Joint Bridge Researchers' & Owners Forum
Kings College, Cambridge.

Draft Notes of meeting held 27th and 28th October 2003.
At King's College, Cambridge.

PRESENT

Representing Universities

Dr Chris Burgoyne	U. of Cambridge
Prof Ramiz Delpak	U. of Glamorgan
Prof Mike Forde	U. of Edinburgh
Dr Tim Ibell	U. of Bath (Also representing Concrete Society)
Dr Colin Jolly	RMCS Shrivenham. (Also representing Concrete Bridge Development Group (CBDG)
Dr Robert Lark	U. of Cardiff
Dr Wanda Lewis	U. of Warwick
Dr John Macdonald	U. of Bristol
Prof Ian May	Heriot-Watt U.
Prof. Clive Melbourne	U. of Salford
Dr Campbell Middleton	U. of Cambridge
Dr John Owen	U. of Nottingham
Prof. Gerry Parke	U. of Surrey
Dr Paul Reynolds	U. of Sheffield
Dr Su Taylor	Queens U., Belfast.

Representing Research Organisations

Dr Martin Ogle	TWI Ltd.
Dr Andrew Pitchford	CIRIA
(with Dr Carlos Sicilia Gaillard, Mott Macdonald, CIRIA Contractor)	
Dr Richard Woodward	TRL Ltd.
	Concrete Society) See representatives above
	CBDG) "

Representing Bridge Owners

John Clarke	BRB (Residuary) Ltd.
Rod Howe	British Waterways
Greg Perks	CSS
Edward Bunting	Department of Transport
Andrew Oldland	Department of Transport
Ronnie Wilson	Department for Regional Development (Northern Ireland)
Awtar Jandu	Highways Agency
Jim Moriarty	London Underground Ltd
Brian Bell	Network Rail
Raymond Johnstone	Scottish Executive.

Other Attendees

John Darby	Technical Secretary
Paul Fidler	U of Cambridge
Daniel Imhof	U of Cambridge
Graeme Walker	U of Cambridge

Apologies for Absence

Martin Bassett	Serco Docklands Ltd
John Collins	National Assembly for Wales
Gery Hayter	Highways Agency
David Yeoell	London Bridge Engineering Group (LoBEG)

1. INTRODUCTION.

Delegates were welcomed to the meeting by the Chairman, Cam Middleton, who appreciated the attendance of so many researchers despite the busy mid-term period. The bridge owners forum had held 10 meetings to date, and two consultants meetings, but this was the firs Bridge Researchers Forum. The eventual goal is to have an international forum.

Cam Middleton summarised the achievements of the Bridge owners forum to date, and encouraged an open debate on the subject 'Where should we be going.' The UK organisations involved in Government funding of bridge research were outlined, and in particular the Bridges Board. This board did not have to take outside advice, but it was felt that they would value the expertise the Forum was able to offer.

The meeting was to be held over two days, with presentations from 19 researchers over five sessions. Each session included a discussion period. The final session was to review how the Forum should move forward.

2. SESSION 1. AM 27th October

2.1 Presentation 1. Dr Chris Burgoyne. University of Cambridge.

Chris Burgoyne questioned how many engineers rely on plasticity theory, and illustrated his point with examples for a reinforced concrete slab. Finite elements showed the original design to be unsafe in the transverse direction. The original design used Wood Armer, with Denton Foster Correction. Was the designer wrong to use lower bound? Was the checker wrong to use elastic? Chris Burgoyne concluded that the FE analysis method can be used for design, but NOT for analysis of a structure.

Chris Burgoyne then discussed new materials, and considered why we are not using FRP's more in view of the obvious problems with corrosion of steel. He concluded that FRP as a direct replacement of steel reinforcement was not its most viable application, because the full capacity of the FRP was not utilised without excessive

deflection of the element. Performance was improved by confinement. The most effective application of FRP materials was therefore as prestressing, rather than reinforcement. The bond of composites was also variable, but critical. Current FRP proposals frequently misunderstood the true behaviour of the material, and this inevitably led to needlessly high cost.

A wide range of developments and ongoing work were then illustrated: -

- Knitted composite reinforcement.
- Magnetic Resonance Imaging (MRI). This allows 3D imaging of internal cracking.
- A layout of concrete and FRP which may not satisfy codes, but did satisfy structural principles.
- The cost of composites for strengthening is of the same order as that for prestressing steel.
- The poor state of the US Bridge stock – and the need to improve that in the future.

