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Predicting the Ultimate Load Capacity of Concrete Bridge Beams from the "Relaxation Ratio" Analysis of AE Signals

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ABSTRACT: This paper builds on earlier work at the Universities of Edinburgh and Kumamoto and suggests a new paradigm for assessing the load carrying capacity of existing structures. Earlier work presented an alternative approach to the problem, based on "full-scale site testing" the real structure rather than trying to model it using a finite element program with inevitable divergence from reality due to a combination of over-simplification and lack of material property details. Experiments on Reinforced Concrete (RC) beams, representative of bridge beams, are described. The beams were loaded in cycles up to failure whilst recording the acoustic emissions (AE) generated. The analysis of the AE signals was then undertaken based on a proposed new parameter, named the "relaxation ratio". This quantifies the AE energy recorded during the unloading and loading phases of a cycle test and it showed a clear correlation with the bending failure load of the RC beams. A change in trend was noted when the load reached approximately the 45% of the ultimate bending load. The results appeared to be influenced by factors such as the concrete strength and loading rate and further work is needed to extend the results to full scale testing of bridge beams.

1. INTRODUCTION

Bridges are major infrastructure assets in all countries and their assessment and maintenance is now an understood issue. After a period of relative neglect in the 1970s there is a worldwide growing awareness of the necessity to safeguard and maintain the stock of bridges as part of national infrastructure assets.

This paper describes a different approach that aims to predict the degree of damage and failure load of concrete beams by directly testing the structure. The ultimate aim would be to implement this method on to real bridge structures. The method proposed uses a newly developed type of Acoustic Emission (AE) data analysis, which utilises the parameter, *relaxation ratio*. This is based on the principle that the presence of AE energy during the unloading phase of an AE test is generally an indication of structural damage of the material and/or structure under study. The results of experiments on several RC beams are described, the relaxation ratio is calculated and the results are discussed. The emerging trend of the values of the relaxation parameter seem able to provide an estimation of the bending failure load of the tested specimens, although some external factors (discussed later on) appeared to affect the results. The validity of the proposed method was finally validated by a comparison with the assessment criterion suggested by the Japanese Society for Nondestructive Inspections (JSNDI).

2. THE RELAXATION RATIO ANALYSIS

An AE test consists of several load cycles on the material or structure of interest. Each cycle includes a loading and an unloading phase. The initial idea that led to the development of this analysis derives from observations made during the undertaking of experiments. The AE activity recorded during the unloading phase of the cycling loading procedure was increasing as the damage on the beam was progressing. In fact, AE activity observed during the unloading process is generally an indication of structural instability [1,2] This is consistent with the Kaiser effect for dilatant microcracks and implies that shear cracks do not form until near the macroscopic structural failure. While generally in an AE test, the activity generated during the unloading phase is neglected, the analysis presented here focuses on this particular activity.

A parallel can be drawn with earthquake sequences, recognised in seismology. The foreshocks and aftershocks can be seen as the acoustic emissions generated respectively during the loading and unloading phases.

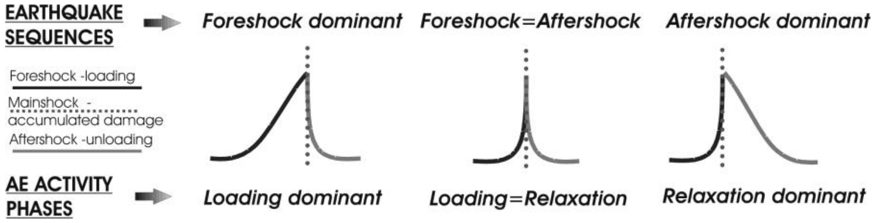

Figure 1. Schematic representation of earthquake sequences and AE activity phases. Each individual diagram shows the number of events, as a function of time, with the vertical dotted line being the time of the mainshock

Following these preliminary observations, a "*relaxation ratio*" is proposed to quantify and compare the AE activity during the loading and unloading phases. Previous experiments have shown [3] that the AE energy is an effective parameter to describe the structural damage of a beam, therefore the relaxation ratio is expressed as:

RELAXATION RATIO *= average energy during unloading phase/ average energy during loading phase* where the average energy is calculated as the cumulative energy recorded for each phase divided by the number of recorded hits. The use of the average energy overcame the problem of the different time duration of the varied cycles that could affect the results. A relaxation ratio greater than one implies that the average energy recorded during the unloading cycle is higher than the average energy recorded during the corresponding loading cycle, therefore the relaxation (aftershock) is dominant. Vice-versa, the loading (foreshock) is dominant. The analysis consisted in simply calculating the value of the relaxation ratio for each loading cycle of a sample. The process was repeated for all the specimens.

