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# FEASIBILITY OF BUILDING LEN LYE'S KINETIC SCULPTURE "SUN, LAND AND SEA"

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## 1. Introduction

New Zealand born artist Len Lye (1901-1980) is internationally renowned for his pioneering work in direct film and kinetic sculpture [Horrocks 2009]. Lye was interested in 'composing motion' through the creation of highly flexible and dynamic sculptures. Lye understood the engineering limitations of his day restricted the size of the works he could produce. He developed detailed plans for his grand-scale works which he intended to be built in the 21st century. Interest in Lye's work continues to grow and the Govett-Brewster Gallery in New Plymouth, New Zealand that archives the major body of Lye's art has recently confirmed a $NZ10m extension for the sole purpose of exhibiting Len Lye's work.

The Len Lye Foundation is tasked with preserving Lye's existing work and producing the sculptures that he envisioned being built at a larger size. The University of Canterbury in Christchurch, New Zealand, has been involved in implementing Lye's vision to create a number of his sculptures including: *Trilogy, Universe, Water Whirler, Wind Wand* and *Blade*. This paper concerns the design and analysis of the sculpture, *"Sun, Land and Sea",* to establish the feasibility of building a full size sculpture, approximately 50m long.

The performance of *"Sun, Land and Sea"* includes travelling 'humps' or rucks in ground supported flexible strips. The travelling ruck is a widely used analogy for phenomena such as earthquake slip pulses and is a common occurrence in the textile and material handling industries. Little work has been done quantifying the dynamics of travelling rucks, with the exception of two recent studies [Vella et al. 2009], [Kolinski et al. 2009]. Implications of increasing the scale of a ruck in a flexible strip while maintaining static similitude are considered in determining the feasibility of building the full size sculpture.

## 2. Observation of models and drawings

An essential requirement when reproducing a sculpture by a deceased artist is that the artist's intent for the work is preserved. Len Lye's intentions for *"Sun, Land and Sea"* are detailed in his drawings, written material and the static scale model that he created. Lye's notes about the motion and performance of the sculpture reveal what *"Sun, Land and Sea"* was intended to look like. The following extract from his diary is an example of what the artist intended for the sculpture:

> *"While I watch the serpent ensemble enacting their series of harmonic waves, sometimes in unison, sometimes in sequence, and sometimes in pairs and trios, I get to feel the might of the sea as it rolls in to the shore."* **Len Lye 1965**

### 2.1 Description of the sculpture

Len Lye's *"Sun, Land and Sea"* is a performing kinetic sculpture that is intended to be viewed at night under lights. The performance is staged upon a marble plinth situated in a body of water. An overhead structure provides suspension points for hanging components of the work. The structure will not be visible at night. The general layout of the sculpture is shown in Figure 1.

The sculpture consists of seven strips of highly polished metal symbolising "Sea Serpents" lying parallel on a wet marble plinth. The middle strip is called the "God of the Sea" and lies on a raised, dry section of the plinth. Each of the strips is fastened to an actuating mechanism at one end. The actuating mechanism is housed out of sight within the plinth. This mechanism creates a ruck in the end of the strip and sends it travelling along the length of the strip until it flicks up the free end. The actuating mechanisms will be programmed to send the rucks down the strips at varying amplitudes and frequencies in order to create the sense of an "increasingly agitated serpent ensemble", as described by Lye.

The travelling rucks make up the first part of the performance. For the second part of the performance the three strips on either side of the plinth remain stationary. The middle strip is lifted up in a series of short movements as shown in Figure 2. At each static suspended step the actuating mechanism induces a short period of high frequency vibrations (standing waves as opposed to travelling waves) and the strip appears to shimmer. The final shape of the strip has its free end level with the centre of a gold sphere suspended from above (the "Sun God"). Suspended between the free end of the strip and the "Sun God" is the "Cave Goddess". Following the lifting and shimmering motion of the strip, the "Cave Goddess" flips inside out and the performance finishes with an electrical arc between the head of the strip and the sphere.