Chris Burgoyne ended with a plea for engineers to improve the publicity of their achievements.

2.2 Presentation 2. Andrew Pitchford. CIRIA

Andrew Pitchford manages the Infrastructure Asset research programme, and illustrated the range of projects involved. In particular, he spoke about the Arch Bridges Project, which had been developed from a CSS outline. Funding has been provided by Dtp, Network Rail and Core CIRIA members. The project has now been let to Mott Macdonald, who were represented at the meeting by Carlos Gaillard.

Carlos Gaillard described the arch bridge project in greater detail. The final objective was to produce a Good Practice Guide. This was considered an important project because of the high proportion of masonry arches within the national bridge stock, and the poor condition of many of them.

It was recognised that the masonry arch comprised a structurally complex system, but the intention was to recommend a maintenance strategy that achieved Best Value. However, this was not a research project, but involved liaison with user groups. A literature survey will be followed by consultation with experts, workshops, and liaison through a website.

Loads on arch structures are increasing whilst capacity is decreasing. Cost effectiveness is essential, and will be demonstrated with Whole life costing Typical problems were illustrated.

2.3 Presentation 3. Colin Jolly. RMCS Shrivenham and Concrete Bridge Development Group (CBDG)

Colin Jolly spoke first on behalf of the CBDG, of which he is a council member. The broad aim of the CBDG is to develop wider and better use of concrete within bridgeworks. Research aspects were the responsibility of the Technical Committee,

which assessed research needs and offered funding of small projects, and seedcorn funding to encourage larger projects. To date, projects to the value of £45.1k had been completed, with £24.5k value in progress.

Colin Jolly then described the current work of RMCS, and in particular the research related to materials. These included: -

- Bonded external reinforcement
- Durability of lightweight concrete
- The integrity of repaired structures. FE Elastic analysis was not considered relevant for assessing existing structures in military situations. Very fast assessment is required in the field.
- FRP winding of composite piles has been researched, and 40 N/sq mm increased to 270 N/sq mm by this method.

Load Response research includes: -

- Fibre Optic Monitoring
- Vulnerability of bridges to terrorist attack
- Bridge resonant dynamics and its use to monitor component integrity.

2.4 Presentation 4. Martin Ogle. TWI Ltd.

Martin Ogle is Principal Design Consultant of the Structural Integrity Design Group, and described the nature of the organisation and Bridge Research activity at TWI. TWI operate from new premises near Cambridge, including laboratory and office facilities. Activities relate primarily to joining processes. Originally restricted to welding – and hence the name Welding Institute – new adhesives and mechanical bonding are now also covered. For all types, the performance and assurance of joint quality are investigated. The materials have also extended beyond metal, and now include plastics, composites and ceramics.

The work at TWI is supported by some 3000 industrial member organisations, representing a wide range of industries. 50% are UK based. Turnover is £25m, with 450 staff, 50% of which are graduates. Contracts hae been undertaken for Highway and Railway Authorities, consultants, fabricators and materials suppliers.

Examples of work undertaken include: -

- Design rules, fabrication methods, testing techniques, repair schemes and specification.
- Major research from the 1950's onwards on fatigue and welding rules, through to BS5400.
- More recently, work on brittle fracture, crack inspection and lighting columns for standards and advice notes.
- Specific bridge projects, such as investigation of failures and repair procedures.

Examples of potential research areas were outlined, including new joining methods, such as Friction stir, Friction Hydro pillar, Friction Taper plug, and laser welding. New methods of NDT also require research.

2.5 Presentation 5. Ian May. Heriot-Watt University.

Ian May described the projects in hand at Heriot-Watt University, which has a particular interest in the use of non-linear finite elements applied to biaxial bending of RC slabs.

Examples were shown of the application of Mxy moments, and it was illustrated that Wood-Armer is not satisfactory. i.e. it is unconservative.

Work is in hand on precast bridge decks, and in particular an example on Scotland. The joints have been tested, and will enable advice to be given to SCI on the use of precast decks.

Benchmarking has been undertaken of non linear FE analysis for concrete deep beams.

Research is in hand of impact on reinforced concrete members. This seeks to gather data on what happens during the impact, rather than investigation restricted to the after effects. This is achieved by the use of very high speed video.

Finite element analysis has also been used to design composite patch repairs to steel members.

Suggestions made for future research included knowledge based systems, and analysis of the causes of cracking in masonry.

