Teaching Engineering Materials through Experiential Learning

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ABSTRACT: The authors designed and implemented a novel semester-long laboratory-based project to complement traditional lectures in a first year materials engineering module. The examinable lecture component involved the customary description of physical, mechanical, and electrical properties of materials, exemplified by studying real examples of different materials used in solving design problems. Comprising civil, mechanical and electrical elements, the multi-disciplinary project involved the development of an understanding of the material behaviour of bamboo, concrete and semi-conductors separately and the construction of a temperature sensor using semiconductor diodes and a microcontroller to allow the display and logging of temperature. This culminated in the measurement of different temperature maturities of hydrating cement in a sustainable bamboo reinforced concrete beam containing recycled materials to allow its flexural strength to be established. The sustainable materials in the concrete included recycled concrete and shredded rubber tyres as aggregate and slag as a low carbon cement substitute. The use of bamboo culms ensured a ductile tension or shear failure of the composite beams, thus exemplifying the desirability of warning of failure through controlled crack growth, influenced by the presence of steel fibres. In addition to the technical aspects of the module, the 240 students involved also learnt about aspects of statistics, project management and report writing.

KEY WORDS: Bamboo; Recycled concrete; Shredded tyres; Temperature sensors

1 INTRODUCTION

Problem-based design courses have been extant in engineering for quite some time [1]. In this paper, the authors, from three different engineering disciplines, describe the creation of a novel module, worth 10 ECTS credits, entitled Engineering Materials and their Applications, delivered to student engineers in the first semester of their degree programme. By combining traditional lectures with a fresh approach to problem-based learning, the lectures were enhanced by parallel integrated experiential learning on a weekly basis.

The ultimate objective was to examine and explain the flexural behaviour of recycled aggregate bamboo and fibre reinforced concrete beams cured under different temperature regimes, where the component parts were used as exemplars of many of the principles covered in the lectures. There were four stages in series, where each of the 240 students had the same 2 hour laboratory session every week (timetabled over 6 such sessions per week) – exposure to exploring bamboo mechanical properties, concrete manufacture and fresh/hardened properties, the construction of a temperature logger, culminating at the end of the module in the flexural testing of the composite beam whose curing was monitored by the logger. One individual report and three group reports, with 48 groups of 4-5 students in each group, were submitted in weeks 3, 6, 10 and 12, with active feedback provided to the groups after each stage. Guidance was given on the *formal structure of a technical report, how to present data properly, referencing systems, and technical language and grammar* (in this paper the skills and knowledge which the students had the opportunity to acquire in this module are highlighted by italics).

Each group elected a project manager where matters of leadership and individual and group responsibility came into play - an *appreciation of collective responsibility was quickly developed*. A system of a sliding scale of penalties for late entries was put in place and in the submission of the second report, 47 of the 48 reports were submitted on time. The students had gained an understanding of *the importance of meeting deadlines*.

Lectures were supported by tutorials leading to a traditional end-of-semester examination. Unusually, this programme was supported through a compulsory weekly class laboratory briefing which, with the laboratories themselves, amounted to 7 contact hours per student per week. Using a student card scanner, attendance was monitored, where personal attendance below a threshold (75%) was penalised by lower marks being awarded to the individual. The use of the card scanner had the desired effect of securing *an awareness of engagement through attendance*, with average event attendances of over 90%. The group's team dynamics were improved by an awareness of *the collaborative nature brought about by strong peer participation*.

The lecture content and load were shared between the three academics and coordinated to avoid overlap. The broad materials covered are listed in Table 1. The content of the laboratory sessions developed in parallel with the lectures.

2 LABORATORY COMPONENTS

2.1 *Phase I: Mechanical properties of bamboo and other materials*

Laboratory exercises during the first three weeks aimed to introduce mechanical properties, especially stiffness and strength. Such was the timetabling congestion that the first groups were taking their laboratories on the second day of term, having had only two lectures in the subject. No testing

Table 1. Physical phenomena and the materials used to illustrate these in lectures

Concepts	Materials
Mechanical Properties	Concrete
Stress-strain/ Elasticity	Steel
Elastic/Plastic; Brittle/Ductile	Timber
Creep/Shrinkage/ Fatigue	Glass
Moisture/Temperature/CO2	Aluminium
Sound/Heat/Light	Semi-
Electrical conductivity/resistivity	conductors
Durability/Diffusion/Corrosion	Reinforcement

equipment was provided, rather, the students were asked to create their own equipment from a selection of items given to them, including string, tape, metal weights, a bucket, a G-clamp, callipers, etc. This developed skills in *design of experiments* and challenged the students to consider concepts of *measurement accuracy*.

