AN INTEGRATED APPROACH FOR MARINE STRUCTURES SURVIVABILITY ASSESSMENT: THE FASTNET LIGHTHOUSE WITHIN THE STORMLAMP PROJECT

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KEY POINTS

- *Fastnet lighthouse*
- *Extreme event analysis*
- *Field modal test*
- *Discontinuous FEM model with contact interfaces*

1 INTRODUCTION AND OBJECTIVES

Historic rock-mounted lighthouses play a vital role in the safe navigation around perilous reefs. However their longevity is threatened by the battering of waves. The history of these landmarks of engineering has not been smooth. Lighthouse engineering has evolved after repeating collapses of under-designed structures. The majority of the surviving rock-mounted lighthouses are built based on an ingenious design: a tapered masonry structure with large-scale interconnected blocks, proposed by John Smeaton in the mid-18th century. As an island trading nation experiencing some of the world's strongest storms, the UK is particularly vulnerable to maritime navigation failure, and loss of one strategic lighthouse might have incalculable effect on safety and trade. Virtual navigational aids such as GPS are fallible, and reliance on them can be disastrous. Mariners will therefore continue to need the physical visual aids of these strategic structures. The importance of the lighthouse network to the safety of navigation, in combination with the heritage value of these iconic structures, provided the motivation for the STORMLAMP project. The project brings together different expertise from three UK institutions. University of Plymouth coordinates the project and is in charge of the hydrodynamics investigation. University of Exeter is in charge for the dynamic assessment of the lighthouses and UCL leads the structural numerical modelling. Hence the project proposes to use field, laboratory and mathematical/computer modelling methods to assess six of the most vulnerable rock lighthouses in the UK and Ireland. Through the paper, after a site-specific extreme wave characterisation, the study evaluates the dynamic response of Fastnet lighthouse (Figure 1) under the action of different wave loadings by means of a validated FEM numerical model. The aim of the study is to provide a comprehensive survivability assessment methodology for this type of structure.

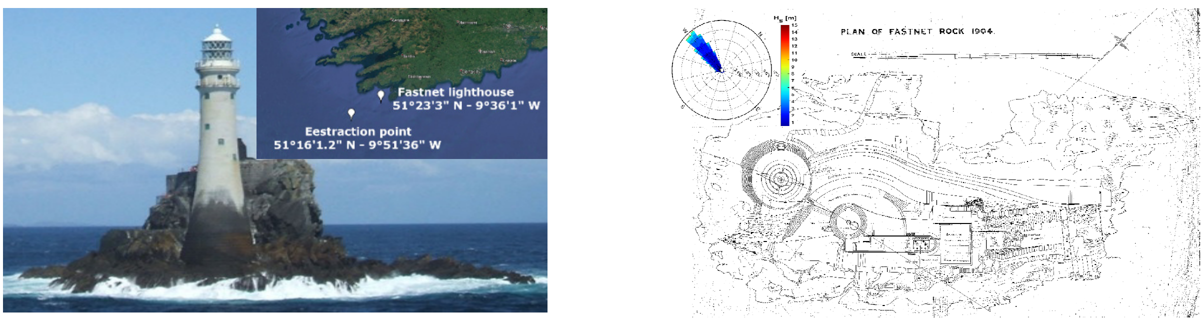

Figure 1 Left, Fastnet lighthouse rock and location (inset); right, archive drawing of the Fastnet rock and wave rose

2 METHODS

Three main activities characterise the study:

2.1 Extreme analysis and impact wave loading description

The adopted process leading to the impulsive wave loadings definition is composed of five steps similarly to the method proposed by *Trinh et al.* (2016). *i*) Firstly, directional extreme wave analysis is completed in order to provide a description of the extreme wave climate by means of a GPD-Poisson distribution, Figure 2 upper panel and lower-left panel. *ii*) Secondly, the variation in H_S within the surf zone around Fastnet rock is estimated by means of *Goda's* (2000) approach, *iii*) the previous results are adopted as input parameters for estimating the site specific wave heights distribution through *Battjes and Groenendijk's* (2000) method. *iv*) Asymmetry between wave crest and wave trough at the breaking point is calculated according to the empirical results presented by *Buhr Hansen* (1990). It is worth noticing that the identification of site specific wave heights distribution and wave asymmetry require knowledge of the local bathymetry (i.e. local slope and water depth); such data have been carefully considered through the archive drawings supplied by the Commissioner of Irish Light (http://www.irishlights.ie/) and through the information available on the INFOMAR website (https://jetstream.gsi.ie/iwdds/map.jsp). *v*) Finally, *Wienke and Oumeraci's* (2005) method is applied in order to define the total horizontal dynamic (slamming) load due to plunging waves breaking, Figure 2 lower-right panel. Moreover, despite the original *Wienke and Oumeraci's* method already introducing a spatial pressure distribution, in this study two other different distributions are analysed with the aim to identify the local effects on the most exposed course of the lighthouse.