2.6 Discussion of Session 1.

A wide ranging discussion on Session 1 included the following topics, remarks and opinions: -

Analysis methods: Assessment is still largely based on design methods – how can we take this forward? FE methods are commonly used by researches, but how can they be introduced more widely?

Arches: Arches have performed well, should we be building more of them now? There is a need for more research on recent repair methods.

Research / Owner co-operation: New materials and methods require structures for demonstrations and trials. Difficulties arise on busy networks, but some owners have redundant structures. Some owners may be more prepared to offer structures that are satisfactory than one that is weak and will rely upon the new method. Researchers are sometimes charged unrealistic costs that effectively prevent progress. There is a gulf between the real and theoretical world.

Repair Methods: Repair works require more testing in the field, but how can one get more data? More monitoring and validating is required.

SESSION 2. PM 27th October

3.1 Presentation 6. Richard Woodward, TRL.

Richard Woodward described the background to the creation of the Transport Research Foundation in April 1996. TRL now has 550 staff and a £33m turnover, and will be moving into a new building in Spring 2004.

An important aspect of Bridge research has been related to structural assessment, and in particular topics required for the assessment code, such as inadequate anchorage, voided slabs, infill decks, and depth factor. Originally this work was based in particular on the testing of sections retrieved from bridge decks, but more recently there has been greater emphasis on the testing of details to assess behaviour. This has often found reserves of strength.

Condition assessment has included topics associated with corrosion of reinforcement, assessment and repair methods, and monitoring.

Structures management has included several collaboration projects with European partners.

Research associated with strengthening has included columns strengthened with FRP. Work on FRP has also included the cyclic loading of FRP decks.

Sustainable construction is of growing importance. The contribution of recycled aggregate is under investigation by examining its durability when re-used within concrete.

Research needs were then summarised: -

- A comparison was made between bridge and road pavement inspection. Pavements were once inspected by inspectors wielding notebooks. The process had now been automated with a vehicle called HARIS (Highways Agency Road Information System), which collected data whilst travelling at normal traffic speed. In contrast, bridge inspections were still variable in quality and were slow. Studies have found bridge condition data to be unreliable in both the UK and USA. Improvements would result from training inspectors and automated inspection.
- NDT. A lot of testing has been undertaken, but where has all of the data gone?. Is the best use being made of it? Have tests been targeted? There is a need to develop new methods and to improve advice. The HA are producing an advice note on the subject.

Richard Woodward noted that the UK is one of the most innovative nations, with over 50% of the worlds firsts since the industrial revolution. However, we need to be more adventurous to take advantage of this innovation.

3.2 Presentation 7. Robert Lark, University of Cardiff.

Robert Lark described the administrative arrangements at Cardiff, and in particular those relating to the Civil engineering group, Design and Mechanics Group.

A broad list of projects in hand was demonstrated, including properties of normal, waste products and high performance concretes, and a lot of activity on FE modelling.

A range of projects on masonry utilised a geotechnical centrifuge. Network Rail are sponsoring a project on cyclic non-proportional loading of arch rings. This has demonstrated that the condition of the arch ring has a significant effect. One future proposal looks at the FE modelling of dry stone walls.

Work is in hand on probabilistic bridge assessment using reliability techniques. This gives rise to debate as to their meaning and their method of use. The work highlights the parameters of greatest influence. This work on reliability of different bridge types and failure modes enables structures to be prioritised in terms of risk.

In the process of bridge management, serviceability should be assessed in terms of its management, whilst ensuring safety. There is a need to understand how a structure changes with time.

Cardiff have monitored two viaducts by the embedment of VWG's in the concrete. This enabled the measurement of shrinkage and creep movements. It was notable how accurate the predictions were, but this occurred because the researches had full access to the real data at all stages of design and construction.

There is a long history of research on acoustic emission at Cardiff.
The infrastructure is of high value, and more must be understood about its serviceability, with validated results.

3.3 Presentation 8. Mike Forde. University of Edinburgh.

Mike Forde described some of the research work that lay behind the advice notes on NDT in preparation by the HA. He also described the work on Bridge Scour. It was possible to detect the previous patterns of scour if the scour holes had been subsequently filled by silt, but not if they were filled by stone.

The different kinds of sonic wave were illustrated. Pressure (longitudinal), Shear (transverse), and Rayleigh (surface).