In Len Lye's description of the full size sculpture, the "Sea Serpent" strips are 45m long by 1.2m wide with 3m high rucks. The "Sun God" is to be suspended 30m above the ground.

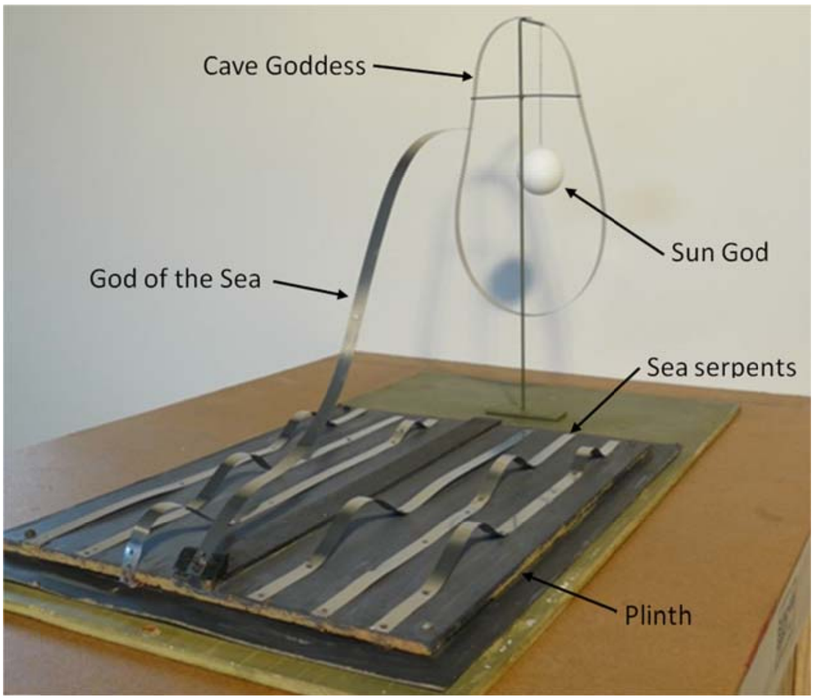

**Figure 1. Photo of the static scale model of *"Sun, Land and Sea"* built by Len Lye**

### 2.2 Scale drawings and the working model

Lye produced a set of scale drawings of the sculpture showing side elevations (Figure 2), end elevations and a plan view of the work. These drawings are a similar shape and scale to the static model as shown in Figure 1. The drawings and model allow the dimensions of components of the sculpture to be determined.

