Non Destructive Testing Group

University *of* Edinburgh
School *of* Engineering

Current load carrying capacity of a structure or component from a Relaxation Ratio Analysis of Acoustic Emission NDT: *Influence of ground borne vibrations*

Professor Mike Forde

FREng, FRSE, FACI

University of Edinburgh, Scotland

m.forde@ed.ac.uk

FIF4 Cambridge 5-6 September 2012

Industrially Driven Needs

- Need to know residual load carrying capacity of concrete beams – *HA* funded (PhD – Sabrina Colombo)

- Need to know remaining service life of suspension bridge cables – *Forth Road Bridge* (Barry Colford*) & *Bridge Technology Consulting Inc*, NYC (Dr Khaled Mahmoud*)

- Need to know remaining service life of Macalloy Bars tieing p-t beams – where structure is subject to ground borne vibrations - *Network Rail* (Brian Bell*) & *Bridge Owners Forum*

FIF demonstrated a Need: Radically different approach

- Classical Structural & Geotech analysis OK for new structures?
- Classical Structural & Geotech analysis *NOT* OK for existing deteriorated structures?
- FE analysis more flexible but still v. difficult to predict real behaviour
- **New approach proposed - based on AE**

Partners

Universities	Industry
University of Edinburgh	Forth Road Bridge
Heriot Watt University	Bridge Technology Consulting, NYC
Cardiff University	AECOM, Vernon Hills, IL, USA
	Strainstall
Kumamoto University	Network Rail?
Kyoto University	Highways Agency?
	TRL?

BTC BRIDGE CABLE MOCK-UP EXPERIMENT

FUNDED BY:
U.S. NATIONAL SCIENCE FOUNDATION

BRIDGE TECHNOLOGY CONSULTING

Outline

- **Wires are zinc-coated made of 5-mm in diameter high strength steel.**

- **Wires are made from the same stock of wires used to fabricate the main cables of the San Francisco-Oakland Bay Bridge Self Anchored Suspension Bridge in California, USA.**

- **Each wire in the Mock-up carries the same level of load in a real suspension bridge wire.**

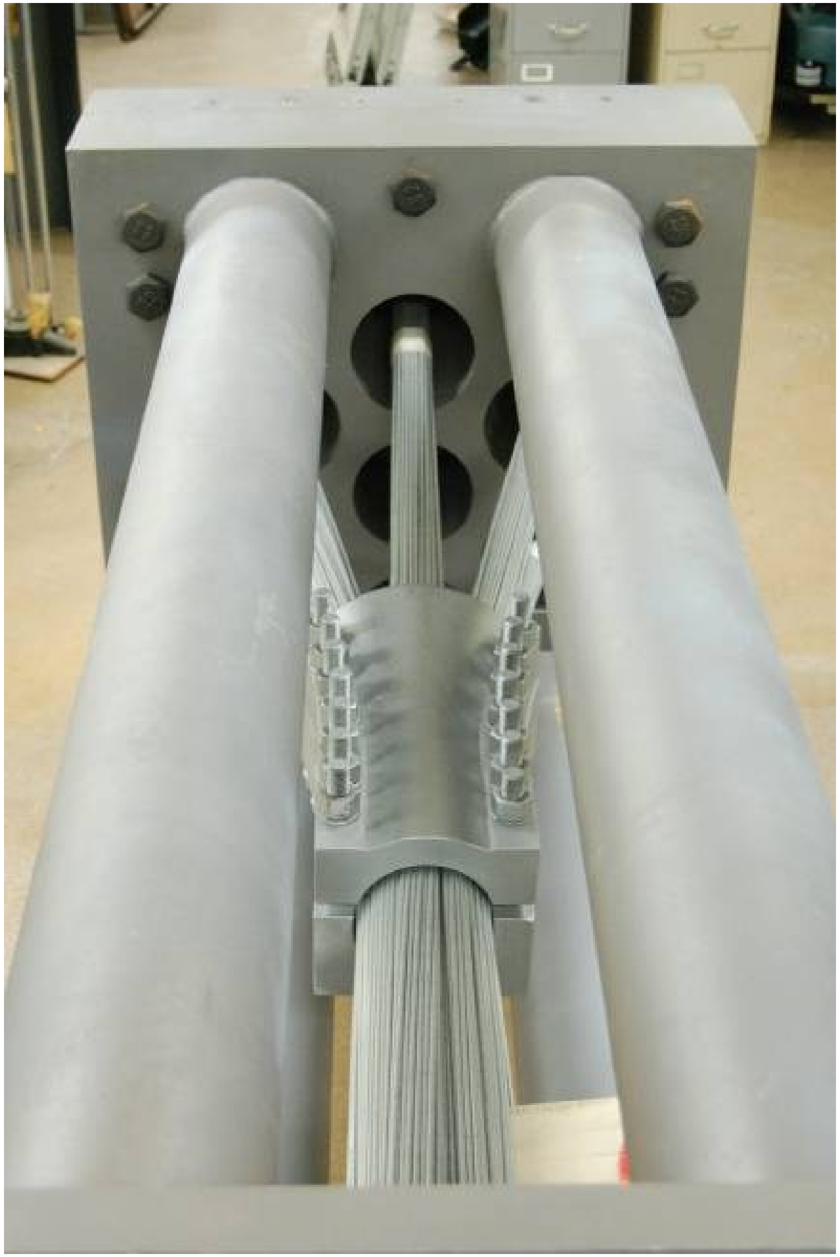
- **BTC is currently building an environmental chamber around the cable Mock-up.**

- **The environmental chamber is to mimic real weather condition as follows:**
    - **Rain, Salt and Fog.**
    - **Cyclical variation of temperature.**

- **The cable Mock-up will be instrumented with:**
    - **Corrosion sensors to monitor corrosion activities.**
    - **Acoustic monitoring sensors to monitor wire breaks.**
    - **Temperature and humidity sensors.**