3. EXPERIMENTS

The relaxation ratio analysis was applied to three different sets of data (a total of sixteen RC beams), representative of a significant range of cases, in terms of type of failure, design, load configuration, concrete properties and type of sensors. Tables 1 and 2 provide a summary of the tested specimens - part of them were tested at the University of Edinburgh (UoE) whilst the remainder were tested at Kumamoto University (KU).

	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

Table 1. Summarised description of the beams tested at the University of Edinburgh (UoE).

	Section	***Span***	***Reinf.***	***Concrete***	***wave vel.***	***Failure***	***Sensors***	***Threshold***
K1	150x250	2.2m	Stirrups cage	46 MPa	3600m/sec	bending	UT-1000	40dB
K2	150x250	2.2m	Stirrups cage	46 MPa	3600m/sec	bending	UT-1000	43dB
K3	150x250	2.2m	Stirrups cage	46 MPa	3600m/sec	bending	UT-1000	43dB
K4	150x250	2.2m	Stirrups cage	46 MPa	3600m/sec	bending	UT-1000	43dB
KL1	150x250	2.2m	Simply reinf.	46 MPa	3600m/sec	bending	UT-1000	43dB
KL2	150x250	2.2m	Simply reinf.	46 MPa	3600m/sec	bending	UT-1000	43dB

Table 2. Summarised description of the beams tested at Kumamoto University (KU)

Loading was applied in different positions according to the type of failure wanted in cycles up to failure. Each cycle consisted of a loading phase and an unloading phase – with the final number varied from different specimens. The beams were simply supported and the AE signals recorded using a PAC AE system. Different types and models of AE sensors, resonant (R6I) and broadband (WD and UT-1000) were used - Tables 1 and 2. The sensors also varied in number and locations. ensuring that the results were not affected by these factors. Figure 2 a beam tested at Kumamoto University.

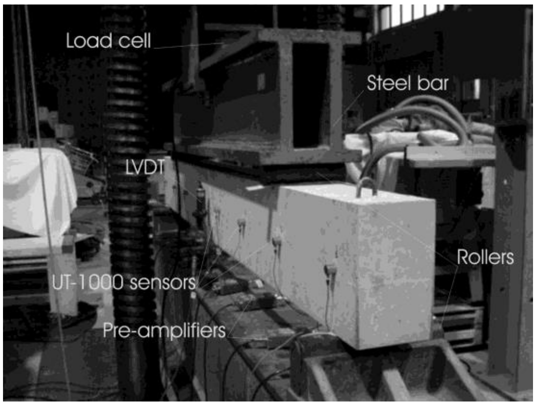

Figure 2. Photo of a test set-up at Kumamoto University.

4. DATA SET 1 & 2

Results from Data set 1 (beams BF2, BF3, BF4 and BF2c, tested at UoE) are shown in Figure 3 and a common behaviour can be noted. Initially, the loading phase is dominant and the values of the relaxation ratio all lie below the horizontal dotted line. A change of trend then occurs when the load reached approximately 45% of the ultimate failure load of the specimen. (The percentage figures refer to percentage of ultimate load.) The relaxation phase then becomes dominant. The data related to the resonant sensors on beam BF2c indicate the change of trend at a lower percentage (36.9%). This can be explained by the fact that the beam was pre-damaged. The resonant sensors might then be recording more activity and/or noise generated by the closing of the pre-existing cracks during the relaxation of the sample.