Students were given the open-ended objective to find a specific mechanical property for a given material. For example, the challenge for the first week was to “Find the Young’s modulus of a rubber band” by stretching it in tension with a known force. Before starting to construct their apparatus, each group had to present their plan to the teaching assistant, consult their lecture notes etc. for the necessary theory. Students were encouraged to bring laptops, tablets etc. for this purpose. Once their plan had been approved, the group constructed and used their equipment in different ways to the same end. Students were encouraged to learn from their mistakes in an open positive way. Each group was then required to complete the necessary calculations to obtain the property value required and to check that this value was reasonable by comparing it with values for the same material found online.

The equipment provided was of a sufficient range that there was always more than one way of achieving the objective, with some approaches being easier and/or more accurate than others. Students were encouraged to *brainstorm ideas and criticise them* before commencing.

The most organised groups completed their work in 15-20 minutes, others much longer, demonstrating a capacity in some students to *self-organise and work as a team.*

For the second session each group was given a culm of Moso bamboo, approximately two metres long and one centimetre in diameter. They were required to find its tangent Young’s modulus and ultimate strength. For this they had to appreciate that a simple tensile test was not going to be possible for practical reasons and that a bending test was needed. The students devised their own tests and Figure 1 shows an example of the equipment created, using three-point bending.

In the third and final session the objective was to measure the fracture toughness of paper. This required them to apply force to a sample of paper into which they had first introduced a crack by cutting. A common mistake was to underestimate the amount of force that would be needed. This encouraged them to carry out *order of magnitude estimates* before commencing.

Each of the 240 students was required to submit an individual laboratory report on one of these experiments. A template was provided, structuring the report in the style of a typical research paper. It was interesting to observe the very high quality of these reports, their use of images and diagrams, citations of relevant work from the literature and observant criticism of their experiments and results. This part fulfilled the objective of *learning to write technical reports.*

Figure 1. Students working in groups to establish how best to evaluate bamboo flexural stiffness and strength.

2.2 Phase II: Concrete properties

In Phase II, over three weeks of lectures and laboratories, students working within their groups learnt *how to perform standard fresh and hardened concrete tests* where now the tests were not open-ended as in Phase I – they had to be performed strictly following international standards. Tests were undertaken to establish densities, workability (though a slump test), cube compressive and beam flexural strengths. Each group manufactured their own specimens for testing and performed all their own tests. The week after testing, the collective results were shown to the class in the next briefing lecture, from which lessons were learnt about *the sources of variability* – the concrete batch, the test method, the person doing the testing, the influence of delay in conducting the workability tests, the influence of different compaction, curing and temperature regimes, all of which supported points made during the prior lectures.

For example, in assessing density, student groups put fresh concrete into a cylinder and calculated the density, as they had been instructed. But then they were, unexpectedly, asked to do it again, this time compacting the concrete in layers as they proceeded to fill the cylinder. In explaining the difference between these two calculated density values the students gained an appreciation of *why concrete needs to be compacted* and were thus able to estimate the surprising amount of entrapped air content in an uncompacted sample. Subsequently, all concrete was either hand-tamped or compacted on a vibrating table and the students understood the *importance of doing this properly when trying to manufacture consistent specimens*.

In terms of workability, with the six separate batches being made over the six laboratory sessions that week, there was considerable variability in the results of the slump test, as shown in Figure 2. The importance of using basic statistics to analyse a histogram to quantify this variability was emphasised by calculating the average (Av, of 100 mm) and standard deviation (SD, of 54 mm), thereby deriving the coefficient of variability CoV (= SD /Av, of 54%), which was abnormally high for the slump test. It was explained that while every group used the same method for testing and the mixes should have been the same, one set of groups had used a new batch of sand which had a much higher moisture content which changed the workability measurably. Thus, the students developed an awareness of *the difference between systematic and random effects* especially when data has a high CoV. With justification to omit the outliers at the upper end, the new statistics (80mm Av, 30mm SD and 40% CoV) were calculated for the remaining results. The high nature of the revised CoV was mostly attributed to students queuing to do the slump test which could be 45 minutes apart, by which time the slump could have changed appreciably – an observation made by students unsolicited in their Phase II reports. So the lesson learned was the importance of *controlling all the key parameters in a test procedure as well as the mixing and the testing method* so that only the random differences in the constituents were responsible for the variations in the slump test result.