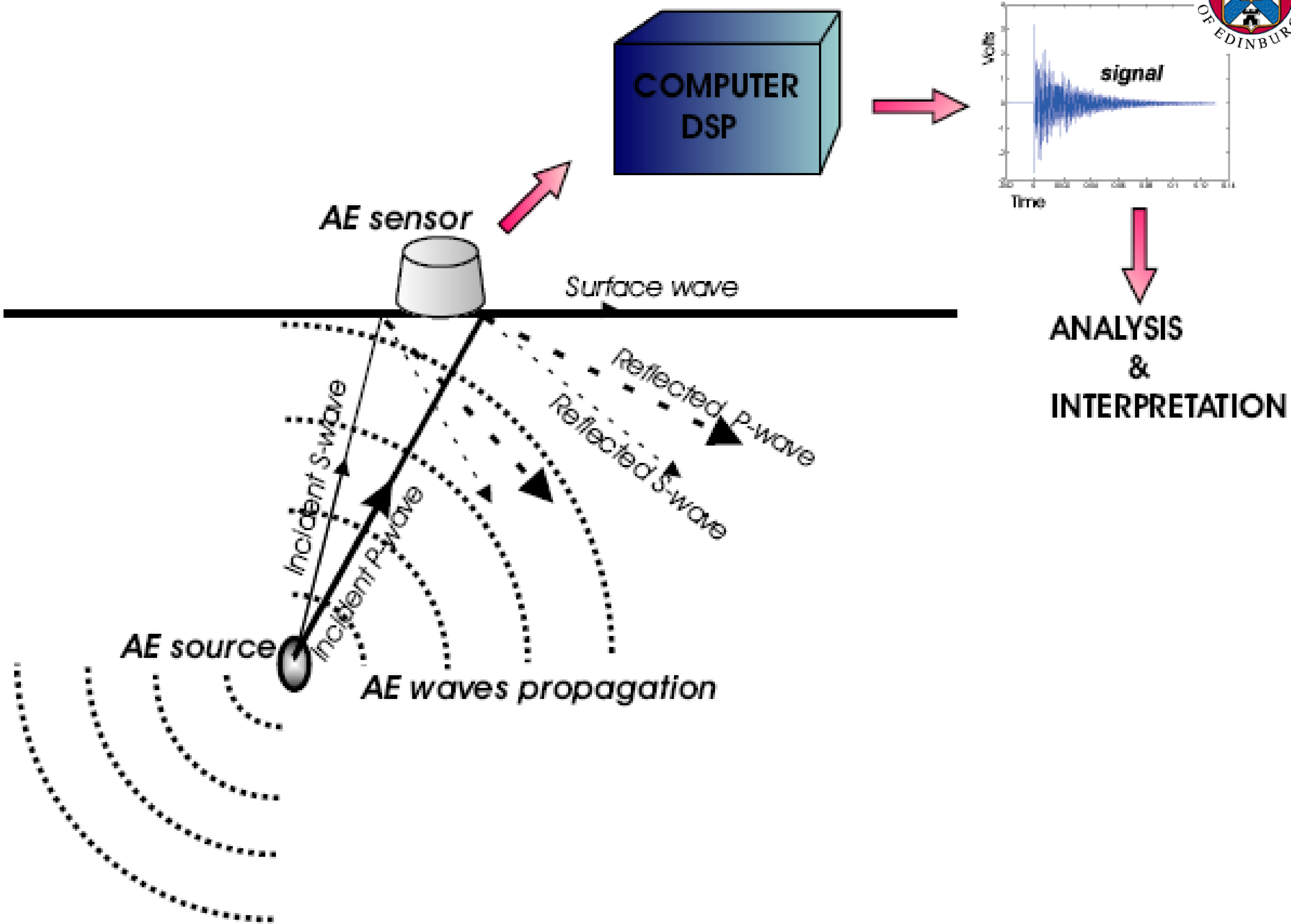
Cable Monitoring

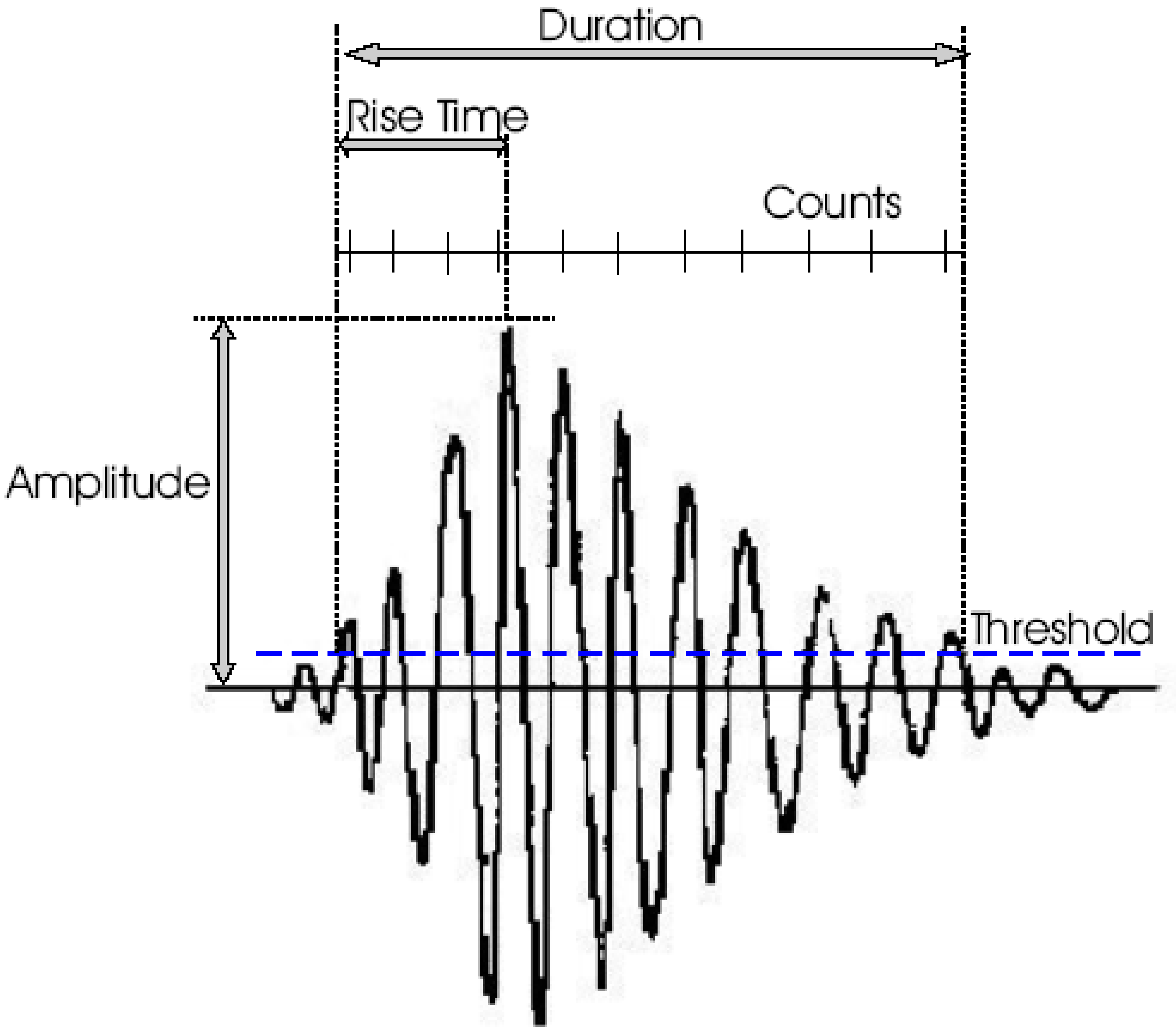
Cable Monitoring



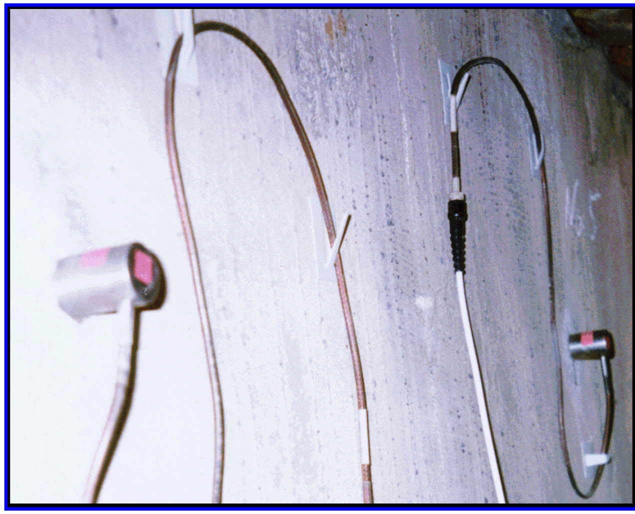
Cable Monitoring

Cable Monitoring


COMPUTER
DSP
signal
Volts
Time
ANALYSIS
&
INTERPRETATION
AE sensor
Surface wave
Reflected P-wave
Reflected S-wave
Incident S-wave
Incident P-wave
AE source
AE waves propagation


Duration
Rise Time