Research has included ultrasonic tomography using the pundit equipment. Russian work has demonstrated improved penetration by the use of shear waves. This indicates the scope to improve penetration due to their reduced attenuation.

Research work using radar on post-tensioned ducts was illustrated. Radar waves can pass through air, but not conductors. Radar therefore cannot pass through salt water.

Sonic waves cannot pass through air. It is therefore necessary to select appropriate methods.

3.4 Discussion of Session 2.

A wide ranging discussion on Session 2 included the following topics, remarks and opinions: -

Inspection of Structures: Most owners repeat the same inspection regime for all structures. Is all of the testing currently specified good value on good condition structures, and should the testing and frequency be varied according to structure type and condition.? An audit of inspection data would be instructive. How can we make proper use of all of the stored data on structures. How can we separate out data that is useful or not useful. The budget available to authorities for inspection is variable, and not all authorities can afford to follow the Highways Agency frequency.

Nature of Research: The expenditure of owners is dominated by concern over serviceability. Is that reflected in the efforts of researchers? What is the mechanism for bringing high tech research into more general use?

Management of Structures: There is a need to follow an effective management process for structures, including for any variation in inspection frequency. Bridge managers must be aware of the need to contain risk, and justify to the HSE if required. This is a fundamental problem. Micro sensors may be installed, but need to ask if they would be useful? What information is really required?

SESSION 3. PM 27th October

4.1 Presentation 9. Tim Ibell. University of Bath, but also representing Concrete Society.

Tim Ibell discussed four areas of research activity, the first two on behalf of concrete society and the second two on behalf of the University of Bath.

Inadequate anchorage of reinforcement is a common cause of shear failure. A working party considered that a new approach was required, but that new approach had to be both rational and compatible with existing methods. A Research was undertaken to devise a new method of analysis with improved correlation with test results. This was an example where research led to very large savings by, avoiding needless strengthening of structures.

The concrete Society has published TR55, the use of FRP for concrete Strengthening. A task group is currently revising this, and there will be some specific changes in the recommendations. The new version will be updated in areas such as Shear and columns. A new section will provide flow charts to aid decision making and explain emerging technologies.

The University of Bath has undertaken research on the effect of soffit curvature on CFRP strengthening. For example, the current figure quoted as acceptable unevenness is 5mm departure from a straight edge of length 1m., but it was not known if this is accurate. Trial beams were constructed, and it was found that there was a reduction of 30% in the strength due to a global curvature of this magnitude. Anchoring of the strengthening at intervals was found to avoid this reduction, and even to raise the strength above that for flat plates without anchors.. The anchors also prevented the reinforcement falling off at failure.

Research has also been undertaken on the shear strength of slabs and bridge beams. Elements were drilled, and FRP bars inserted from the soffit. Shear strength was found to increase if 3 or more bars were inserted. An assessment tool is now under development in collaboration with Network Rail.

Tim Ibell then listed ongoing research, and research needs. These included whole life costing models and life expectancy models.

4.2 Presentation 10. Paul Reynolds representing University of Sheffield.

Paul Reynolds summarised the Department and Sheffield, and indicated particular research strengths and areas of interest specific to bridges.

The Department has particular expertise in the vibration serviceability of civil engineering structures, particularly footbridges. The expertise has been developed since 1993, although general awareness of the subject was only raised more recently as a consequence of the problems with the Millennium FB. Paul Reynolds in indicated the areas of uncertainty in the source of excitation, The Path (how excitation is transmitted through the structure), and the receiver (acceptable levels of vibration).

Analytical modelling is compared with dynamic testing of real structures, and hence it is possible to learn now to improve modelling. Tests have been undertaken on Aberfeldy footbridge. Small controlled forces are emitted by a shaker, and the effect on the structure is measured by accelerometers. Similar tests were undertaken on the Millennium Bridge, although in that case larger shakers were required. It is also possible to avoid the use of shakers, and to undertake ambient vibration testing. In this case, the vibration is induced by traffic or wind, and the nodal properties determined.

There remains scope for further research on vibration to reduce the areas of uncertainty discussed. Work on the sources should come before that on receivers. The general area of vibration will become more important as structures become more slender.

Sheffield are to undertake work on FRP footbridges, and also join with others on collaborative projects. More research is required on the subject of FRP, including Whole Life Costing. Research is also required on permanent formwork, including new materials, and masonry parapets.