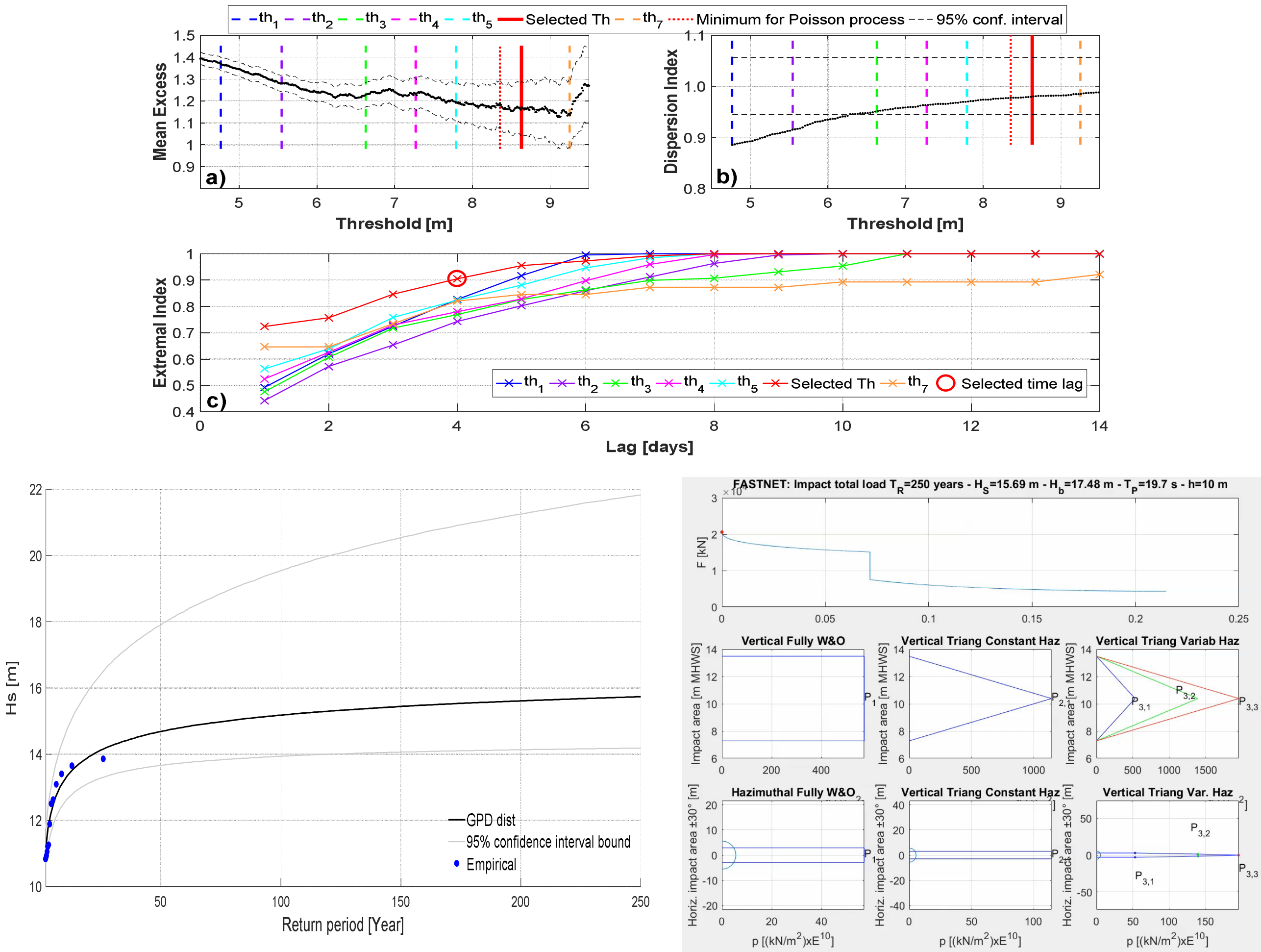

Figure 2 Upper panel: a), mean residual life plot, b) dispersion index considering 7 threshold values and c) extremal index for 7 threshold values and 14 declustering time lags. Lower panels: left, extreme wave climate; right: total impact load, vertical and horizontal pressure distributions