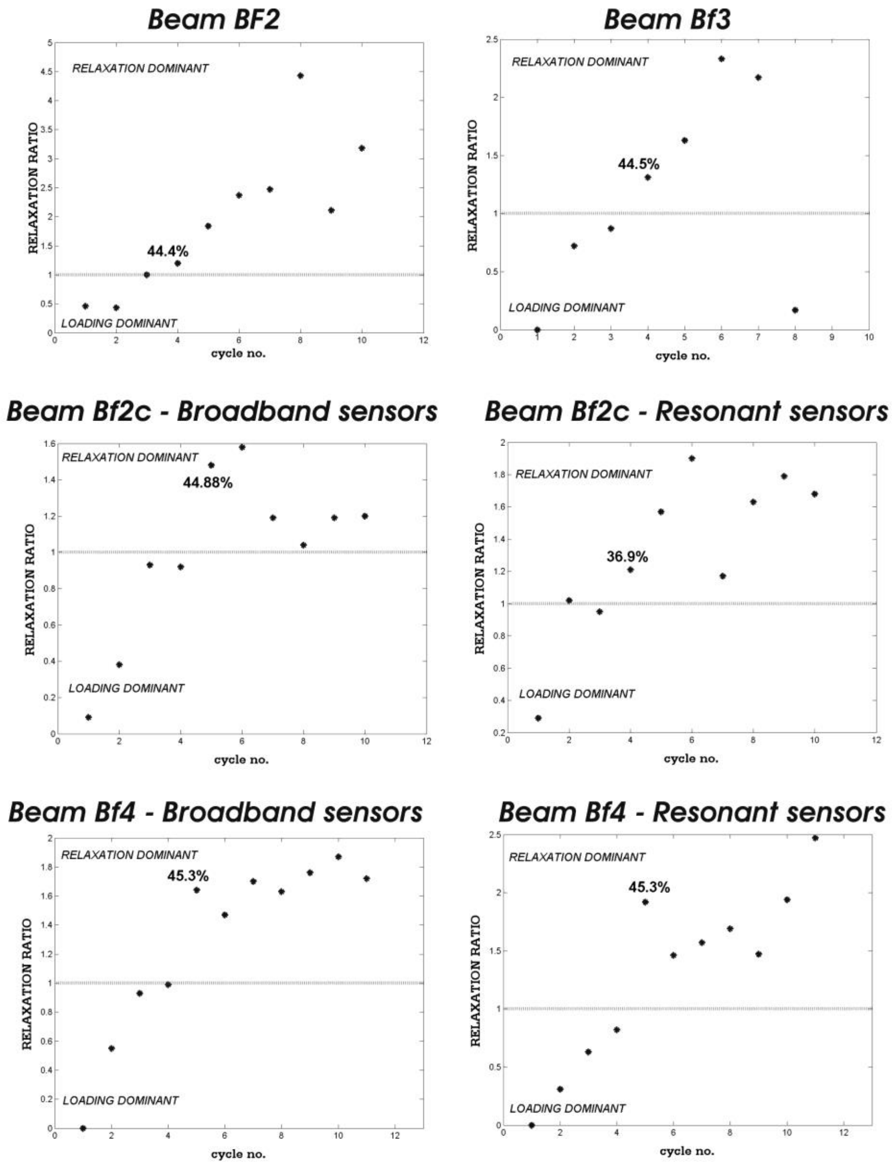

Figure 3. Relaxation ratio results of data set 1. The dotted line = relaxation ratio equal to one. The dots represent the value of the relaxation ratio (on the vertical axis) for each relative number of cycle, that can be read on the horizontal axis.

The general effect can be explained as a dominance of the primary AE activity [4] during the early stages of the fracture process when the cracks are forming and thus the damage is still restricted. Conversely, once the damage has seriously progressed, the secondary AE activity due to the friction of the existing cracks starts to prevail - manifesting itself during the relaxation phase of the tests. Data set 2 (beams K1, K2, K3, K4, KL1 and KL2 tested in KU) with their results illustrated in Figure 4. The data are more scattered and this is probably due to the fact that during these tests a higher threshold value was used (see Tables 1 and 2). The higher threshold generates a higher "signal to noise" ratio, resulting in the dispersion. However, no clear pattern can be identified in any of these six cases. In some graphs (beams K1, K4 and KL2), the relaxation ratio never exceeds the threshold value of one represented by the dotted line. In the remaining cases, some values go beyond the horizontal dotted line, but without a constant trend.