Counts
Amplitude
Threshold

Equipment



Reinforced Concrete Beam Test at University of Edinburgh

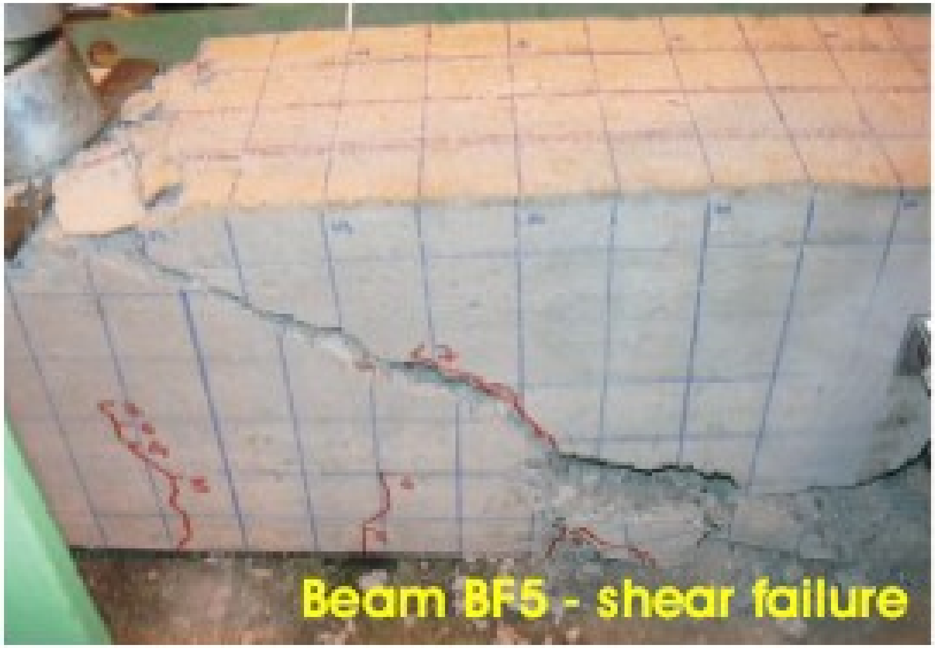
Sabrina Colombo

AE

&

Soundprint transducers

University of Edinburgh Beams



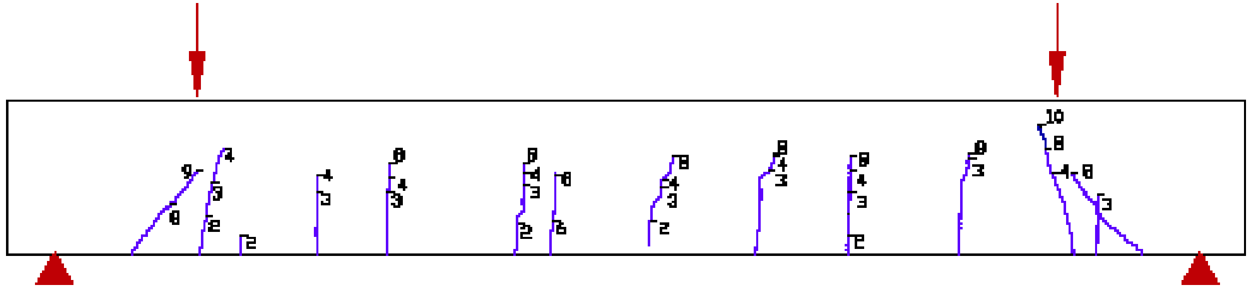


Figure 6.11: Final crack pattern of beam BF2.

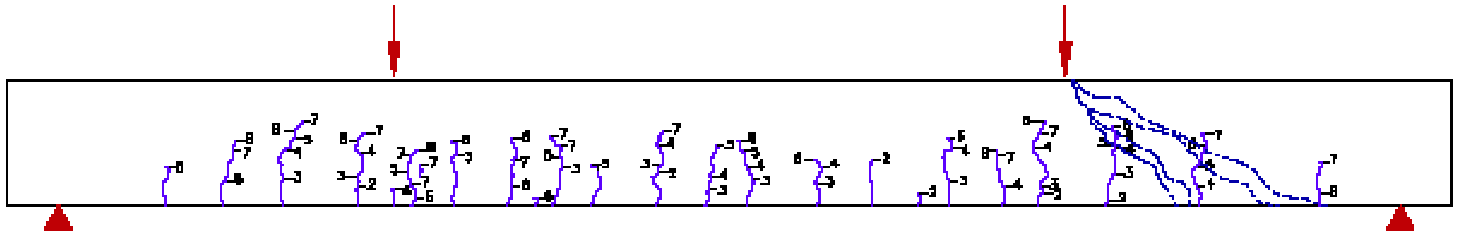


Figure 6.12: Final crack pattern of beam BF3.