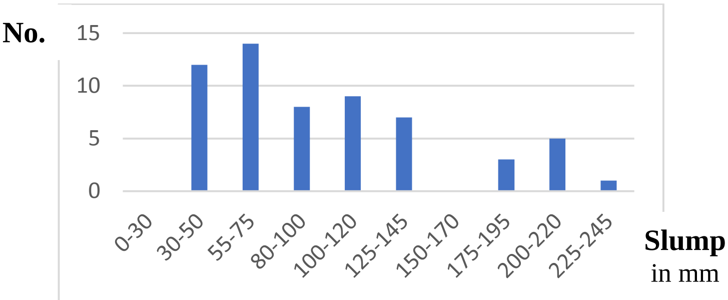


Figure 2. No. of cases in whole class slump results.

Having made their group's concrete cubes for assessing the compressive strength, σ (= force / area), 7 days later (when they had their next laboratory session), unbeknownst to the students the laboratory staff deliberately left half the cubes out of the curing tank while curing the other half in water at 20°C, as specified in standard IS EN12390-2:2019. The definition of stress and strain, as stated in lectures, helped students understand their group's load-deflection plots for cube results, where each group used a QR code to download their individual data from the cloud. This also meant that students had to learn *how to pick up a large file of Excel data and manipulate it into a relevant professionally presented plot* in their group report.

On presenting the histogram of the collective results of the cube strengths to the class, the lecturer noted again the high degree of variability, despite the proper compaction of the cubes, with a CoV of 18% and an average of 18.5 MPa (Figure 3). If the collective group load deflection plots are inspected (Figure 4), it may be observed that there appears to be two different data sets here – the cured and uncured. In announcing to the class that actually two different curing regimes had been used, it was realised by the students that such an action had a very significant influence on the results (a 25% lower strength on average in this case) (with Av = 21.2MPa and CoV = 7% for cured and with Av = 15.8 MPa and CoV =14% for uncured specimens). The students learnt *the importance of curing concrete* to ensure the cement hydration continues for the full duration before testing.

The students, in their reports, were asked to explain the shape of the load deflection plots, where initial linear behaviour cedes to reduced stiffness as microcracks propagate within the cube as load increases. This again illustrated, in practice, some of the *principles of crack behaviour* as espoused in the lectures.

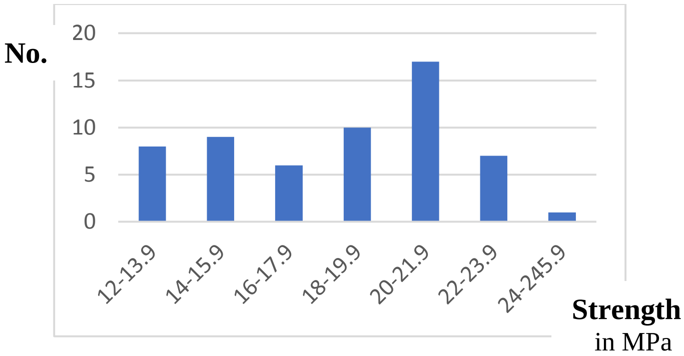


Figure 3. No. of cases against whole class cube compressive strengths.

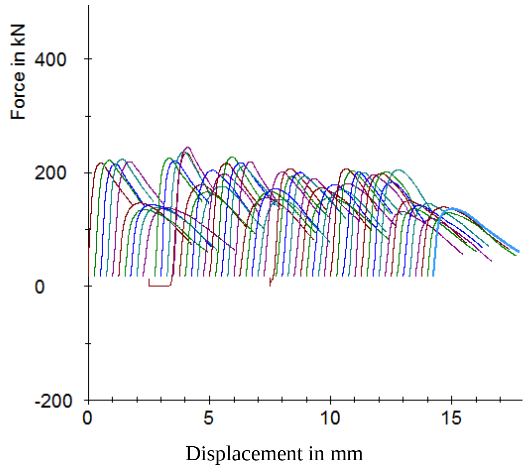


Figure 4. Plots of load versus deflection for all 48 sets of cube compressive tests.