5. DISCREPANCY BETWEEN DATA SET 1 AND DATA SET 2

From Tables 1 and 2, the main significant differences between the tests used in Figures 3 and 4 consisted of:

- type and model of the AE sensor
- dimensions, design and type of failure of the beams
- characteristics of the concrete

The difference in the type of sensor was an un-likely cause. A similar conclusion can be drawn regarding the dissimilarities in design and dimensions. The last of the above mentioned possibilities is related to the characteristics of the Portland Cement concrete. The concrete used in Japan, was Rapid Hardening Portland type - this could therefore be the reason for the dominance of activity recorded during crack nucleation and formation, i.e. during the loading phase. Full details in [5].

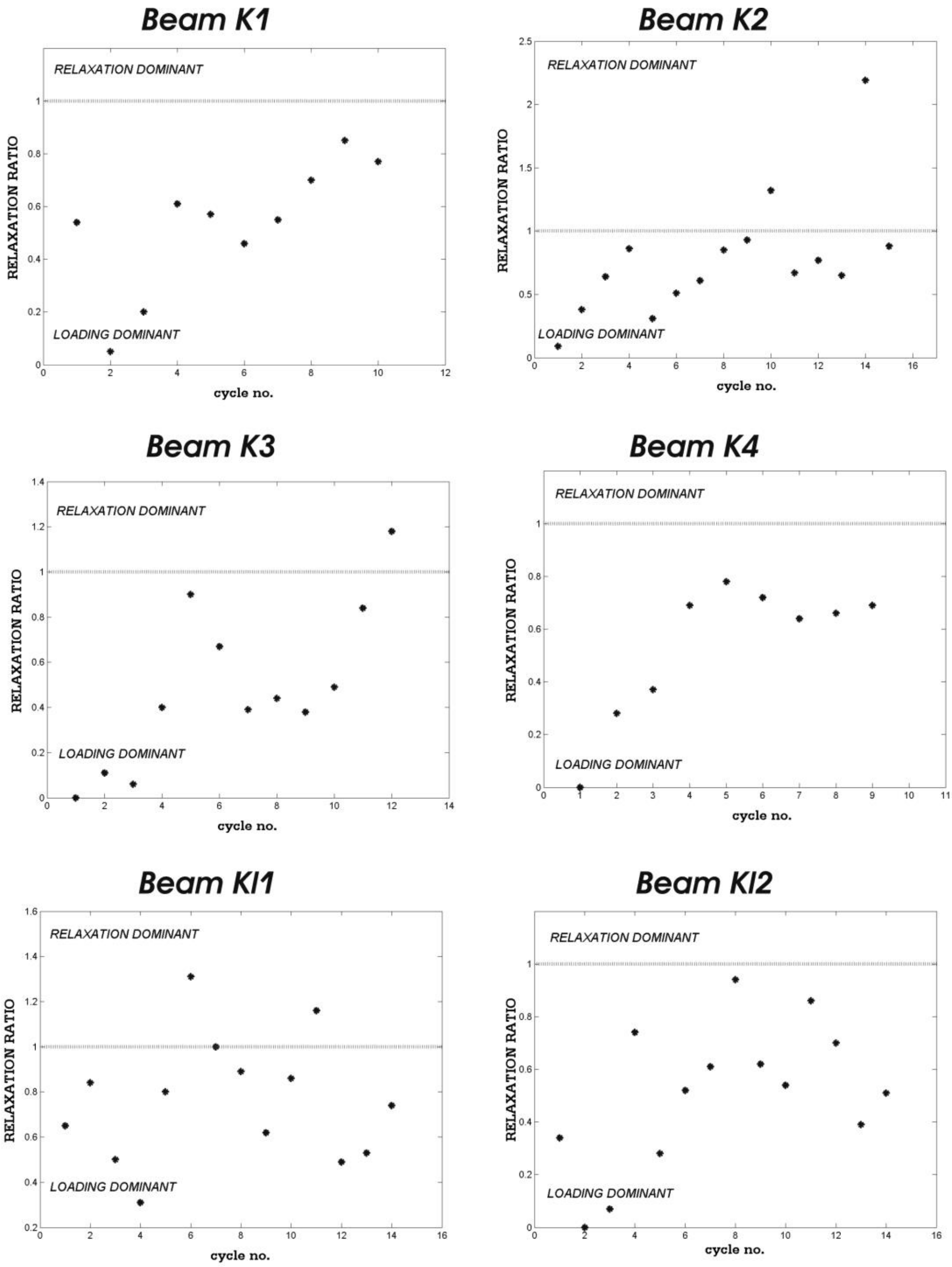

Figure 4. Relaxation ratio results of data set 2, plotted as for Figure 3.

