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# Reinforced Rubber Membranes for the Clam Wave Energy Converter

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## Abstract

The Clam is an offshore toroidal structure housing 12 air cells which are sealed from the sea by means of reinforced rubber membranes. For the desirable membrane lifetime of between five and ten years to be realised there are a number of conditions which must be met, including large vertical strength together with horizontal elasticity which permits flexibility without buckles and kinks.

To achieve these characteristics two layers of reinforcing cords are laid at angles close to the vertical.

This paper reports some mathematical modeling, together with small and full scale tests of membranes.

**Key Words:** Wave energy, rubber, reinforced membranes

## Introduction

The Clam is a floating rigid toroid. Twelve air cells are arranged around the circumference of the toroid each of which is interfaced to the waves by a flexible rubber membranes. Figures 1 and 2 show a 1:15 scale model of the Clam. Apart from separating air and water the membrane is one of the dominant factors in determining the energy capture performance of the system. These cells are all coupled together by an air ducting which contains twelve Wells turbines. Thus the air forced from one cell will pass through at least one turbine on route to other cells. Wave activities create differential pressures on these membranes which respond by exchanging air with each other via air turbines. Each cell is sealed against the water by a flexible rubber membrane. Performance measurements, together with mathematical modelling and outline full scale design and costings, reported in Duckers and Lockett (1993) and Duckers etal (1994), lead to a predicted cost of delivered electricity of about £0.05/kWh or 8 US cents/kWh. Figure 3 shows the optimised performance characteristics of the Clam. Although a full scale Clam membrane has not yet been tested, a substantial amount of reinforced membrane information has been obtained through a number of wave energy and Low Head Hydro contracts. It is suggested that the membrane work to date strongly supports the claim that the Clam will be a cost effective wave energy converter, but it is also recognised that the membrane represents the largest risk factor with the Clam. A positive assessment of the Clam was made by Thorpe (1992 and 1998). This paper therefore states the future work necessary to improve confidence in the membrane.

## Brief History of Clam membrane developments

The Clam was initially conceived as a collection of double sided, pillow shaped, air bags attached to, and linked to each other via, a long spine. During various contracts on this 'Linear Clam' membrane work was concentrated on developing model scale membrane materials and air bags and on consideration of full scale materials. Performance tests at between 1:50 and 1:10 scale were carried out in the Cadnam wide tank in England and at Loch Ness in Scotland. During these tests the scaled bags were also tested, and in addition; a) a 1:10 scale size bag manufactured using full scale materials and was fitted to the Loch Ness model for dynamic testing, b) a 1:2 scale size bag was manufactured using full scale materials and was tested statically by inverting it and filling it with up to seven tonnes of water. This inversion procedure completely reproduces the shapes and loads which would be found in the 'correct' air filled mode.

A novel low head hydro-electric scheme which required a membrane of similar characteristics to that of the Clam was developed and tested on the river Amber at Borrowash in Derbyshire, England. This afforded an excellent opportunity to explore many aspects of the Clam membrane. For example shape prediction techniques could be checked, manufacture, installation and repair strategies could be tested. Although the success of the hydro-electric scheme as a whole has been limited, the experience with the membrane has been invaluable. The many failures have helped refine the design criteria for membranes.

## Membrane Requirements

Long membrane lifetimes are critical to the economic performance of the system. This can be achieved by satisfying a number of stringent criteria: materials choice for environmental robustness, vertical strength coupled with horizontal elasticity to give multimillion buckle free operational cycles as they flex through large volume changes to cause the air flows carrying the energy, and appropriate clamping with ease of replacement and repair.

The membranes required for the Circular Clam wave energy device will have the following outline specification. For comparison the Borrowash specification is also reported.

**Table 1** membrane specifications

| | Clam | Borrowash |
|---|---|---|
| length m | 16 | 32 |
| height m | 8 | 6 |
| thickness mm | 6 | 6 |
| 'vertical' strength kN/m | 40 | 150 |
| 'vertical' elasticity % | 0 | 0 |
| 'horizontal' strength kN/m | 20 | 10 |
| 'horizontal' elasticity % | 10 | 50 |

In order to achieve these orthogonal properties the membranes will be anisotropically reinforced so that the predominant cord direction is in the vertical plane.