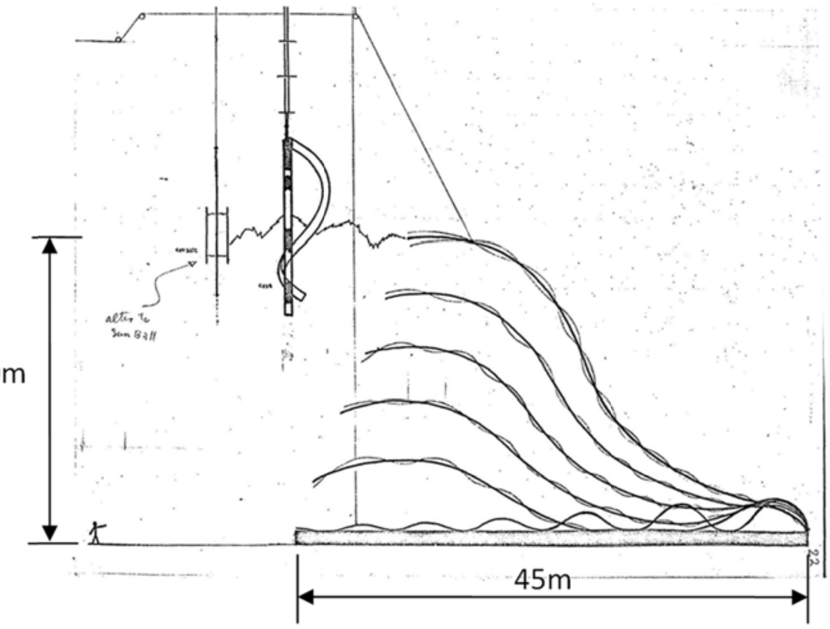

**Figure 2. Drawing of the side view of *"Sun, Land and Sea"* [Lye 1965]. Dimensions show the full size sculpture**

### 2.3 Working "sea serpent" model

Lye built a working model of a "Sea Serpent" with a travelling ruck running down its length. The model mechanism consists of an electric motor driving a pair of cams. The second cam is attached to the end of the steel strip. The mechanism, shown in Figure 3, induces a moment in the end of the strip, lifting the strip from its supporting surface at the attached end and pulling the free end towards the mechanism. The second cam is returned quickly to its original position by a spring, causing a ruck to travel down the length of the strip. The strip is approximately 9m long, with a constant width of 209mm (8-1/4 inches), constant thickness of 0.81mm (0.032 inches) and made of stainless compressor valve steel supplied by Uddeholm in 1969. The motion observed in the working model is consistent with the description Lye gives in his writings, what is shown in the static model and his scale drawing.

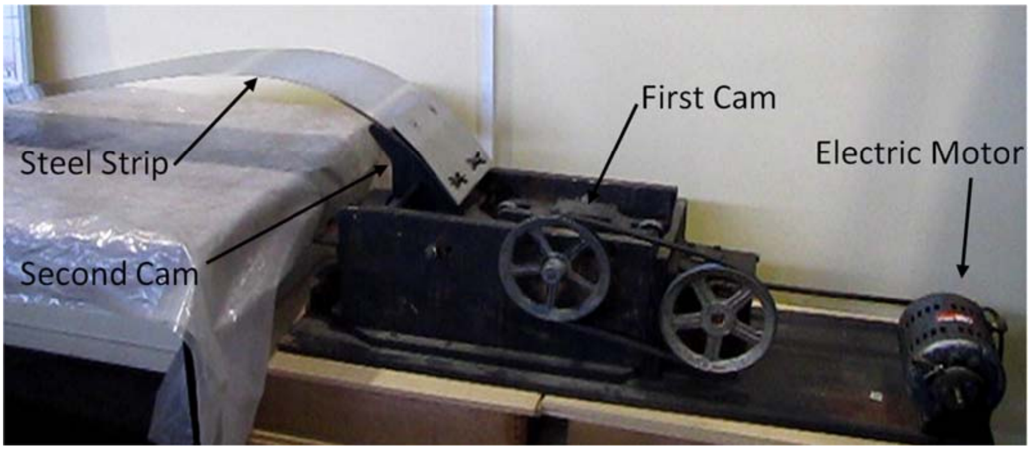

**Figure 3. Mechanism in Len Lye's working "sea serpent" model**

## 3. Scaling a ruck in a flexible strip

### 3.1 Statics and dynamics of a ruck

The shape of a ruck in a "Sea Serpent" can be described as a post-buckled heavy long elastica with a one-sided constraint. Post-buckling of an elastica describes the local separation of a slender flexible beam from the rigid foundation it rests on due to the displacement of the ends of the beam toward each other. The resulting ruck shape depends on the ratio of the beam's density and bending stiffness and the magnitude of the end-to-end displacement. The 'long' elastica is defined as having a finite section in contact with the foundation [Wang 1986].