6. DATA SET 3

To have a further confirmation, the data related to the beams BF5 and BF6 were analysed and the results are shown in Figure 5. To verify the influence of the load rate, the load was applied and removed as slowly as possible, within the limits of the test machine. The average value of load rate was in fact calculated as approximately 0.04 kN/sec [5].

The results obtained from the data sets recorded by the broadband sensors did not reveal a clear pattern. The spacing of the sensors was fixed to be exactly the same as the sensors in Kumamoto. As a consequence, they did not cover the whole length of the beam and this might explain the discrepancy with the results from the data of the resonant sensors.

1. DISCUSSION

At this stage it appeared that two main causes affected the previous results:

- the loading rate
- the properties of the concrete

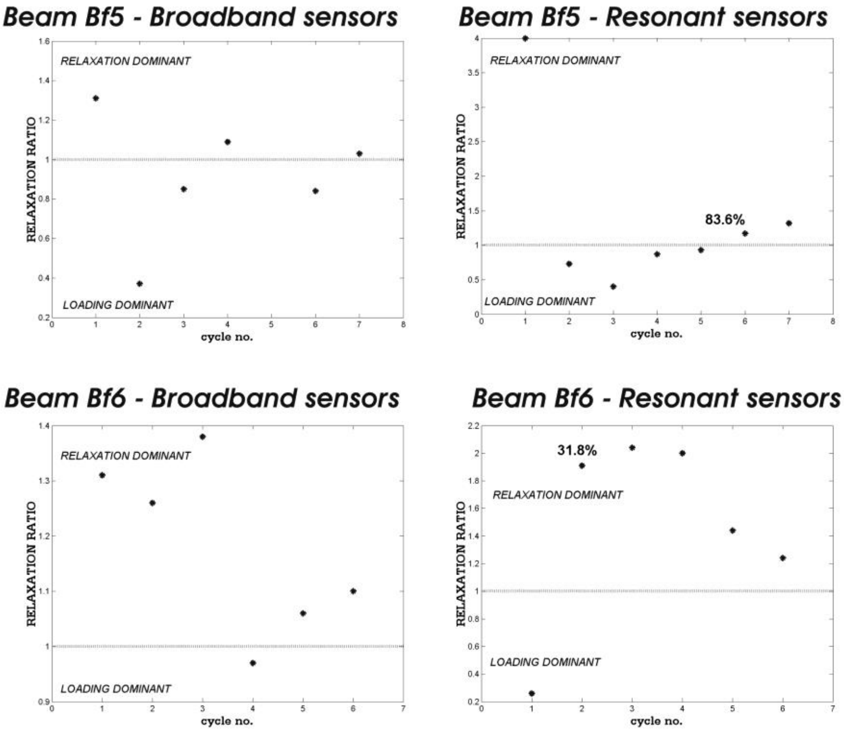

Figure 5. Relaxation ratio results of data set 2, plotted as for Figure 3.

During the loading phase, when the cracks are in the initial stage of their growth, and thus the damage is starting and it is not yet structurally significant, they release high energy and a large number of events. Conversely, once the damage has progressed macrocracks have formed and opened up, generating fewer events. The primary AE activity is therefore dominant and the relaxation ratio value is less than one. In these circumstances, the friction between the surfaces of the cracks plays a dominant role during the unloading phase, when due to the relaxation the cracks close up. The secondary AE activity is then prevalent and the relaxation ratio value is greater than one.

With reference to the work of Mori and Obata [6], it could be said that in the loading phase the cracking sources prevail, whilst in the unloading phase the friction sources are dominant. The explanation of the "silence effect" [7] also states that when the damage increased and therefore is localised, there are fewer AE sources and then less activity. This leads to the "silence time", i.e. to a period of absence of AE activity. The dominance of the unloading phase corresponding to a relaxation ratio greater than one could thus be seen as corresponding to this stage of the fracture process.