2.2 Field modal test

Carrying equipment to an offshore lighthouse requires meticulous planning considering the limited space and lifting capacity of the helicopter. In particular the need for a mechanical shaker aimed to provide external input to the structure must be very carefully considered given the substantial weight of both shaker and amplifier. Due to space and weight limitations the number of accelerometers that could be used is limited, preventing the ideal solution of monitoring all lighthouse levels in both directions simultaneously.

The modal test activities are subdivided into different tasks: one person sets up and runs analysis while other crews arrange the cables system and position and move the accelerometers up and down along the lighthouse. The dedicated time is extremely limited, and unpacking, setting up, running the tests and repacking all the equipment should be carried out during the daylight, i.e. everything needs to be done right the first attempt.. All 9 levels were instrumented with an accelerometer except the level where the shaker was located (i.e. the kitchen at level 8), which was equipped with both x-y accelerometers.

The aim of the modal testing was to identify horizontal vibration modes expected to occur around 5 Hz and some higher modes to validate the numerical model *Brownjohn et al.,* (2017). The main findings of this activity are in the form of sets of modal properties: *i*) natural frequencies, *ii*) damping ratios, *iii*) mode shapes and *iv*) modal masses (Figure 3 and Figure 4).

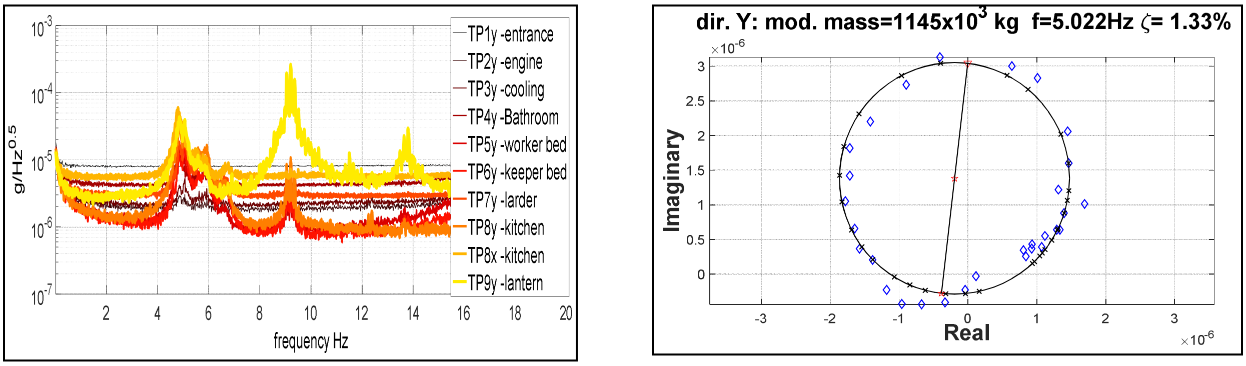

Figure 3 Upper panel: Auto-spectrum for ambient response; lower panels: SISO circle fit for forced vibration test.