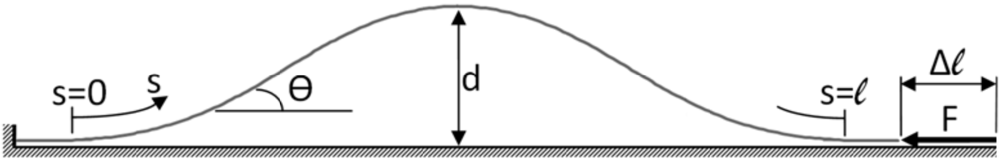

Figure 4. **Schematic of one-sided post-buckling of a long elastica**

The shape of a ruck can be found by solving Equation (1) numerically [Vella et al. 2009]. $\theta$ is the local angle of the strip from horizontal, $L$ is the non-dimensional total length of the strip separated from the foundation, $S$ is the non-dimensional arc length of the strip from its point of separation from the foundation. σ is the non-dimensional compression force, $F$. The subscripts in Equation (1) denote differentiation. The resulting ruck shapes can be specified by their non-dimensional end-to-end displacement parameter, $\Delta L$ [Vella et al. 2009]. The local bending moment and stress in the strip can be calculated from the radius of curvature [Frisch-Fay 1969].

$$\theta_{SS} = -\sigma \sin\theta + (L/2 - S)\cos\theta \tag{1}$$

Equation (1) has had all lengths and forces non-dimensionalised with respect to the bending length of the strip, $l_g$, as in Equations (3) and (4). Equation (2) shows that the bending length is the ratio of the beam's bending stiffness per unit width, $B$, and weight per unit area, $\rho gh$, where ρ and $h$ are the strips density and thickness, respectively.

$$\ell_g = \left(\frac{B}{\rho g h}\right)^{\frac{1}{3}} \tag{2}$$

$$\Delta L = \frac{\Delta l}{\ell_g} \tag{3}$$

$$\sigma = F\frac{l_g^2}{B} \tag{4}$$

There is limited literature describing the travelling ruck. Vella et al. investigated a similar motion to Lye's "Sea Serpent" in which a travelling ruck was produced by the vertical excitation of the end of a strip. This study concluded that a steady state travelling ruck is analogous in shape to a stationary ruck. Also, it was found that the ruck will 'stick' or maintain its shape where sufficient compressive force, $F$, is present and 'slip' or lose its shape when the compressive force is insufficient [Vella et al. 2009].

### 3.2 The implications of scaling a ruck

A small scale prototype will be created in order to validate predictions made about the motion of a "Sea Serpent" and properties of a travelling ruck in a strip. This prototype will be approximately 1/5th the size of the full scale work and will fulfil the artist's intentions for a "Sea Serpent". Validated findings from the prototype can be used in conjunction with scaling rules developed in this section to make predictions for the full scale work. Previous work on increasing the scale of kinetic sculptures notes the importance of conserving qualities of a model as its scale is increased [Raine et al. 1998]. The following requirements are necessary when increasing the scale of the prototype:

- Maintain static and dynamic similitude with the prototype.
- Conserve the appearance and acoustic properties of the metal strip in the “Sea Serpent” model.

### *3.2.1 Material thickness for static similarity of a ruck*

The first scaling requirement implies that the shape of the ruck in the prototype “Sea Serpent” must be conserved when increasing the scale. Maintaining the non-dimensional parameter of end-to-end compression, $\Delta L$, ensures the shape of the ruck in the model and large size strips are the same (5). Subscripts $m$ and $l$ refer to the model and large size scales respectively. A requirement for static similarity is that the ratio between the geometric dimensions ruck length, $l$, and end-to-end compression, $\Delta l$, is conserved (6). The scale factor, $SF$, is the ratio of ruck length of the large size and model strips (7).

$$\Delta L_m = \Delta L_l \tag{5}$$

$$\left(\frac{\Delta l}{l}\right)_m = \left(\frac{\Delta l}{l}\right)_l \tag{6}$$

$$\frac{l_l}{l_m} = \frac{\Delta l_l}{\Delta l_m} = SF \tag{7}$$

Equation (8) is found by substituting (2) and (3) into (4). The bending stiffness term is expanded into elastic modulus, $E$, and thickness of the sheet, $h$. Equation (8) describes the effect on the thickness of the strip as the scale is increased. Equation (9) assumes the $E/\rho$ ratio for the material is the same for the prototype and large scale strip.