In the flexural strength determination of the student's beams, the theory of how to calculate the flexural tensile stress from a peak load capacity was derived from first principles in the briefing, resulting in equation (1):

$$\sigma_{tens} = (3P\ L)/(2\ b\ d^2) \qquad (1)$$

where P is flexural load, L is span, b and d are beam width and depth respectively, the students carefully using consistent units.

The flexural stress, reflecting the tensile capacity of the beams, had a class average of 3.3 N/mm^2 (now introduced as equivalent to MPa) which was significantly lower than the compressive stress of 21.2MPa. This reinforced in the student's minds, as promulgated in the formal lectures, the fact that *many materials have significantly different tensile and compressive strengths*, which affect their use.

It followed that there is a necessity to use steel reinforced concrete composites in beams, where, when properly bonded to the cement matrix, the steel (strength circa 500MPa) is much more efficient at resisting the tensile forces, while the concrete resists the compressive forces which inevitably arise in all beams under flexure.

Furthermore, the brittle nature of the beam failure is very evident at this stage in the group plots which the students obtained for their individual beam tests (such as in Figure 5).

This reinforces the points made in lectures about *linear elastic materials and the brittle nature of some materials* such as concrete, chalk, ice and glass.

What was gleaned from this was that compaction, curing and temperature history are all important in determining the concrete strength. Thus, for the last phase of this project, the students knew the importance of controlling these variables when investigating the effect of different aggregates on the flexural behaviour of bamboo reinforced concrete beams.

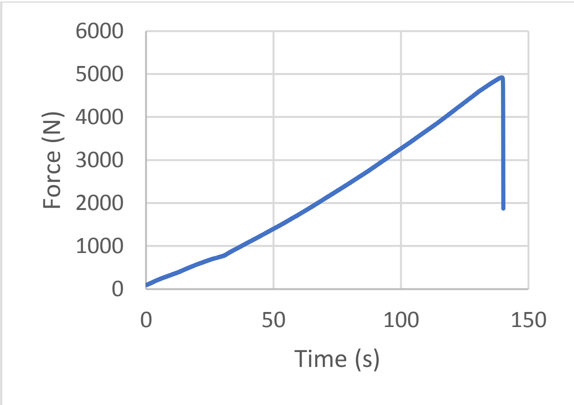


Figure 5. Typical flexural load resistance capacity vs time plot for a plain concrete beam.

2.3 *Phase III: Measuring and logging concrete curing temperature*

In the electrical section of the module, in lectures students were introduced to the electrical properties of materials. These concentrated primarily on an introduction to Silicon semiconductors, the ideal bipolar Silicon diode and a number of other properties exploited in modern electronic sensors. The laboratory programme enabled students to use a Silicon diode as a temperature sensor and to interface this, using a small breadboard based circuit, to a Uno R3 Arduino microcontroller, which then displayed the measured temperature. It used an SD card to log recorded temperatures of a concrete beam over the course of a week. The recorded data was compared with data simultaneously logged by a professional k-type thermocouple-based temperature monitor over the same period and some basic statistical analyses were performed in comparison.

In the first laboratory session, students learned through practical experience how to *correctly solder a number of diodes onto a piece of stripboard*, shown in Figure 6. The sensor was then sealed in a heat-shrink shroud to prevent water ingress.

In the second session each group had to *establish calibration parameters* for their diode sensor by measuring the voltage drop **V** across the sensor at two different temperatures **T** when excited by a constant current. Students also *constructed the simple circuit on a miniature breadboard* needed to activate the sensor and interface it with the Arduino microcontroller. Calibration amounted to *fitting a straight line equation* $V = mT + C$ *to data measured* for their particular sensor. The values of the m (slope) and C (y-axis intercept) parameters were then *entered into the programme running on their controller via an interactive user software interface* running on a PC. An example of the curves of Voltage vs Temperature for a single Silicon diode measured at a range of exciting currents is shown in Figure 7.