### Materials

There is a long experience of the use of rubber compounds in sea water. Suitable choice of constituents, such as ultra violet inhibitors, can lead to prolonged life of rubber blends at sea.

The choice of reinforcing material is important and is something that has been investigating in connection with the Borrowash project. Very strong materials are now available , e.g. Kevlar and Twaron, as well as the usual nylon, polyester and steel. The Clam requirements are quite modest in terms of the strength of these materials, and with careful geometric design a long fatigue life can be envisaged.

The present design of membrane for the Borrowash scheme is to lay the two plies of aramid (Kevlar) at an angle of 15 degrees to the short axis (equivalent to the vertical ) axis of the device. This means that the plies are at an angle of 30 degrees to each other. The rating of this fabric in both vertical and horizontal planes is given in Table 2.

Evidence from the manufacturers of reinforcing material suggests that these materials have a breaking stress which is governed by their loading history and the associated creep. In order to avoid creep being a limiting factor on membrane lifetimes it is recommended that operational loadings should not exceed 25% of nominal strength. Some cord history tests were carried out in preparation for the Borrowash project and they confirmed the manufacturers trends. It is clear that the +/-15 degree arrangement using nylon would be more than adequate for the Clam membranes ( with estimated loads of 4OkN/m vertical and 2OkN/m horizontal ), although Kevlar may still be prefered to provide the additional strength safety factor.

**Table 2**
Strength of two ply reinforced material as a function of cord material and angle.
(units are kN/m)

| | nylon | polyester | aramid |
|---|---|---|---|
| +/-30deg horizontal | 85 | 104 | 250 |
| +/-30deg vertical | 254 | 311 | 750 |
| +/-25deg horizontal | 61 | 74 | 179 |
| +/-25deg vertical | 279 | 340 | 821 |
| +/-20deg horizontal | 40 | 49 | 117 |
| +/-20deg vertical | 300 | 366 | 883 |
| +/-15deg horizontal | 27 | 28 | 67 |
| +/-15deg vertical | 373 | 386 | 932 |

### Geometry

Spring rate

The efficiency of the Clam is governed to a large extent by the spring rate of the air cells. Spring rate relates air pressure and volume of the air cells and the best performance in a particular wave climate depends upon the damping and the spring rate. The control of spring rate is effected by the internal shape of the membrane support as the membrane runs into the cell. A mathematical model of the membrane shape in two dimensions has been written and used to determine the optimum membrane support shape for a sea of a given energy period. The efficiency is given by

$$E= 4w^2 D^2 /((SR-w^2 M)+ 4w^2 D^2 ))$$

where w = angular wave frequency ,
SR = spring rate,
M = added mass,
D = damping

Clearly efficiency can be maximised by setting $SR=w^2 M$ , and in general this requires that SR is about 1 kPa/m2 per metre device front, in contrast to 3 kPa/m2 which was dictated for the double sided bag by hydrostatic forces. SR would be selected to optimise the annual energy capture at a chosen site by careful selection of the internal slope of the membrane support..

### Mathematical modelling

The two dimensional mathematical membrane shape models have been validated by experiment. Shape predictions for wave energy membranes have been borne out by physical measurements. See figure 4 for details of the membrane shapes computed at various positions during an operational cycle. The diagram also gives the landmarks used for the mathematical computation of the overall system performance. A similar two dimensional shape modelling for the Borrowash membrane has also proved to be extremely accurate.

Full three dimensional modelling is highly desirable but very difficult. Some tentative approaches have been made and may be developed in the future.

## Model scale membrane tests.

Methods have developed to appropriately scale the material properties of membranes down to laboratory size test samples. This is not a trivial problem since it demands that material is scaled in both size and Young modulus. This has been achieved by using very thin latex on a low count rate reinforcing net. These provide valuable insight into geometrical shapes, distortions and spring rate, but are not convincing in themselves of the full scale technology. Clam performance tests have always been carried out using appropriately scaled membranes. For example a 1:10 scale Loch Ness model was fitted with a scaled bag (displacing about 1.5 tonne of water) in order to test fatigue and this was exposed to more than 1 million waves without apparent damage.