$$\frac{h_m}{h_l} = \sqrt{\frac{E_l \rho_m}{E_m \rho_l (SF)^3}} \tag{8}$$

$$h_l = h_m \times (SF)^{\frac{3}{2}} \tag{9}$$

### *3.2.2 Effect on bending stress of increasing the scale of a ruck*

Frisch-Fay derived that the local bending moment is proportional to the radius of curvature in a buckled flexible beam [Frisch-Fay 1962]. The local bending stress, $\sigma_b$, can be calculated from the bending moment, thickness and elastic modulus of the strip (10).

$$\sigma_b = \frac{Eh}{2}\frac{d\theta}{ds} \tag{10}$$

As the scale increases the local radius of curvature along a ruck must increase by the scale factor to maintain static similarity with the prototype ruck shape (11).

$$\left(\frac{d\theta}{ds}\right)_m \times \frac{1}{(SF)} = \left(\frac{d\theta}{ds}\right)_l \tag{11}$$

$$\frac{\sigma_{bm}}{\sigma_{bl}} = \sqrt{\frac{E_m \rho_m}{E_l \rho_l (SF)}} \tag{12}$$

$$\sigma_{bl} = \sigma_{bm} \times (SF)^{\frac{1}{2}} \tag{13}$$

Equation (12) is found by substituting (8) and (10) into (11). Equation (12) shows the effect of increasing the scale on the bending stress. Equation (13) assumes the $E/\rho$ ratio for the material is the same for the prototype and large scale strip.

## 4. Analysis and scaling of Len Lye's "sea serpents"

### 4.1 Ruck shape

#### *4.1.1 The travelling ruck*

Len Lye's working "Sea Serpent" model was used to investigate the travelling ruck. An experiment performed with the model aimed to confirm that, for the same end-to-end displacement, the stationary or steady state ruck is the same shape as a ruck that is 'slipping' or losing amplitude. The method of creating the ruck employed in the model causes the ruck to 'bounce' as it travels, therefore, quantitative results were not able to be gained from the experiment. Observation of the travelling ruck revealed some valuable insights. The amplitude of the ruck does not decrease linearly as proposed in Lye's drawing in Figure 5. Instead, the amplitude remains relatively constant until a point where it quickly decreased to a lower height at which it remained until reaching the free end.

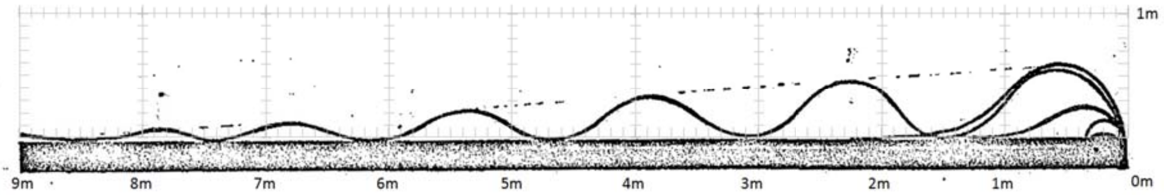

**Figure 5. Side view of a scale drawing produced by Lye with a grid (size corresponding to the model strip) overlaid**

#### *4.1.2 The stationary ruck*

The ruck shapes produced by Lye's "Sea Serpent" model strip were compared to the ruck shapes in his drawings (as in Figure 5). The bending length of the model strip was measured using the loop test [Stuart 1966]. The method outlined in Section 3.1 was used to calculate the expected ruck shapes that the model strip would produce for various end-to-end displacements. The calculated ruck shapes accurately matched experimentally produced static ruck shapes with the model strip. Superimposing the calculated ruck profiles onto Lye's scale drawings allowed a comparison of the physical ruck shape achievable with the model strip and the shapes drawn. Figure 6 shows that there is good agreement between the ruck shapes in Lye's drawing and those produced with the model strip.