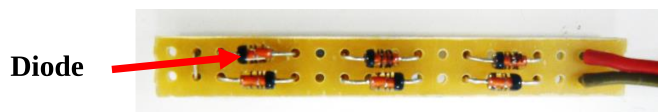


Figure 6. An example of a soldered diode temperature sensor.

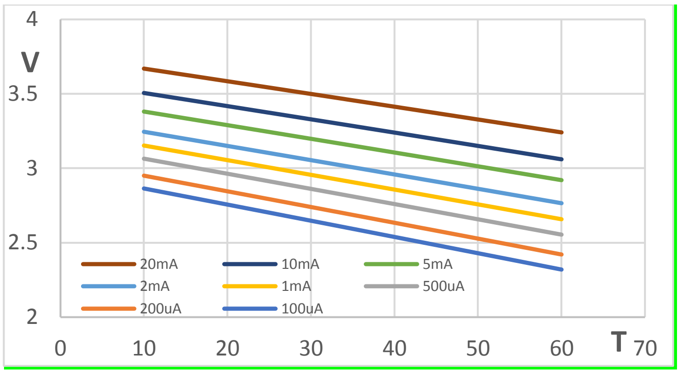
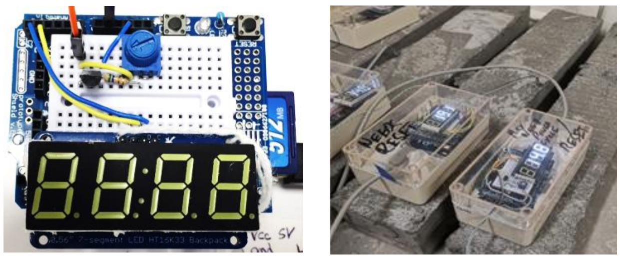


Figure 7. Voltage vs Temperature at different currents for a 4-diode sensor.

In the final laboratory session each group had to set up its microcontroller to interface with an on-board SD memory card and check that it was reading, displaying and storing temperature values correctly (Figure 8(a)). The components and boards were then mounted in a box, as shown in Figure 8(b) and initialised to allow data to be stored at 15 minute intervals over a week during Phase VI of the laboratory programme.



(a) (b)

Figure 8. (a) Temperature sensor and (b) data logger in finished product form.

The logged data in Phase IV was exported to an Excel file along with the corresponding data from the professional thermocouple-based monitor. The two sets of data were compared and aspects such as *the minimum and maximum differences, the mean square error and error variability were evaluated* as an assessment of the accuracy of the constructed sensor. An example of the data obtained from one group's sensor is shown in Figure 9 in which the discrepancy that can be seen between the two curves is due to an incorrect offset having been added during the calibration process.

2.4 *Phase IV: Sustainable concrete beam manufacture and flexural testing*

In an attempt to introduce the first year students to a relevant exciting project, it would be a world first to make a sustainable low carbon bamboo and fibre reinforced concrete beam

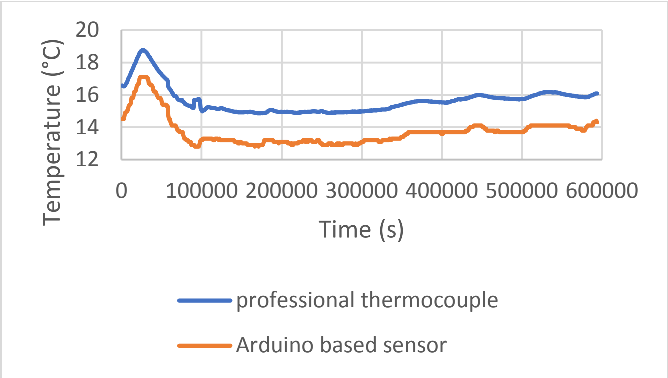


Figure 9. Temperature history data obtained from one of the constructed temperature sensor units.

utilising recycled concrete or shredded car tyres and a recycled cementitious material (GGBS). A dedicated lecture was delivered on the source, waste problem and advantageous characteristics of each of these materials. The effect of the shredded tyres as aggregates on concrete density, the slump reduction of recycled aggregate concrete due to the high water absorption of the adhered cement paste and the anticipated compressive strength reduction of shredded tyre concrete due to the high flexibility of the rubber in the concrete matrix, were observed and reported on by the students in their final reports.