## Full Scale Experimental Experience

Full scale testing of membrane components for the Clam wave energy device has been carried out to some extent on the Borrowash hydro-electric scheme. The operational regime and the physical size of the Borrowash membrane exceed those envisaged for the Clam membrane.

The prototype low head hydro electric device at Borrowash was fitted with a membrane which had much in common with that specified for the Clam and the development of the technology for Borrowash has substantial benefits for the wave energy membranes. The Coventry team in collaboration with Avon Rubber plc has devised a method of fabricating and fitting a 32m by 6m membrane without the use of special equipment. The operation was labour intensive but it is possible to identify methods of reducing fabrication time. The major drawback of the Borrowash membrane is the joining together of 24 panels to make up the complete sheet. These joints were deliberately made to be weak so as to provide damage limitation in the event of failure. There have been a number of membrane failures at Borrowash. Onsite repair techniques have been developed. A later experimental sample of continuous length of membrane was fabricated but not tested.

### Installation

The Borrowash membrane was more or less manually fitted into the concrete duct and raised into the clamping rails. Working in an enclosed duct of restricted space made the installation particularly difficult. The Clam membranes would be rather easier to install and indeed a specialised fitting facility would be highly desirable.

It is proposed that operational Clam membranes are factory fitted to a clamping frame to ensure a uniform load transition form membrane to clamp (a significant cause of Borrowash failures has been non uniform load transitions which create a cascade effect of cord breakage). This clamping would facilitate rapid membrane replacement at sea. Major membrane repairs would therefore be carried out on an exchange basis.

### Clamping

Considerable experience has been obtained from the Borrowash exercise on the attachment of membranes to solid structures. The main desire in all membrane fixings is to provide a uniformly loaded membrane edge to the steel or concrete interface without puncturing the membrane.

The Borrowash device imposes enormous loads on the attachments because the water mass is supported almost entirely by the membrane. In early tests this led to catastrophic failures at the lower end of the device because the clamping mechanism was inadequately designed and fitted to survive such high loads. Modification to the design, replacement of the rope bead with a steel bead ameliorated these problems. Figure 5 shows a laboratory test of material and clamping arragement.

It is now possible to design adequate clamping arrangements for Clam membranes. A removable clamping frame is proposed for the Clam.

### Damage to Membranes

The effect of a damaged membrane on the performance of a Clam device is of some concern. A seriously torn or split membrane will lose air rapidly and will allow water into its cell. The Clam is designed to survive total loss of the air pressure, but the total air system pressure will thus be reduced to atmospheric pressure and the remaining cells will also become inoperative. One damaged membrane will effect all twelve.

It is proposed , though, that each air cell will have an emergency sealing system which reacts to the presence of water and inflates a bag in the air ducting to that cell. The technology for such emergency bags is well developed in military and safety applications. Sealing one cell leaves the other eleven to continue exchanging air with each other without the lost one. Experiments at the Cadnam wide tank with the Linear Clam showed that 'disabling' one, two or four bags affected the energy capture only in proportion to the lost 'frontage' and this is expected to be the case in the circular Clam.

It is difficult to predict all the possible damage mechanisms at this stage. The most obvious is that of puncture by a foreign body, but experience at Loch Ness has shown that floating bodies are extremely unlikely to puncture a membrane. A vessel colliding with the Clam could damage a membrane, but this should have a low probability of occurring.

Much more probable is the damage arising from wear against the clamps and saddle and the consequent effects of misfitting the membrane or of failing to get the three dimensional geometry perfectly specified. It is these latter points that can only be resolved by full scale trials of a single cell, and ultimately of a sea going prototype. Certainly the experience at Borrowash indicates that precise fitting to the clamps is essential. There will have to be an evolutionary process to lead to membranes of reasonable lifetimes.