2.3 Structural numerical model

The finite element numerical model is created with the software Abaqus 6.14 (2014). In order to be able to capture the potential uplift of the horizontal joints, the structure is modelled as discontinuous with contact interfaces between each course of stones. It was found that this modelling approach yields more realistic results than an FE model with continuous material properties *Pappas et al.* (2018). Structured and swept mesh with 8-node reduced integration linear brick elements C3D8R is used. Elastic and homogeneous material properties are assigned to the masonry courses. The horizontal contact surfaces between the courses are governed only by constant friction behaviour law with friction coefficient equal to 0.8. All the courses of the model, including the lowest one, are given the same material and contact properties, and are hence capable of manifesting relative displacements. Non-structural masses are added on the top stone course of the structure to simulate the lantern mass. The weight of the rotating device itself is estimated around 6 tonnes *Pappas et al.* (2017). The total mass of the model (without the added mass at the top) was 4382 tonnes. This differs by less than 3.6% from the estimation of 4300 imperial tons (i.e. 4232 tonnes) of granite used for the construction, *Morrissey* (2005). The calibration of the numerical model is performed in terms of frequencies, mode shapes and modal masses, achieving very good correlation with the experimental dynamic identification, Figure 4 upper panel. Lower panels in Figure 4 present the horizontal and vertical displacements for a duration of 1.8 s, including the impact time and the damped post-impact free-vibration. Very modest values of maximum horizontal and vertical displacements reveal suitability of the structural response. Regarding the stress distribution during the dynamic phase, the stress level is lower than 2% of the compressive and 16% of the tensile strength of the granite material with which the lighthouse is constructed.

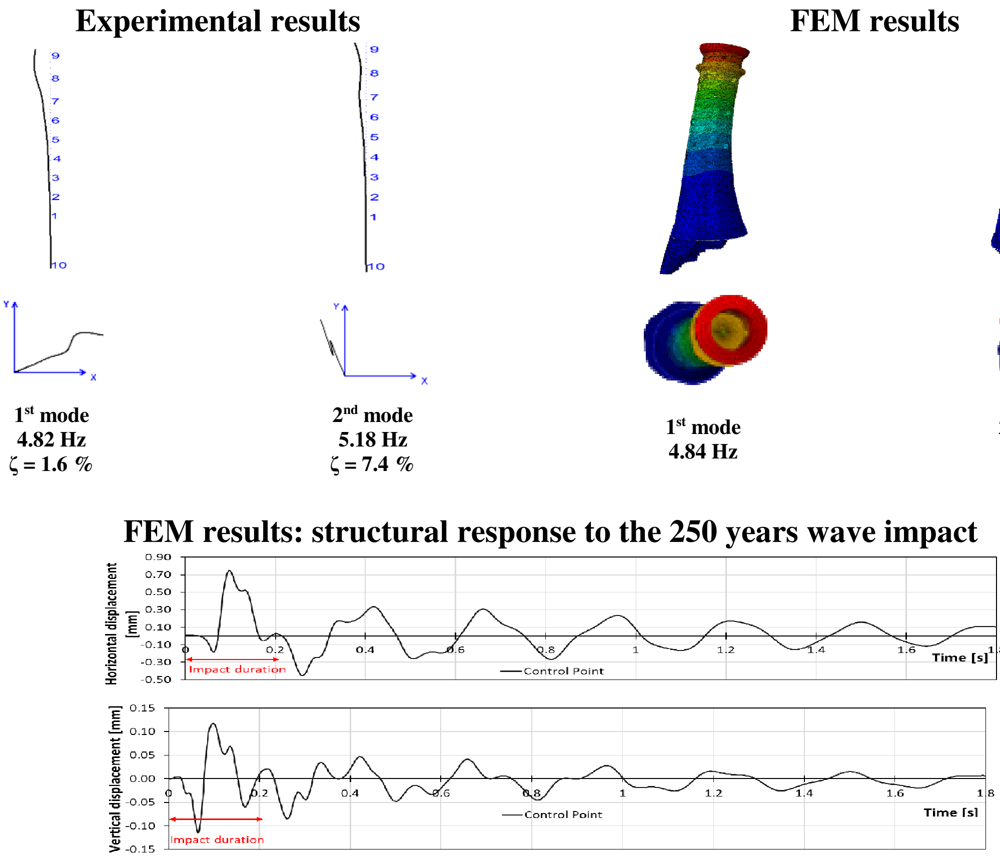

Figure 4 Upper panel: comparison between numerical and experimental modal properties; lower panels: vertical and horizontal displacements under the action of 250 years return period wave impact

3 DISCUSSION

The adopted multidisciplinary approach allows a comprehensive survivability assessment of this type of marine structures, highlighting the possibility to extend similar approach to other types of structures like vertical wall breakwaters and seawalls. The main findings of the specific Fastnet lighthouse analysis show: the hostile nature of the environmental in which the wave action is the most important factor, a first natural mode of the lighthouse at around 5 Hz and the suitability of the structure to survive extreme wave loadings condition.

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