$$l_g = \frac{d}{D} \tag{14}$$

As well as comparing the ruck shapes from the model strip, the rucks with the best agreement to Lye's drawing were found. Non-dimensional ruck shapes were visually fitted to each of the rucks in the scale drawing in Figure 5. For each ruck shape fitted the corresponding natural bending length was calculated using Equation (14) where $d$ is measured from the scale drawing as the height of the centre of the ruck from the foundation and *D* is the calculated non-dimensional height. All the rucks were found to require a bending length of 0.5m. Using the material properties of the model strip and Equation (2) the thickness of the 'ideal' prototype strip was calculated to be 0.7mm. A summary of the comparison between existing model strip and the ideal prototype strip is shown in Table 1.

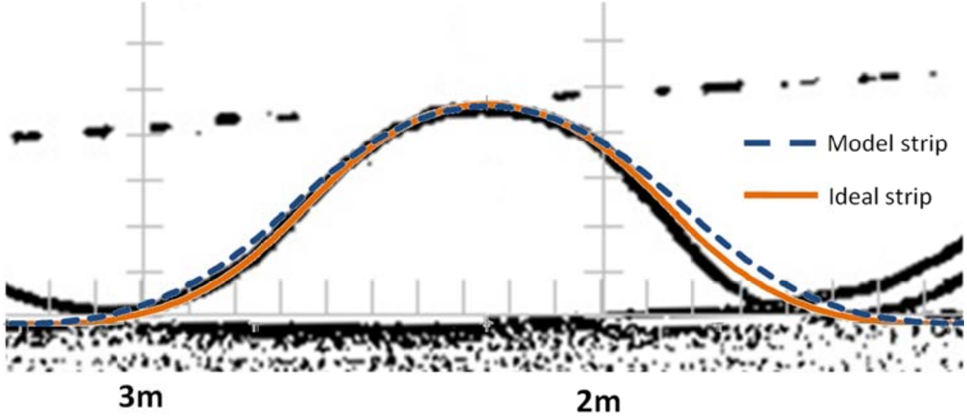

**Figure 6. Section of Len Lye's scale drawing with ruck shape of the model strip and ideal strip superimposed**

The largest stress induced in the model strip due to bending will be a result of the ruck with the smallest radius of curvature, which corresponds to the largest $\Delta L$ value. The ruck in the ideal prototype strip with the smallest radius of curvature that matches Lye's scale drawing has a $\Delta L$ value of 0.93 and a maximum stress of 254 MPa. A ruck in the model strip with the equivalent height has a $\Delta L$ value of 0.76 and maximum stress of 256 MPa.

**Table 1. Summary of model strip and ideal prototype strip**

| **Dimension** | Model strip | Ideal prototype strip |
|---|---|---|
| **Length** | 8.97m | 9.15m(30ft) |
| **Width** | 209mm (8 ¼ inch) | 244mm(4/5ft) |
| **Bending Length, $l_g$** | 0.55m | 0.5m |
| **Thickness, h** | 0.81mm (0.032 inch) | 0.7mm |
| **Max theoretical bending stress, $\sigma_{max}$** | 256MPa | 254MPa |

### 4.2 Shape and vibration of the lifted "God of the Sea"

An experiment was performed to investigate whether the shape of the elevated middle strip in the sculpture can be produced using a method similar to that shown in Figure 2. The experiment involved fixing one end of the model strip to the ground and lifting the free end from a single point to the corresponding height from the drawing. The profile of the raised strip was recorded and compared to the shape from the scale drawing. Also, when in the lifted position, the strip was shaken by hand to investigate the possibility of inducing the shimmering motion in the raised strip.

The comparatively limp shape created in the model strip when lifted by a single point, shown in Figure 7, implies that the bending stiffness of the model strip is too low to produce the lifted shape in Lye's drawing. Although, by shaking the base of the strip in its lifted position, the vibrations observed had a similar wavelength and amplitude to Lye's drawing. These results imply that the bending stiffness of the model strip must be kept the same in order to accommodate the desired vibration in the lifted strip, therefore, the shape of the lifted strip must be achieved by means other than increasing the stiffness of the strip.