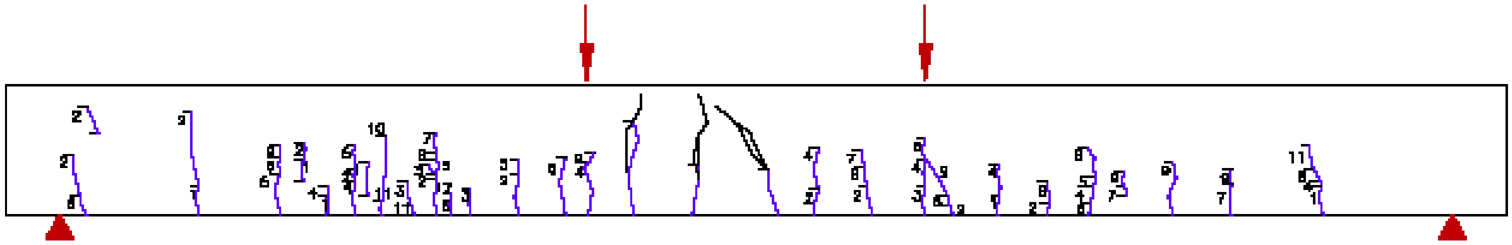
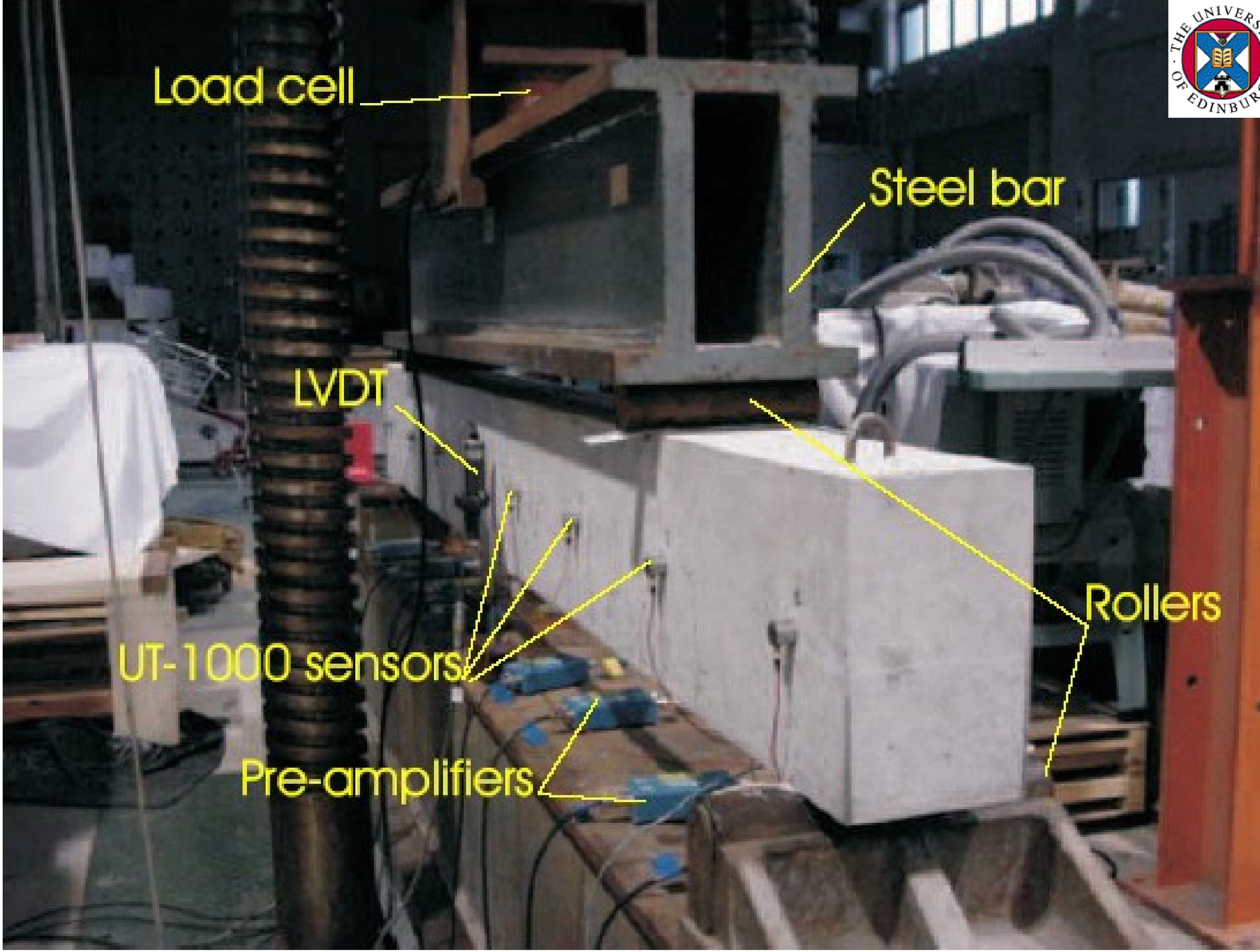
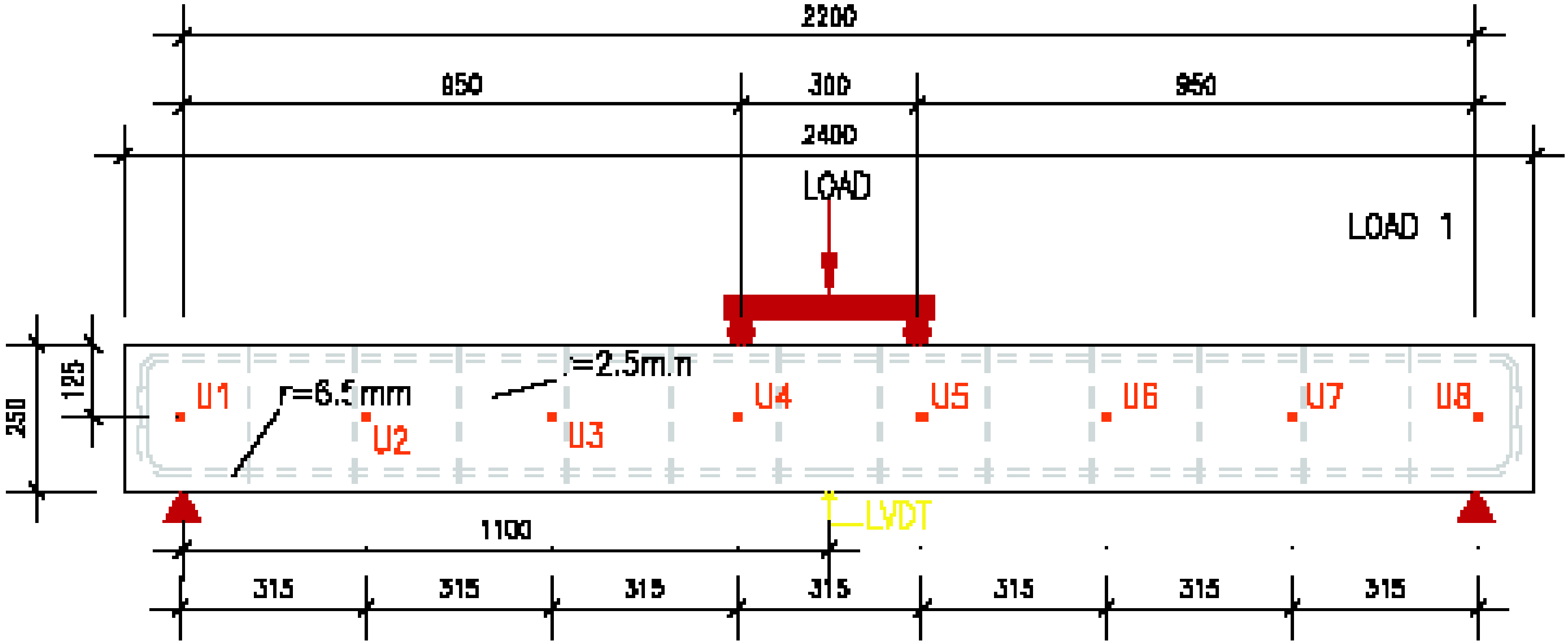