Crack Development was examined by means of high speed video. Shear cracks were shown to appear before flexure cracks developed. The load pad left the beam as the

beam oscillated. The camera was able to achieve 5000 frames / second. Higher speed was possible, but at reduced resolution. Measurement of the speed of crack propagation was not possible as cracks appeared at less than the time of a single frame.

4.2 Presentation 11. Awtar Jandu, Highways Agency.

Awtar Jandu spoke on the subject of New Technologies for Highway Structures, and described the Highways Agency Vision – 'Safe Roads, Reliable Journey, Informed Travellers.' He described the current Highways Agency organisation, and indicated that the current head of Research and development of Standards was Gerry Hayter.

Awtar Jandu outlined the HA business processes for strategic planning, engineering process and operational process. The engineering process included advice on whole life costing now under preparation as BD36. Information is currently lacking on whole life performance.

SMIS Decision support process continues under development. Modules relating to the recording of basic information are complete, but those aspects relating to performance and whole life costing are not yet available.

11 items of future research were indicated, including maintenance strategies, intelligent bridges, NDT methods, life cycle analysis, environmental issues, monitoring methods and risk and reliability.

4.4 Discussion of Session 3.

A wide ranging discussion on Session 3 included the following topics, remarks and opinions: -

Bridge Management: Are we making maximum use of the information gained during inspections and assessment?, or are we having to start afresh each time? The DTp are to let a contract to prepare a specification for a database of bridge information. A national database of all bridges was suggested, but others considered expensive and owners have their own needs. The view was expressed that the most critical need was a means of extracting information from existing databases for exchange between owners and researchers. The issue was thus a standard data transfer format. The current deficiency of existing databases was acknowledged.

Bridge Testing and inspections: Are tests undertaken as a matter of routine during examinations, but are not always required?. Frequency of Inspections can be varied by owners, but must be fully justified. Some bridges on quiet networks, such as BWB, are little seen by the public who may report defects. Regular inspection is more important for them.

Bridge Monitoring: Comparison was made with the aircraft industry, where much greater use was made of previous records and use of monitoring.

Arch Bridges: The greatest need in the management of arches was a reliable means of detecting ring separation. Currently a hammer test to detect a hollow sound was the most likely method.

Assessment: More shear capacity has now been demonstrated, unfortunately at the end of the first round of assessment. There is a feeling that codes have been too onerous, but will those codes now be amended? Amendment may be 5 years away, but data will be stored in a database and readily available. Assessment undertaken by some analysis methods underestimated the capacity by a factor of 2, and there was therefore great scope for improvement by adopting more appropriate methods. One speaker suggested that proof loading as a means of demonstrating bridge capacity deserved a re-loo, whilst others expressed concern about potential damage to structures. This was not the preferred method in the UK despite extensive investigation.

Research: CBDG, amongst others, are very keen that research report should be in the public domain.

Use of FRP: Several speakers agreed that FRP is most useful as external prestressing, Not as a steel replacement in RC. FRP also has a role in the reinforcement of masonry.

5. SESSION 4. AM 28th October

Sessions 4 and 5 were chaired by Greg Perks. (CSS)

5.1 Presentation 12. Gerry Parke. University of Surrey

Gerry Parke summarised bridge related research at Surrey.

The composites research group was active in many areas relating to the behaviour of materials, including damage and the effects of folding of reinforcement fabrics. Fibre optic sensors were used to detect damage. Work including the testing of composite structures, and the design of composite shells.

Risk and reliability research was used to improve the management of an ageing bridge stock, enabling the modelling of uncertainty and performance. Such models were applied to concrete deterioration, and deterioration due to chloride ingress. This work will lead to improved deterioration prediction.

A similar approach has been applied to fatigue assessment. Future research areas were outlined.

Materials deterioration is of critical importance due to the high cost of repairs. Investigation using nuclear magnetic resonance is proving to be particularly interesting. This equipment is able to determine the presence and location of water. This enables the determination of pore size and pore distribution as the concrete cures. Characteristics of materials such as silane can be investigated. For instance, it has

been found that silane is not effective against ingress of standing water after a period of two days.

Many other areas of current research were indicated, including non-linear analysis of stiffened plates, impact analysis, dynamic analysis of steel bridges, and whole life costs and whole life performance.

5.2 Presentation 13. John Owen, University of Nottingham.

John Owen spoke principally about structural health monitoring, which he defined as collecting data in a continuous manner to improve bridge management.

Innovative methods included the use of GPS to detect movement in long span bridges.