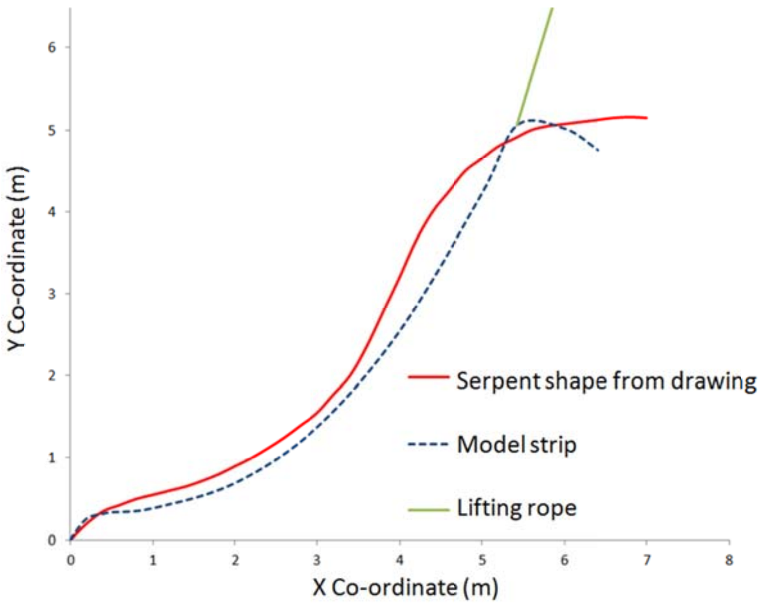

**Figure 7. Results of lifting the model strip compared to Len Lye's "God of Sea" shape**

Assuming the strip is lifted without inducing a large amount of axial and shear forces, the stress in the lifted strip can be calculated as in Equation (10). The radius of curvature is calculated from a plotted shape of the "God of the Sea" in Lye's drawings. The calculated maximum bending stress induced in the lifted static strip is well below the stresses calculated in the ruck. From Lye's drawing it can be seen that the intended shape of the vibrating lifted strip does not cause the minimum radius of curvature in the strip, therefore, the maximum stress induced in a "Sea Serpent" strip will be caused by the ruck.

## 5. Material feasibility for a full size "sea serpent"

Using the scaling rules developed in Section 3.2 and the theoretical maximum stress calculated for the ideal size strip in Section 4.1, the maximum stress in a full scale strip can be predicted for potential strip materials. For each material considered the required thickness and maximum bending stress are calculated using Equations (8) and (12) respectively. Table 2 summarises the results found for each material investigated, noting that for a thin flexible strip, *E = Young's Modulus/(1-poissons ratio*$^2$*)***.** [Wang 1986]. The compressor valve stainless steel is the same material as the model strip.

**Table 2. Summary of materials considered for the full scale sculpture**

| | Compressor valve stainless steel | Titanium Ti-6Al-4V (Grade 5) | Aluminium alloy 7050 | CFRP |
|---|---|---|---|---|
| **Elastic Modulus, *E*** | 234GPa | 126GPa | 80.5GPa | 110GPa |
| **Density, ρ** | 7789kgm$^{-3}$ | 4480kgm$^{-3}$ | 2830kgm$^{-3}$ | 1550kgm$^{-3}$ |
| **Thickness, h** | 7.8mm | 8.0mm | 8.0mm | 4.8mm |
| **Maximum bending stress, $\sigma_{max}$** | 567MPa | 593MPa | 583MPa | 339MPa |
| **Yield strength, $\sigma_y$** | 1000MPA | 1100MPA | 469MPa | 350MPa |

The maximum bending stresses induced in a ruck in the full size strip is below the yield strength of the engineering metals considered, with the exception of Aluminium alloy. Carbon-fibre-reinforced plastic (CFRP) results in a thinner strip with a lower bending stress than the engineering metals due to a high stiffness to weight ratio.