Two full bamboo culms, of the same species (Moso) as tested in Phase I, were used in the casting of the bamboo reinforced beams, where the culms were held in position by end screws in the formwork (measuring 100 x 100 x 600mm, as shown in Figure 10). Before pouring the concrete, students had to measure the culm's internal and external diameters so that flexural stress calculations could be undertaken after testing.

Figure 10. Formwork and bamboo culms for the concrete beams in Phase IV.

Each concrete session had its own concrete type (fibre reinforced, shredded rubber or recycled aggregate) and each of these mixes had three different curing temperature regimes (20, 25 and 30ºC), monitored by the students' temperature sensor and logger (see Figure 11). In essence then, each group could contrast their own result with all of these nine scenarios (with five to six beams of each type, depending on the number of groups in each batch allocation) and had to comment on the effect of the other mixes and maturities, thus developing a well-rounded experience of the *consequences of different sustainable mix designs under different curing regimes*.

During the laboratory briefing session, the equation for the force, F_b, in the two bamboo culms during a flexural test under peak load, P_{max}, was derived, as shown in equation (2), where c is the cover to the bamboo culm from the bottom of the beam.

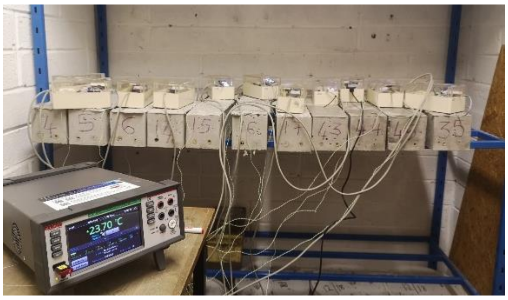


Figure 11. Multiple beam loggers in use in a given curing regime.

$$\mathbf{F_b} = P_{max}\, L/(4\,(5\mathbf{d}/6 - \mathbf{c})) \qquad (2)$$

Using this equation, the force required to break the bamboo culms in tension could be calculated. Finding the tensile strength of bamboo is not straight forward so this is a preferable way to establish bamboo's tensile capacity. The students could also observe *the large variability in the tensile stress of a natural material* (culm), much wider than many man-made materials. The corresponding stress in the concrete in compression in the beam under flexure is as given in Equation (3) (in which b is the beam width and F_c is the force in just one culm, half of the value given by Equation (2)); it was observed by the students that this stress was much smaller than the concrete's compressive strength (established by a cube test) and so the beam was under-reinforced. This meant that the ability of the bamboo beam to exhibit post-cracking toughness (a concept discussed in lectures) was evident from the typical force-displacement plot in Figure 12. In this figure the failure of the smaller of the two bamboo culms is observed at a displacement of about 10.8 mm. The *"ductility" and under-reinforced nature of this behaviour is exemplified in this figure and reinforces these concepts,* as promulgated in the lectures.

$$\mathbf{f_c} = 4\ \mathbf{F_c} / (\mathbf{b}\ \ \mathbf{d}) \qquad (3)$$

Interestingly, two different failure modes were observed, whereby the recycled aggregate concrete strength was high enough to develop a good bond with the bamboo and so the bamboo snapped in tension (Figure 13(a)), whereas the shredded rubber concrete beams were much lower in strength and so there was debonding of the bamboo from the cement matrix, the ends of the culms retracted into the concrete (Figure 13(b)) and a shear failure and beam splitting occurred (Figure 14).

The students produced load-deflection plots and photographs to explain their beam failures, contrasting them with the brittle failure observed in Figure 6. The post-cracking ductility and residual load capacity post peak also featured as students were asked to calculate the area under the load-deflection diagram as an indication of relative energy absorption capacity. Here the students learned important lessons, through experience, of *the nature of ductility and energy absorption* of materials. They also observed the fact that *a composite structure can have synergistic properties which combine the advantageous characteristics of the component parts*.