In an HA sponsored project, the damage of sample beams due to loading was investigated. Vibration properties were measured daily. It was found that the natural frequency reduced, and the deterioration was more rapid with higher loading. The methods developed were applied to full sized beams made available at Oxford.

Further lab work was undertaken on bridge decks, which were loaded to failure. These tests showed a similar reduction in frequency to that for the beam tests.

The department has also measured the responses of bridges to wind, including the monitoring of Kessock Bridge in Scotland. The responses found were considered to be due to vortex shedding. An animated simulation of vortex shedding clearly demonstrated the phenomenon.

Other research in hand included work on the SPACES bridge with composite enclosure, and moment continuity for prestressed beams.

Future work is likely to include additional aspects of structural health monitoring, including integration into bridge management.

5.3 Presentation 14. John Macdonald. University of Bristol.

Bristol University have a new laboratory facility due for completion in 2004 called BLADE – 'Bristol Laboratory for Advanced Dynamic Engineering.' This will include an earthquake shaking table. Other laboratories are being developed.

The goals of BLADE include the aim of Developing a viable performance based engineering framework, and John Macdonald described the BLADE strategic framework.

The process models that have been developed for structure asset management were illustrated. There is a need to identify uncertainty, and acceptable / Unacceptable performance.

The work of Bristol on the subject of site monitoring was described. The Second Severn Crossing has been monitored during construction, and for several years afterwards, but the use of accelerometers. This gave rise to the following benefits: -

- Performance measurement and the design of specific solutions
- Improved methods of analysis and parameters.
- Development of tools for long term management.

Work on the bridge resulted in the addition of secondary cables. Vortex induced vibration was found to be greater than predicted. This work led to the addition of baffles to the deck which reduced the response of the deck.

John Macdonald summarised other bridge related research at Bristol, and suggested the future direction of research.

5.4 Presentation 15. Wanda Lewis. University of Warwick.

Wanda Lewis described research on the Form Finding of Suspension bridge cables, which has been ongoing at Warwick for 20 years.

The shape equation is applied to an inextensible cable. However, the cable does extend in practice, thus changing the equation. Numerical non-linear analysis is therefore required. The numerical form finding methodology uses dynamic relaxation methods.

It was concluded that an extensible cable loaded with its own weight requires non linear analysis, and form finding is required at the outset. If this is not done, errors in the hanger lengths will result, and adjustment on site will be required.

A computer program has been devised to aid analysis, called cable.exe.

5.5 Discussion of Session 4.

A wide ranging discussion on Session 4 included the following topics, remarks and opinions: -

Bridge Vibration: The oil industry use vibration mode changes. The changes due to damage were very much less than the effect of day to day changes such as sun, wetting and drying etc. There was general agreement to this, and there is a need to take account of the whole response. On the Severn Bridge, the environmental response has been measured and understanding built up over several years.

Form Finding: Concern was expressed at analysis assuming elastic range, as many bridges were complex, built with gravitational effects which introduce errors. This was agreed. The analysis may be amended and the problem solved.

Silane: Other work has also shown that silane is not effective with standing water, although this was not widely appreciated in existing specifications. The nuclear magnetic resonance method offered a promising method of increasing understanding.

6. SESSION 5. AM 28th October

6.1 Presentation 16. Clive Melbourne. University of Salford.

Clive Melbourne illustrated a variety of attractive arch bridges in the introduction to a summary of the problems of management of arch bridges, and work at the University of Salford.

The internal structure of arch bridges may be unknown from external appearance, and may include features such as vaulting. Materials used for the barrel, spandrel and backfill are variable, and interact. This complicates the problem of accurate modelling of behaviour, and different strategies may be adopted. Further complication is the possibility of ring separation.

A perfect structure would fail be crushing only, but in practice the geometry of arches is much more likely to form hinges. Clive Melbourne then demonstrated the failure mechanisms found from laboratory tests. Ring separation was modelled by the introduction of sand layers, and was found to considerably reduce the load capacity.

Significant building of arches in the UK ceased around 1900 due to the cost of labour, but continued in China until the mid 20th century.

The problem of skew arches was discussed, and the line of failure of such structures was illustrated. Laboratory tests monitored skew arches with pressure cells embedded in the fill. These showed complicated interaction between adjacent spans. This was also a feature of the work on masonry jack arches.