## 6. Discussion

Experiments have shown that the static ruck shapes observed in the "Sea Serpent" model are very close to the shape of the travelling waves in Len Lye's drawings. Lye was not an engineer, his drawings were based on real observations of physical systems. It appears that the shape of the "Sea Serpents" in Lye's drawing are based on his observation of a ruck in the "Sea Serpent" model. Lye used working scale models to capture aspects of the movement he desired in his large scale sculptures. The motion of a "Sea Serpent" shown in Lye's drawing is depicted with varying levels of accuracy in his working "Sea Serpent" model. The method of creating a travelling ruck by inducing a moment in the end of a strip is observed in the working model, whereas, a ruck with linearly decreasing amplitude travelling down a flexible strip, as in Figure 5, is not observed in the working model. From Lye's writings it is clear that his intention is to have a linearly decreasing ruck, therefore, the working model shall not be considered a precise depiction of the intended motion of a "Sea Serpent".

Lye intended for the audience of *"Sun, Land and Sea"* to "feel the might of the sea as it rolls into shore" when watching the performance of the "Sea Serpents". At the sculpture's full scale, it is expected that the audience could not discern between the two ruck shapes, shown in Figure 6, in a "Sea Serpent". It is concluded that neither ruck shape is more correct and that either will sufficiently fulfil the artist's intention of creating the described experience for an audience. This conclusion is advantageous from an engineering design perspective as it allows for leniency in the ruck shape that is to be produced.

Equations (8) and (9) allow predictions of the thickness required in order to maintain static similitude when increasing the scale of ruck in a flexible strip. Equation (9) shows that the thickness of the strip must increase by (scaling ratio)$^{3/2}$ when the materials are similar. The bending stress increases by (scaling ratio)$^{1/2}$ for similar materials, as in Equation (13). The scaling equations developed for a ruck are the same as scaling equations for the vertical cantilever in Lye's sculpture *Blade* [Raine et al. 1998]. This result is expected as both cases involve the deflection of a flexible strip in which the shape is related to the ratio of the strip's stiffness and density. Predictions of stress and static similarity of a ruck in a flexible strip will be verified by experimental observation of a large scale "Sea Serpent" prototype.

The feasibility of the sculpture has been confirmed based on conclusions that the yield strength of each material considered is greater than the predicted maximum stress in a full scale "Sea Serpent". Further work is required to verify assumptions made in determining that the ruck will induce a greater stress in a "Sea Serpent" than the lifting and vibration of the "God of the Sea". Experimental observation of a prototype will allow verification of the similarity of the static and 'slipping' rucks to confirm the validity of the stress results presented in Section 4.1.2. The conclusion of adequate yield strength does not imply a material is suitable for use as a "Sea Serpent". For a material to be suitable for a "Sea Serpent" factors such as its acoustic properties, aesthetic appearance and internal damping must be consistent with the artist's intent. Consideration of the wider scope of material factors will be addressed in future work.

In previously reproduced Len Lye sculptures the use of engineering polymers has been deemed unacceptable due to the acoustic requirements of the material [Raine et al. 2000]. Considering the scale and type of motion involved in *"Sun, Land and Sea"* the acoustic impact of the performance may be created by other means, therefore, plastics or composites such as CFRP may be suitable as the "Sea Serpent" material.

## 7. Conclusions

While engineering analysis is useful for predicting the performance of "Sun, Land and Sea", the same analysis is also valuable in establishing the artistic integrity of the artwork. Observations and analysis in this study show that Len Lye intended the "series of harmonic waves" in the "Sea Serpents" to be travelling rucks created by an end moment. This paper has identified scaling rules that allow predictions of structural properties (e.g. thickness and induced stresses) to be made when changing the size of the ruck in a flexible strip. A brief review of material suitability found that high strength engineering metals and composites are suitable for creating a 45m long "God of the Sea". This paper has established that it is feasible to create a full size *"Sun, Land and Sea"*.

## Acknowledgements

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