Figure 6.13: Final crack pattern of beam BF4.

Kumamoto University Lab Expts


Load cell
Steel bar
LVDT
Rollers
UT-1000 sensors
Pre-amplifiers

Kumamoto Beams K1 & K2



TRL Expts

Figure 6.23: Beam HB2. Test configuration and instrumentation.

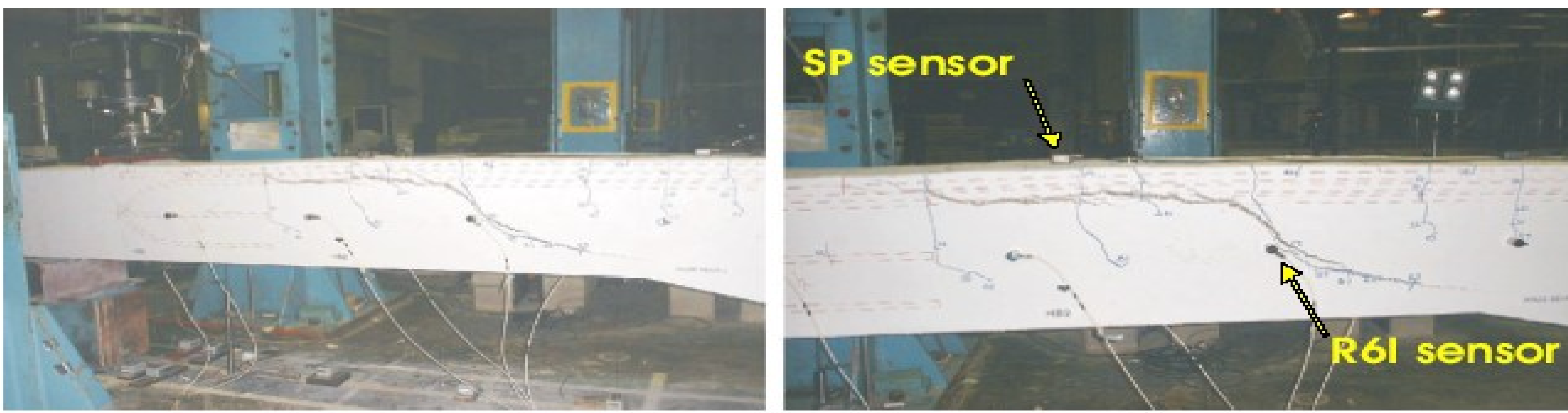


Figure 6.24: Beam HB2. Shear Failure.

Soundprint Data Analysis

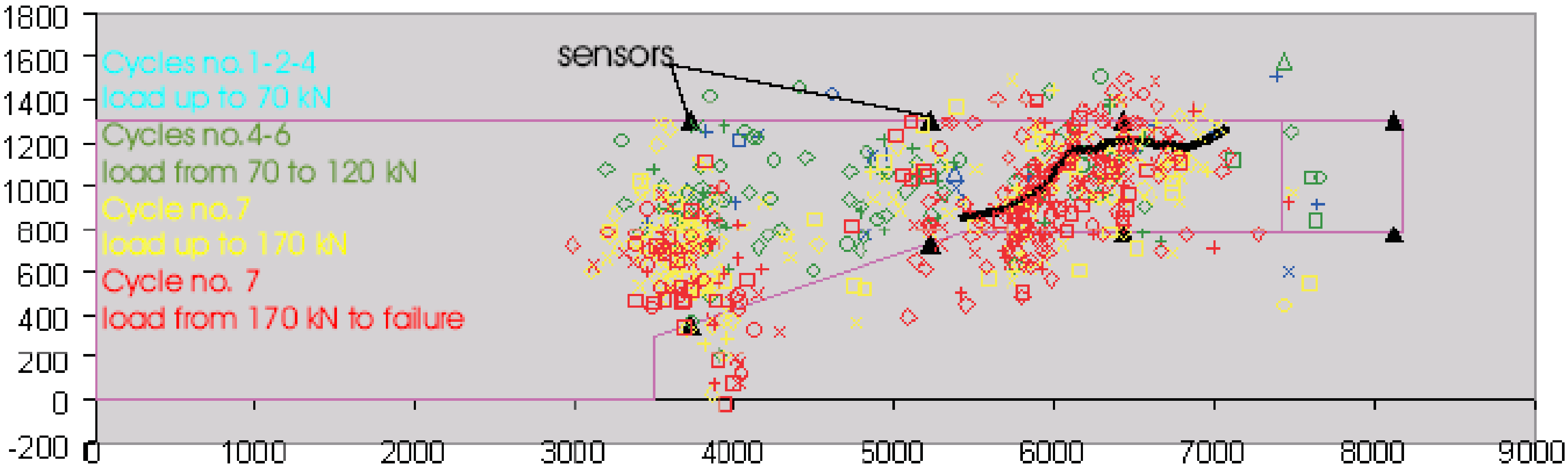


Figure 7.38: Location of SP events during the whole experiment for beam HB2. The different colors indicate different loading stages.