**Repairs**

The various failures of the Borrowash membrane have largely been attributed to clamping or joining problems. With a prototype device some early problems were to be expected. There was also an accidental puncture of the membrane by a temporary support whilst carrying out some repairs to the device. This occurred shortly after the device was run for the first time.

Rather than remove the membrane from the concrete duct for repairs it was decided to develop in situ repair techniques. The time saved by so doing is considerable. In fact two methods have been adopted; Portable presses owned by Avon Rubber can be lowered by crane into the damaged region and patches lm long by 0.15m wide vulcanised onto the membrane. Unfortunately this demands access to both sides of the membrane. Where this is not possible some pairs of purpose built single presses were useds.

The repair to the early puncture was effected with the single presses and it has survived all of the subsequent operation of the device without any further deterioration of the split.

A clamping frame is proposed for the Clam membrane: this would facilitate rapid membrane replacement and would permit accurate factory fitting of the membrane and hence provide for uniform tensioning of the membrane onto the clamp. The damaged membrane could then be factory repaired, or replaced by a new one, and fitted back into the clamping frame. Only the repair of minor damage would be tackled at sea.

**Experimental Measurements**

Figure 6 shows static strain measured at Borrowash, when the membrane was supporting a total of around 100 tonnes of water along a 10 section (i.e. 'vertical' stresses of the order of 10 tonnes $m^{-1}$). The strain reaches magnitudes of over 50% which in general permits the membrane to adopt buckle free shapes throughout its operational cycle. There is a little evidence of negative strain near to the rail and this is a slight cause for concern as it may demonstrate a tendency to buckle at that point.

## Economics

The cost of membranes for the Clam is not a major factor in the overall 'capital cost of the system. The approximate cost of the membrane material will be £50 $m^{-2}$ which when fitted and including transport etc. might well be £100 $m^{-2}$. A complete Clam unit with about 1520 $m^{2}$ of material would require a capital cost of £76k for the membranes. The major influence of the membrane on costs will be in the lifetime of membranes and their repair and replacement costs. It is therefore imperative that each membrane should have a service life of 3 to 5 years.

## Examples of similar products

There are no exact analogues of the Clam membrane, but reinforced rubber material are used in many applications. The most common is the vehicle tyre which flexes considerably on each cycle but not quite to the extent of the Clam membrane. A typical car tyre can execute 30 million cycles before replacement and then the reinforcing is usually perfectly intact but the cover rubber has worn away. In the case of the Clam the abrasive wear will be less but the load on the reinforcing cords may be greater because of the requirement to stretch slightly during each cycle. Thirty million Clam cycles would roughly correspond to ten years of operation at sea.

None the less the car tyre represents a reinforced membrane which is subjected to considerable abuse in that its mode of operation cannot be tightly specified; the vehicle may be simultaneously cornering and negotiating severe road potholes. The lifetime of modern tyres is very long. By contrast it is anticipated that the Clam membrane will operate within well specified limits and so (eventually) there will be a long membrane lifetime.

More than one thousand inflatable rubber dams have been installed by one Japanese company alone. Sumitomo have been fitting 'Sumigate' dams in Japan since 1966. It is understood that the 1966 one is still in place. These are similar in size to the Borrowash membrane and have much in common with the membrane work described here. These dams are not required to flex frequently as our membranes are but they do undergo considerable buckling and kinking when being inflated or deflated. They are subjected to enormous amounts of potentially damaging debris and , of course , are virtually continuously wet and then dry. Nylon is the usual reinforcing material for these dams.

## Conclusion

There is evidence that reinforced membranes for an offshore wave energy converter could be built to perform effectively and to survive long enough for economic demands to be met. Methods of manufacture, installation, clamping and repair have already been carried out A full scale membrane was manufactured and tested in a river application. The problems encountered in the fabrication , installation, clamping and repair processes have given insight into the possible application to off shore wave energy converters. A full scale demonstration Clam single cell followed by a sea going complete device is needed to help achieve this goal. It is only by a process of designing and testing, modifying and refining that confidence in the membrane concept can be fully established.

