# Reefense X-REEFS: hybrid biological and engineered reef structures for Nature-based Coastal Defense


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## INTRODUCTION

Coastal flooding and erosion from extreme weather events affect thousands of vulnerable coastal communities globally. The effects of coastal hazards are predicted to worsen during this century from population growth and climate change-driven sea level rise. As such, nature-based solutions are gaining increasing momentum as a promising strategy to the mitigate risk and cost of coastal flooding and associated hazards. In tropical coral-lined coasts, among the areas globally most susceptible and vulnerable to climate change and sea-level rise, there is increasing interest in the use of coral reef restoration as a form of nature-based coastal protection [1–3]. However, there are limited reef-engineered examples to date that have been specifically designed for coastal protection [4]. One of the key challenges is that it involves the interaction of complex processes at multiple spatial scales [5].

Here, we present the design and development of hybrid engineered and biological coral reef-mimicking structures that are designed to be fast-growing and resilient, while still providing immediate protection from waves. The Reef Engineering to Enhance Future Structures (X-REEFS) is one of the selected projects in the Reefense Program by the Defense Advanced Research Projects Agency (DARPA). The X-REEFS Project aims to develop a hybrid biological and engineered reef system to mitigate coastal flooding and erosion.

## METHOD

The approach relies on combining physical testing with two- and three-dimensional numerical models to assess the hydrodynamic performance of different hybrid reef structure designs in the laboratory and in the field, to meet target metrics of over 70% wave energy dissipation. Different designs were tested in the laboratory (University of Miami Alfred C. Glassell, Jr. Surge-Structure-Atmosphere Interaction (SUSTAIN) Laboratory) and modeled with OpenFOAM for local wave design conditions for a deployment site in Florida. On-site wave-forcing design conditions are defined from historic multi-decadal wave data, locally downscaled using hybrid techniques and spectra information from measurements. The variability in wave heights, directions, and periods were found to critically influence the location and performance of the hybrid reef solution. The design performance was evaluated with different wave models to ensure wave attenuation but also to engineer reef-induced circulation and maximize ecological outputs. The wave models (OpenFOAM and with nearshore phase-averaged models XBeach Non-Hydrostatic and FUNWAVE-TVD) were used in a cross-shore wave tank as well as at the field scale to optimize the cross-section and the layout on the field to meet high wave energy attenuation as well as optimizing the flow through the structures.

## RESULTS

Phase 1 of the project has led to a new hybrid reef design that was developed using innovative multi-layer structures, materials, 2D/3D hydrodynamic modeling, and flume tests to deliver a durable and flexible system that maximizes wave attenuation and biological enhancement benefits. The base structure uses a modular marine and estuarine shoreline protection system based on perforated hexagonal prisms (SEAHIVE®) and lattices, optimized by performance of different lattice volume fractions, that direct the flow in a helical pattern through the structure. The primary function of the base structure is to dissipate wave energy through both wave breaking atop and turbulence through the porous reef structure. The lattice subunits further enhance the physical and biological performance of the structure, as they were designed to further increase wave dissipation and create structural complexity and habitat. Novel aspects of the structure design include influencing wave-structure processes to enhance wave energy dissipation, the combination of different sub elements to enhance wave breaking, enhanced boundary layer friction surface, overall high porosity while reducing wave transmission, and a modular design to create different reef sections (Figure 1).

Figure 1: Example hybrid 6- and 9-unit reefs that were used for constructing the hybrid reef designs. All reef units were numerically tested at 1:5 scale.

Calibrated and validated hydrodynamic modeling efforts supported the design of three innovative and distinct hybrid reef structures and structure layout designs that met DARPA's Reefense Program metrics of 70% wave energy dissipation in the wave tank experiments. Results from numerical model demonstrated that existing empirical formulas for submerged and low-crested breakwaters cannot be used to evaluate the performance of these novel hybrid reef systems. The design is tested and optimized using physical experiments in the University of Miami's SUSTAIN facility and mirrored in OpenFOAM to explore and optimize turbulent kinetic energy dissipation and flow through the structure (Figure 2).

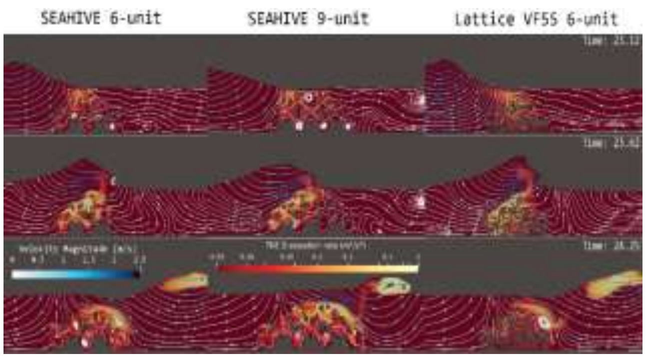


Figure 2 – Snapshots of turbulent kinetic energy dissipation (red colors) and velocity streamlines (blue colors) for three single-row reef hybrid designs. .

The results are used to calibrate and compare simplified, phase resolving models (Non-Hydrostatic and Boussinesq-type models) that are applied at the field scale for designing the field deployment at a site in Southern Florida (Figure 3) to engineer reef-induced circulation and maximize ecological potential. This requires optimizing the reef layout attending for different configurations of reef units to maintain wave energy performance while optimizing costs and flow through the reef system for ecological factors.

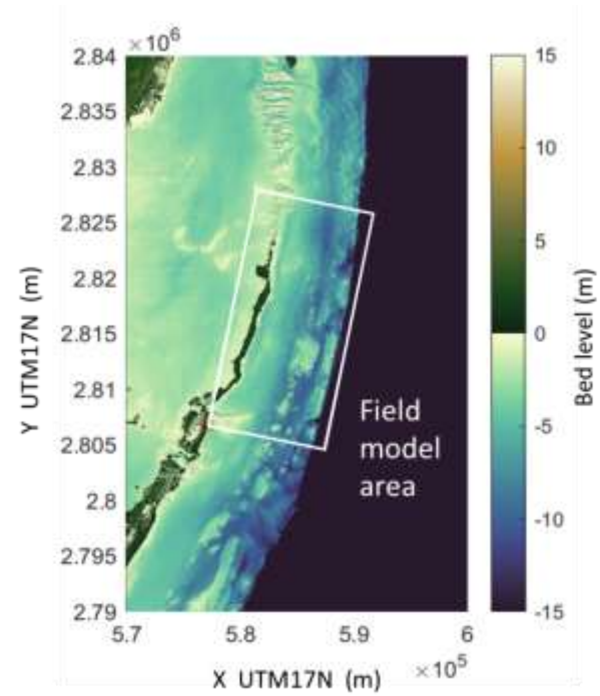


Figure 3 - Topography and bathymetry for the Elliott Key site and domain for field modeling with Non-Hydrostatic and Boussinesq wave models.

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