NDT&E, radar test, thermovision

Recently, Villa Litta Modignani, a XIV century country palace near Milan, was intensively studied by the authors in view of the design the preservation intervention. The building is affected by a variety of decay problems. Most of them can be detected by visual inspection of the decay effects and do not need direct ND investigations. Nevertheless, the design of the repair interventions must be approached only after that a deep knowledge of the material and construction techniques has been obtained. This goal is the motivation of most of the ND investigations (radar, thermovision, ultrasonic test, etc.) that were performed on the building. Four main issues were defined: morphology and detection of hidden reinforcements in the vault structures, detection of voids in the load bearing walls, timber beam position and connections with the walls, material and construction techniques of columns. For each of these main issues the most convenient ND methods were selected by considering their technical potential but also their costs and the specific access conditions (e.g., no scaffoldings were available at the time of the investigations). Thus, an intensive use of thermovision was done

whereas georadar was often used on the floor or on structural elements that could be easily reached. Sonic measurements were performed on the columns.

## **ISSUES ON ASSESSMENT OF HIGHWAY MASONRY RETAINING WALLS**

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**Keywords:** Masonry, retaining walls, defects, NDT, standards

The aim of this paper is to investigate possible ways of rapidly scanning the condition of masonry retaining walls, in order to:

- assess the retaining wall with respect to its thickness and variation of the wall structure.
- identify the condition of the masonry retaining wall itself.
- identify changes in the material properties
- identify areas of high moisture content which could lead to deterioration of the mortar in masonry walls and subsequent delamination.

The paper will also consider the condition of the fill behind the retaining wall, as well as identification of any reinforcement in the wall. Consideration will be given to identifying areas of high water concentration as well as voids, which may lead to a collapsed wall.