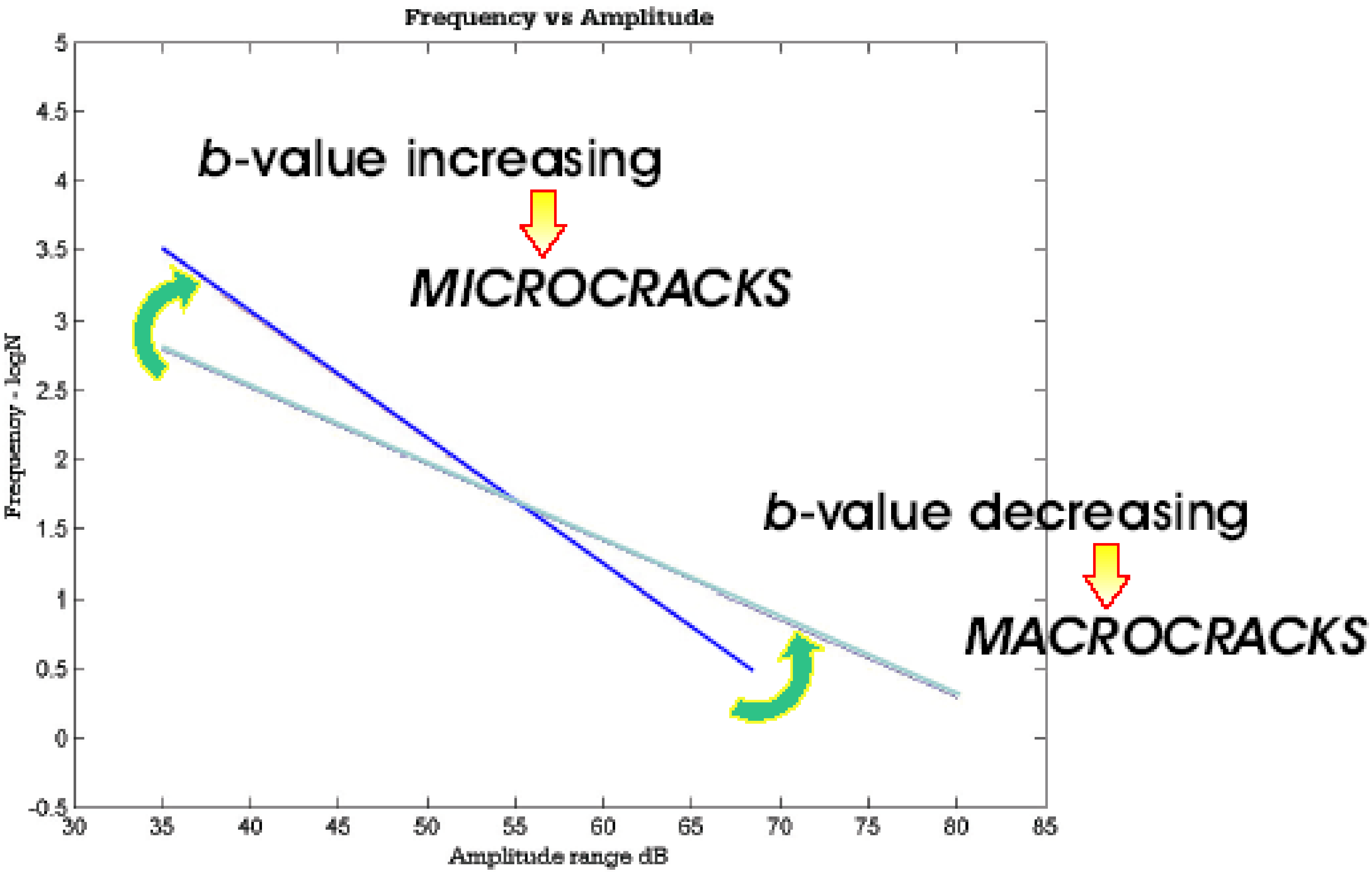
Gutenberg-Ritcher formula can be modified as:

$$\log_{10} N = a - b' A_{dB}$$

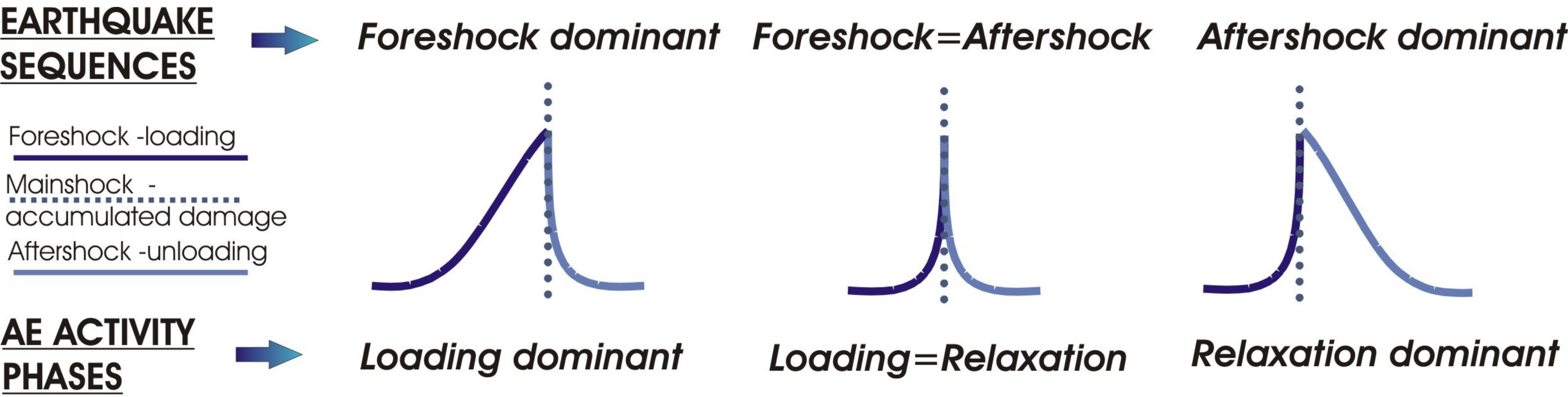
where A_{dB} is the peak-amplitude of the AE events in decibels:

$$A_{dB} = 10 \log_{10} A_{max}^2 = 20 \log_{10} A_{max}$$

b-value	*Cracking process*
$1.0 \leq b - value < 1.2$	Implies that the channel is very near to a large crack; i.e. macrocracks forming
$1.2 < b - value \leq 1.7$	Uniformly distributed cracking; i.e. macrocracks are constant
$b - value > 1.7$	Microcracks are dominant or macrocracks are opening


Frequency vs Amplitude
b-value increasing
MICROCRACKS
b-value decreasing
MACROCRACKS
Frequency - logN
Amplitude range dB
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
30
35
40
45
50
55
60
65
70
75
80
85

"Relaxation Ratio"



$$\textit{RELAXATION RATIO} = \frac{\text{Average energy during unloading phase}}{\text{Average energy during loading phase}}$$