Faults in masonry arches were illustrated, together with two potential repair techniques. For the laboratory trials, reinforcing the intrados was found to aggravate ring separation, which governed the failure. Pattress plates introduced to stabilise spandrel walls were found not to change the mode of failure.

6.2 Presentation 17. Su Taylor. Queen's University, Belfast.

Su Taylor discussed the background to compressive membrane action, which provides inherent strength due to in-plane forces. As a result, there is a significant increase in arching capacity above bending strength.

Compressive membrane action has been modelled in Belfast since 1980 by Ranking. Model decks, comprising less reinforcement than is required by standards, have been tested. It was found that the capacity did not increase with increased reinforcement. As a result, the Northern Ireland code reduced required reinforcement from 1.7% to 0.6%, which leads to improved durability as well as reduced cost. This work also influenced BD8/02 published by the Highways Agency.

Development for the UK looked at single layer reinforcement and fibre reinforcement, with the aim of reducing maintenance costs. It was found that the failure load increased with increase in concrete compressive strength, and failure was by compression failure.

Tests have been undertaken on model decks, simulating Y-beam decks. Although it was found that failure load did increase as reinforcement was added, the design was shown to still be conservative with no reinforcement. Lateral restraint was shown to increase the capacity of the slab.

Compressive membrane action has also been investigated on a real structure, Corrick Bridge. This was constructed with variable levels of reinforcement. This was tested at full scale, with beam centres of both 1.5m and 2m.

Crack widths were measured. All slabs were found to behave satisfactorily, including those with 0.25% reinforcement, with crack widths below code permitted values.

Compressive Membrane action (CMA) has also been tested in GFRP reinforced bridges. Simply supported GFRP did not behave well, although with lateral restraint GFRP was found to behave slightly better than steel.

It was concluded that CMA is now well understood, and it would be good to seen the method more widely used.

6.3 Presentation 18. Ramiz Delpak. University of Glamorgan.

Ramiz Delpak described the use of IR Thermography in structural health monitoring. This work arose from many sponsors, and provided information relevant to strengthening and repairing. Thermal methods may be used to determine the location of irregularities, and changes.

The formation of blisters beneath FRP have been examined, and effects tested for a variable percentage of air voids. Blisters can be detected beneath the reinforcement by IR thermography. Images can be obtained from a distance of 2.5m and 20 m. from the beam. Tests on the beaks demonstrated a detectable reduction in capacity for a beam with air voids.

Work on IR thermography has demonstrated the potential effects of poor workmanship, and a means of detecting it. Thermal imaging can also detect cracking of the concrete behind the reinforcement, as this is shown up by separation. Such cracking can be detected at a lower load than ultimate failure, and can still be seen if concealed by the reinforcement.

6.4 Presentation 19. Cam Middleton, University of Cambridge.

Cam Middleton indicated that there were 5 members of staff in the structures group with a bridge background, and gave a resume of their expertise and experience.

Work in the Department included yield line theory sponsored by HA, with followed on from early work at trl.

The COBRAS program was described – 'Concrete Bridge Assessment Program', which examined complex failure mechanisms. Good correlation had been found with test results, which gave a high degree of confidence. The work had illustrated that may bridges would fail assessment by elastic analysis, but would be satisfactory if analysed by yield line theory. More widespread application of yield line analysis would result in a saving of very large sums of money, far in excess of the cost of research. It was frustrating that the research findings were not more widely applied.

5.5 Discussion of Session 5, and general issues.

A wide ranging discussion followed, and included the following topics, remarks and opinions: -

Bridge Assessment: Tests at Cambridge to develop shear failure mechanisms on model decks had achieved variable results, but remained better than existing methods. A project on uncertainty in inspection and testing of concrete bridges for HA had found that strength and condition evaluation data was variable. Cambridge have investigated the yield strength distribution of reinforcing bars. The risk assessment of bridges needs to ask the question 'How safe is safe enough.' Work has been undertaken on the strength assessment of RC voided slab bridges using yield line analysis, but there is little work in this area.

Techniques: Photographing of strain fields can be used to detect movement. Photo realistic computer vision application is a technique that can locate the section of a structure to which data applies by constructing a 3D image from photographs.

NDT: A multi-mode sensor device is likely to be able to detect the size, location and corroded area lost on a reinforcing bar. Should be sensitive enough to detect significant corrosion.

The Joint Bridge Researchers' & Owners' Forum was followed by a short meeting of the Bridge Owners to discuss the way forward.