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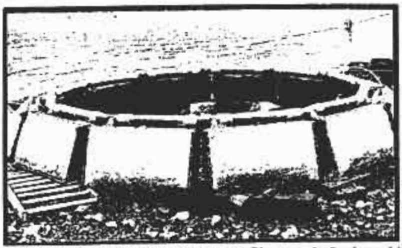


**Fig. 1. A 1:15 scale model of the circular Clam ready for launching at Loch Ness**

The model is 4 m in diameter and carries 12 air cells, each covered by a latex membrane around its circumference.

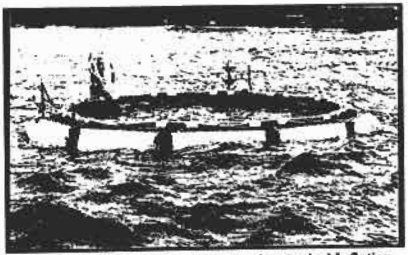
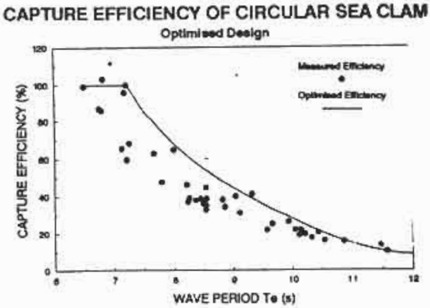


**Fig. 2. The model deployed in the water in a typical Inflation position**

The instrumentation cables can be seen which convey signals from the various transducers back to the shore-based data logging computer.

Fig. 3.



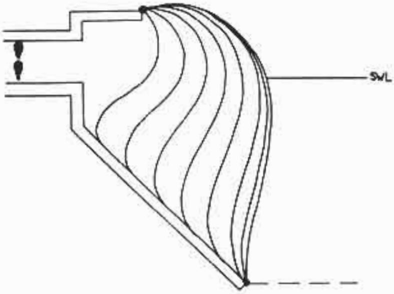




**Fig. 4. A series of membrane profiles obtained by computing the shapes for a range of gauge pressures**

All other parameters such as frame and saddle angles, depth of immersion, length of fabric are held constant.

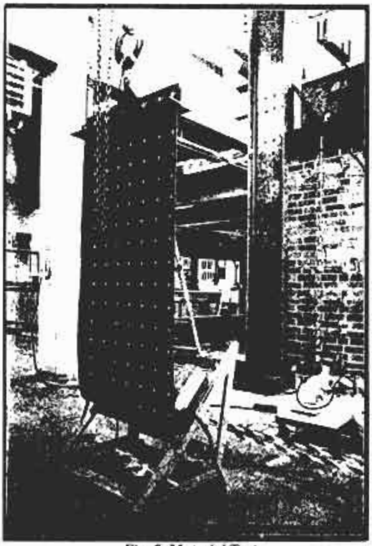


**Fig. 5. Material Test**

A fabric, 0.7 m wide, reinforced with two piles of polyaramid at ±15 degrees to the vertical. The sample has been subjected to a vertical tension of up to 70 kN/m. The floor fixing also serves as a clamp test

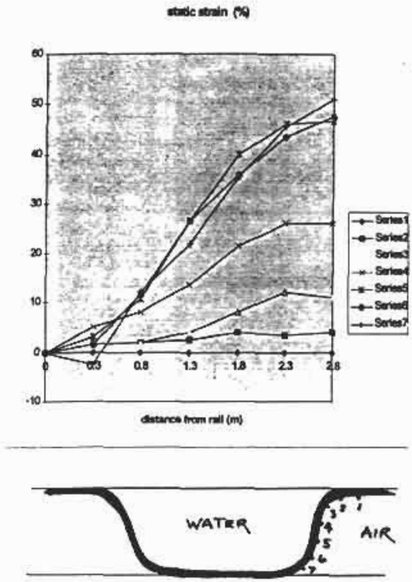



Figure 6 Static strain measurements at a water/air interface.