7. VALIDATION AGAINST THE NDIS PROCEDURE

The analysis described above, was finally compared to the NDIS-2421 quantitative assessment criterion proposed by the committee of the Japanese Society for Nondestructive Inspections (JSNDI) [1]. The criterion is based on the definition of two parameters:

Load ratio = load at the onset of AE activity in the subsequent loading / the previous load

Calm ratio = the number of cumulative AE activities during the unloading process / total AE activity during the last loading cycle up to the maximum and it is represented in Figure 6, where the limits of the classification (i.e. the dashed line that defined the boundary of the area of damage) were fixed on the basis of the crack mouth opening displacement (CMOD). The data from the most active channel are generally used for the calculation.

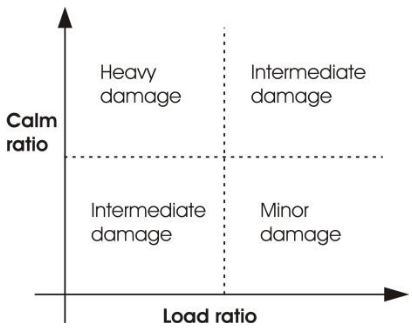

Figure 6. NDIS-2421 assessment table, from [1]

Beam BF4 was considered, for which the new procedure appeared to work (as for all the first set of the BF tests). The NDIS assessment procedure was carried out for both cases, using the data of the most active channel as well as the data relative to all the recording channels. The limits were determined graphically, as the values of the CMOD were not available. The most active channel was number 5, for both beams. The results are shown in Figure 7. The load ratio and the calm ratio are indicated on the horizontal and vertical axes respectively. The number inside the circle represents the corresponding loading cycle number. The areas of different damage are also indicated. It can be noted that the change of trend during the relaxation analysis occurred during cycle number 5. On the NDSI assessment table, that cycle corresponds to the last one falling into the intermediate damage area - after which serious damage takes place. The two results appeared then to support each other.

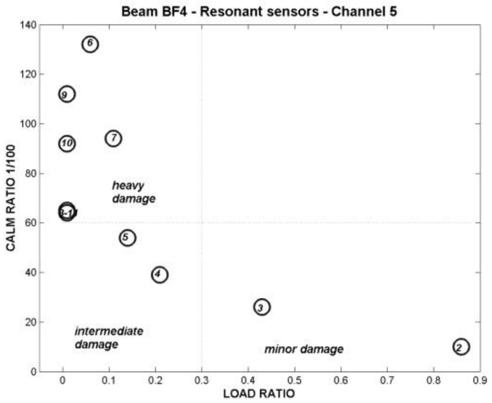

Figure 7. NDIS assessment table for beam BF4. Numbers indicate the loading cycle; the dotted lines define the different areas of damage.

It will be noted that the beams at UoE failed in shear, whilst the beams at KU failed in bending. The differences in results between UoE and KU may in part relate to the differences in concrete strength and rates of loading. It would be appropriate to consider these factors further in an extension of the project.

8. CONCLUSIONS

This paper described the application of a new type of analysis of AE signals (based on a proposed relaxation ratio parameter) to several specimens of RC beams. Although at this stage the conclusions are not definitive, due to some discrepancy in the results, the method appears very promising and suitable to practical applications.

- The values of the relaxation ratio appeared to be related to the percentage of failure load reached in a specific cycle and are therefore related to the degree of damage of the beam. A value greater than one is indicative of dominance of relaxation phase and therefore of structural damage.
- In the first data set of tests, the value of the relaxation ratio always became greater than one when approximately 45% of the ultimate bending load was reached. This gave rise to the possibility to use this method of analysis to predict the failure load of RC beams.
- The results were affected by the concrete strength and loading rate used during the experiments.
- Further work is needed to establish in which exact conditions the relaxation ratio analysis is successful. The limits of its application and the confirmation of its validity need to be investigated.

9. PRACTICAL APPLICATIONS

This work has generated international interest in the possibility of being able to predict/calculate the residual load carrying capacity of damaged/deteriorated concrete bridges.

10. ACKNOWLEDGEMENTS

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