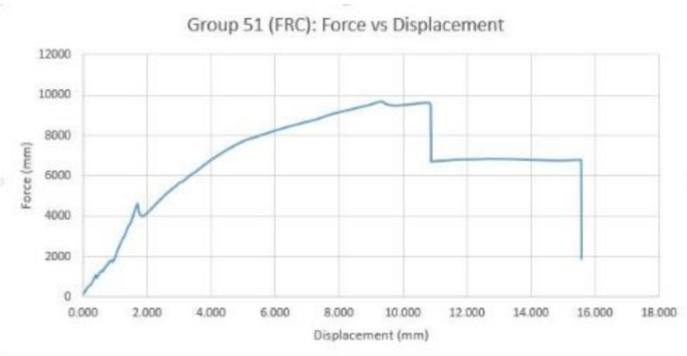


Figure 12. Post-cracking ductility of a bamboo reinforced beam.

Figure 13. (a) A snapped pair of bamboo culms and (b) with debonding, the ends of the bamboo culms retract into the concrete upon flexural failure.

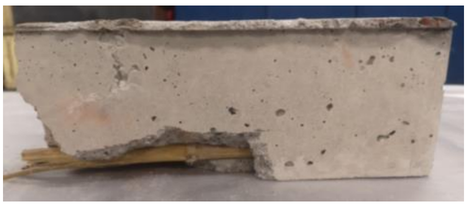


Figure 14. Beam splitting on delamination of the bamboo in low strength beams in flexure.

Students perceived that failure modes can be surprising and an understanding of material behaviour is essential in preventing this from happening unexpectedly. In this sense, during the laboratory session, there was a sense of intrigue in what way their group's beam failed, knowing they were expected to explain it in their final report.

3 CONCLUSIONS

Through experiential learning, a 10 ECTS module in Engineering Materials and their Applications was successfully delivered to a class of 240 first year engineers. Today's school leavers entering university courses in engineering struggle with some concepts, especially the application of mathematics and physics to practical problems. This module was designed to introduce an engineering problem to them which *uses experimentation and maths to achieve an engineering objective*. It also enhanced their confidence to *present and discuss ideas in a teamwork setting and to develop a strong work ethic*.

Students were exposed to aspects of *three engineering disciplines, open-ended problem solving, international standards laboratory testing, data logging, statistics, project management, team dynamics, report writing skills*, etc. while also enjoying and appreciating the execution of some of the lecture principles in practice.

The laboratory sessions added clarity to terms such as *tensile, compressive and flexural strength, stiffness, brittle and ductile failure, shrinkage, bond, under-reinforcing, temperature effects, variability, etc*.

It was shown that materials have very different mechanical properties: *Rubber is highly extensible; paper is very sensitive to the stress-concentrating effects of cracks; bamboo is ductile and highly elastic, but also has weaknesses including its wide variability*. It was also learnt that concrete, for all its adaptability, must be manufactured carefully – the importance of the *customer rather than the manufacturer controlling the water/cement ratio, compaction and curing in optimising its hardened properties* was discovered. The fact that *concrete is weak in tension* was observed through experiments on flexure and compression, and reasons found to explain why most *recycled constituents used in concrete reduce its performance* while making it more sustainable. Finally, it was realised that *a composite material can perform much better than its component parts*.

Students realised that experimental data can be obtained without using expensive, specialised equipment, though the resulting accuracy of the results needs consideration. The *ubiquity of safety in laboratories was evident* to students. Through experience it was realised that *test variability can be high if one does not control the important variables*. So one needs *to follow procedures in international standards to control this variability*. How *to monitor, log, process, analyse and present data* in order to understand material behaviour was learnt by all participants.

The fact that *a Project Manager needs good interpersonal skills* became evident to the students in managing many of the groups. *Teamwork was vital* to optimise marks and missing a deadline has consequences. Many aspects of producing a professional technical report, including the *importance of consistency and attention to detail* were also gleaned over the course of the semester.

In conclusion, although running a project-based module in support of conventional lectures is very resource intensive, it does expose students to many aspects of experiential learning which not only enhanced and reinforced the content presented in conventional lectures, but also introduced them to softer skills, including project management, report writing and statistics. The evidence of success was most seen in the quality of the submitted reports and the degree of engagement by the students who, on a weekly basis, fundamentally enjoyed a more practical way of experiencing how sustainable materials behave.

REFERENCES

[1] O'Kelly B.C., Torrance A.A., West R.P., Burke M.J. and Boland F.M., 2008, Case study of an interdisciplinary problem-based engineering design course' , *Proceedings of the Sixth AECEF International Symposium on Civil Engineering Education in Changing Europe*, Vilnius.