“Relaxation Ratio” Analysis

Record AE parameter data

↓

Convert into ASCII file

↓

Calculation of “relaxation ratio” parameter

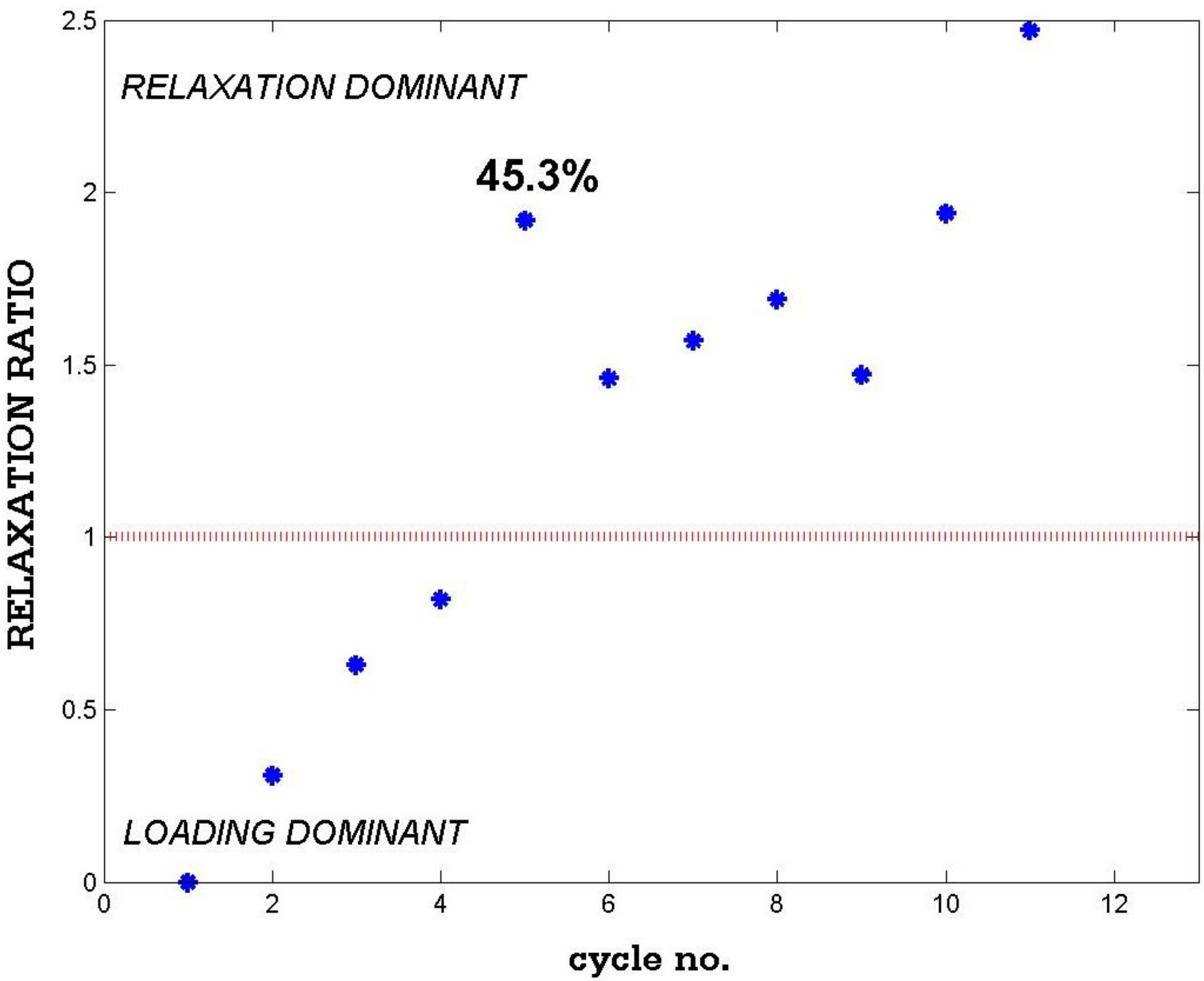
(Excel, MATLAB,…)

Laboratory Experiments - Beam details

	Section	Span	Reinf.	Concrete	wave vel.	Failure	Sensors	Threshold
BF2	125x270	2m	Simply reinf.	25MPa	3800m/sec	shear	R6I	35dB
BF3	200x275	3m	Shear links at ends	25MPa	3700m/sec	shear	R6I	40dB
BF4	200x275	3m	Shear links at ends	25MPa	3300m/sec	bending	R6I & WD	35dB
BF2c	125x270	2m	Simply reinf.	Pre-damage	3300m/sec	shear	R6I & WD	35dB
BF5	200x275	3m	Simply reinf.	25MPa	3100m/sec	shear	R6I & WD	35dB
BF6	200x275	3m	Stirrups cage	25MPa	3100m/sec	bending	R6I & WD	35dB

	Section	Span	Reinf.	Concrete	wave vel.	Failure	Sensors	Threshold
K1	150x250	2.2m	Stirrups cage	45.99MPa	3600m/sec	bending	UT-1000	40dB
K2	150x250	2.2m	Stirrups cage	45.99MPa	3600m/sec	bending	UT-1000	43dB
K3	150x250	2.2m	Stirrups cage	45.99MPa	3600m/sec	bending	UT-1000	43dB
K4	150x250	2.2m	Stirrups cage	45.99MPa	3600m/sec	bending	UT-1000	43dB
KL1	150x250	2.2m	Simply reinf.	45.99MPa	3600m/sec	bending	UT-1000	43dB
KL2	150x250	2.2m	Simply reinf.	45.99MPa	3600m/sec	bending	UT-1000	43dB

“Relaxation Ratio” Analysis - Group 1

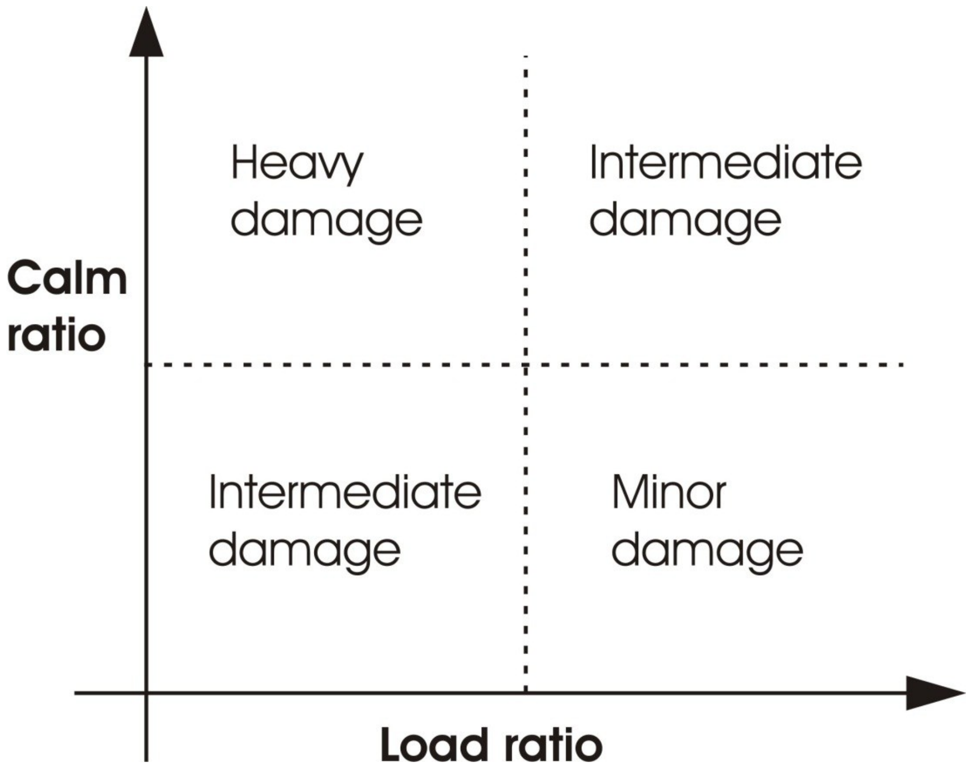


On beams:

BF2
BF3
BF2c-r
BF2c-b
BF4-r
BF4-b

>1 when load = 45%UL

“Relaxation Ratio” Analysis - NDIS - 2412

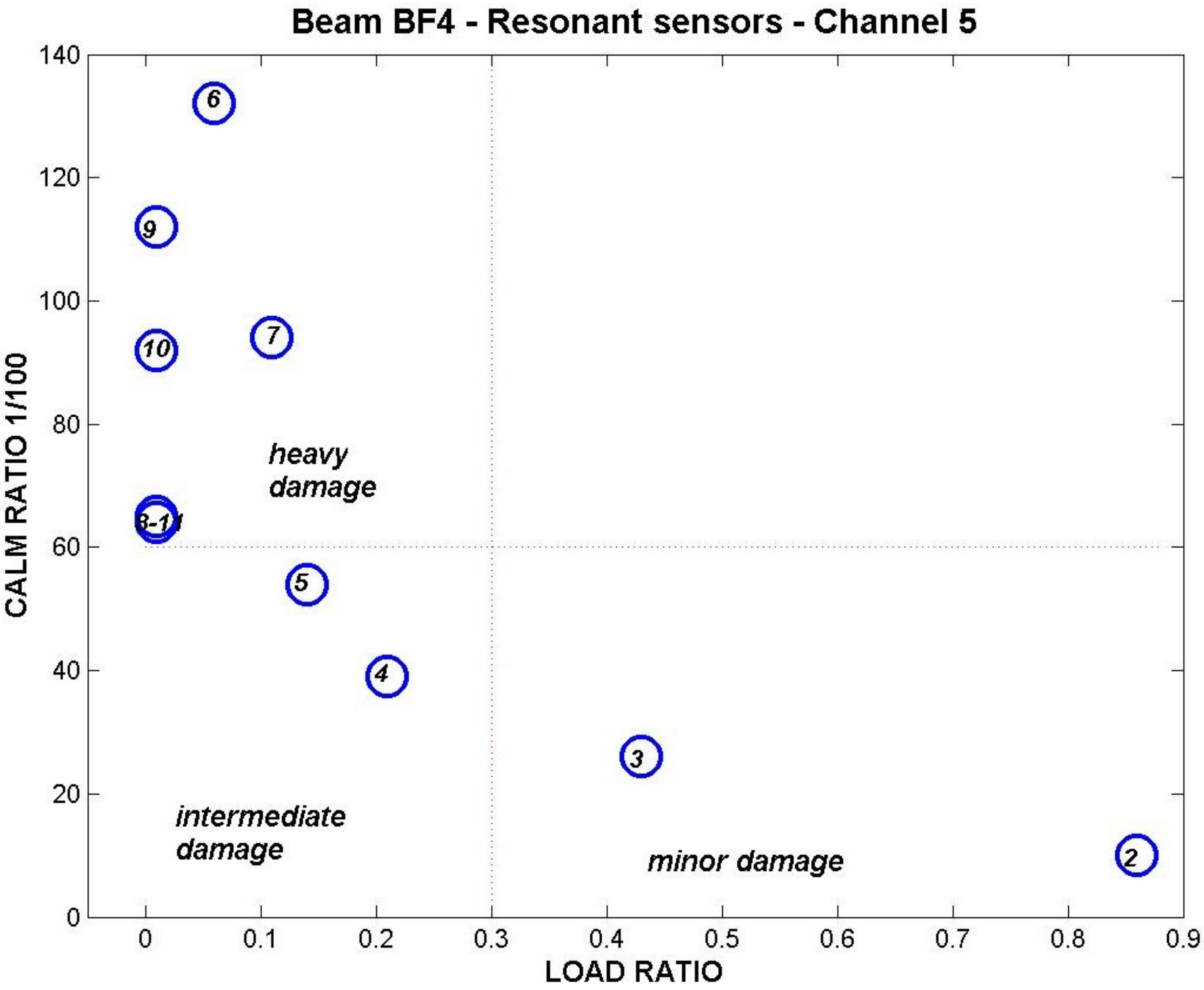


- **Proposed by Japanese Society for Nondestructive Inspections (JSNDI)**
- **after Ohtsu, 2002**

$$\textit{Load Ratio} = \frac{\text{load at onset of AE activity in subsequent load}}{\text{previous load}}$$

$$\textit{Calm Ratio} = \frac{\text{number of cumulative AE activities during unloading}}{\text{total activity during last loading cycle}}$$

"Relaxation Ratio" Analysis - NDIS - 2412



Heavy Damage after cycle no. 5

Supporting relaxation ratio results

Initial AE Conclusions

- AE survey on composite bridge:
  - AE detected on masonry;
  - AE: good results with concrete
- AE detect on-going deterioration in concrete
- AE: type of failure mechanism - moment-tensor method

Key AE Conclusions

- *RELAXATION RATIO =*

$$\frac{\textit{average energy during unloading phase}}{\textit{average energy during loading phase}}$$

- Relaxation ratio became > 1 when approx 45% of ultimate bending load was reached
- **Predict failure load of RC beams by multiplying load at Relaxation Ratio of 1 - by a factor of 2.2**
- **Limitations: Loading rate & concrete mix?**

Relaxation Ratio Conclusions

- promising to define state of damage

- results affected by:
  - properties of concrete
  - loading rate

- suggestion of new load procedure …
  evaluation of carrying capacity of concrete bridge beams?

- Key link between ground borne vibration from trains and failure of Macalloy bars

FIF: Industry Driven Needs

- Assess residual load carrying capacity of concrete beams – *HA* funded (PhD – Sabrina Colombo)

- Assess remaining service life of suspension bridge cables – *Forth Road Bridge* (Barry Colford*) & *Bridge Technology Consulting Inc*, NYC (Dr Khaled Mahmoud*)

- Assess remaining service life of Macalloy Bars tieing p-t beams – where structure is subject to ground borne vibrations - *Network Rail* (Brian Bell*) & *Bridge Owners Forum*