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Design, Fabrication, Installation, and Population of a Novel Fiberglass Reinforced Plastic Coral Nursery Structure Off the South Shore of O'ahu, Hawaii

Bardia Konh[1]* and Matthew Parry[2]

[1] Department of Mechanical Engineering, University of Hawai'i at Mānoa, Honolulu, HI, United States, [2] Fishery Biologist, NOAA Restoration Center, Damage Assessment, Remediation, and Restoration Program (DARRP), Pacific Islands Regional Office, Inouye Regional Center, Honolulu, HI, United States

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Correspondence:
Bardia Konh
konh@hawaii.edu

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Coral reefs support a biologically rich ecosystem and are economically invaluable. Unfortunately, due to several reasons including, but not limited to, human activities, global warming effects, and both biotic and abiotic stressors, coral reefs are gradually disappearing from Hawaii's shorelines. This study introduces novel coral husbandry techniques to help restore injured coral reef habitats. The techniques presented in this work are focused on saving whole coral colonies detached from their bases (via wave action or other physical disturbances) instead of fragmenting existing colonies. Design, fabrication, assembly, and installation details of an in-water Fiberglass Reinforced Plastic (FRP) coral nursery structure are discussed in this work. Material selection and novel design of the coral nursery were specifically adapted to physical ocean conditions of the south shore of O'ahu, Hawaii. Factors such as safety, practicality, cost efficiency, transportation, installation, and attachment of coral colonies for systematic restoration efforts, while maintaining minimal environmental impact, were considered to design and build the coral nursery. Structural fatigue was investigated via finite element methods considering underwater loading and boundary conditions. FRP was chosen for the material by a trade-off comparison method. This structure was built, assembled, and deployed in south shore O'ahu, Hawaii, in April 2018. This study demonstrated the design, engineering, and build of a durable coral nursery structure.

Keywords: fiberglass reinforced plastic, underwater structure, manufacturing, coral nursery, coral rehabilitation, Hawaii, finite element analysis, whole colony

INTRODUCTION

Coral reefs occupy less than 1% of the ocean floor, yet are still one of the most productive and diverse ecosystems in the ocean (Martínez et al., 2007; Descombes et al., 2015). In terms of biodiversity, there are over a million species living in coral reefs either directly or indirectly (Martínez et al., 2007; Descombes et al., 2015). Coral reefs are responsible for several important functions such as supplying food (fisheries), protecting coastal regions from storms and erosion, supporting services (such as biogeochemical cycling, feeding, and breeding habitats), and providing attractive recreational areas for tourism industries (Moberg and Folke, 1999; Wells and Ravilious, 2006; Hoegh-Guldberg et al., 2007; Elliff and Kikuchi, 2017). However, coral reef's health and resilience have been threatened by global and local stressors such as ocean acidification, bleaching, storms, overfishing, predators, diseases, pollutions, sedimentations, eutrophication, and coastal developments (Hoegh-Guldberg et al., 2007; Elliff and Kikuchi, 2017). For example, in 1998, El Nino-Southern Oscillation (ENSO) destroyed about 40% of the world's coral reefs. In recent years (2014–2017), ENSO again caused a profound negative impact on the majority of the coral reef ecosystems around the world (Bahr et al., 2017). The coral reefs have suffered considerable degradation. It is estimated that about 60% of coral reefs may disappear by 2030 due to a combination of biological and anthropogenic stressors (Hughes et al., 2003).

Coral cover in the Caribbean Sea and Great Barrier Reef (GBR) has decreased by about 1.4% (between 1977 and 2001) and 1.51% (between 1985 and 2012) per year, respectively (Gardner et al., 2003; De'ath et al., 2012). The driving factor in coral reduction differs with region. The quick decline in the Caribbean's reef system from 55% in 1977 to 10% today is related to coral diseases, storms, and coral-algae phase shift, while a loss of 51% of initial coral cover in GBR (1985–2012) is due to tropical cyclones (48%), presence of crown-of-thorns starfish (42%), and coral bleaching (10%) (De'ath et al., 2012). In the 1970s, white band disease caused mortality of more than ∼90% of specimens of genus *Acropora* in Caribbean coral reefs (Kline and Vollmer, 2011). The remaining coral communities still suffer from hurricanes, bleaching, and other coral predators. Due to lack of recruitment and recovery, the species *Acropora palmata* and *Acropora cervicornis* were listed as critically endangered on the Red List of Threatened Species in 2008 (Chamberland et al., 2015).

About 85% of the coral reef ecosystems in the United States are located in the Hawaiian Archipelago (Cesar and van Beukering, 2004). The Hawaiian Archipelago is divided into two main parts: Main Hawaiian Islands (MHI) and Northwestern Hawaiian Islands (NWHI). Although the coral reefs in the MHI, which consists of eight Islands, are comparatively smaller, its economic value is much greater than the NWHI coral reefs due to the tourism industry. MHI stands at an estimated economic value of US$10 billion for Hawaii's coral reef (Cesar and van Beukering, 2004).

O'ahu is the third largest island in the MHI and ranks second in reef area with about 504 km^2 (Cesar and van Beukering, 2004). Coral species generally found in the Hawaiian Islands include *Montipora capitata*, *Montipora flabellata*, *Montipora patula*, *Porites compressa*, *Porites lobata*, *Pocillopora meandrina*, *Pavona varians*, and *Pocillopora grandis/eydouxi*. Corals surround much of the island, but the highest of coral coverage is located in Kaneoh'e Bay, which is a large sheltered area (Friedlander et al., 2008; Franklin et al., 2013; Bahr et al., 2017). Between 1937 and 1944, extreme damage to the coral reefs in O'ahu (specially in Kaneoh'e bay) was observed caused by dredge and fill operations due to the development of ship channels and seaplane runways (Rodgers et al., 2017). With the local environmental conditions (e.g., higher sea surface temperature average and possible ocean acidification), the damaged corals have not been able to fully recover for the past 60 years (Rodgers et al., 2017). The presence of a sandy substrate in the area may be preventing the coral larvae from settling. However, a successful coral reef restoration project at this region showed that transplanted corals live and grow at the current local conditions (Rodgers et al., 2017). Overall, heavy anthropogenic impact associated with tourism and marine recreation, overfishing, subsequent terrestrial runoff, and coastal pollutions are among the major threats to MHI's corals. These factors could also contribute to spreading coral diseases (Aeby et al., 2011; Bahr et al., 2017; Rodgers et al., 2017).

Damaged corals recover naturally; however, with no restorative actions, this process can be very slow. The recovery time depends on different factors such as extent of colony tissue mortality, coral species, and human activities in the local environment (Bahr et al., 2017; Stimson, 2018). The recovery rate is highly influenced by pollutants (Bahr et al., 2015). For example, damaged corals at Kaneoh'e bay were able to recover even when facing bleaching and flash floods; however, it took about 10 years for these damaged corals to fully recover (Bahr et al., 2015).

To ameliorate widespread coral decline and to recover loss of coral reef ecosystems, several approaches have been practiced such as coral transplantation, coral gardening, artificial underwater, and electrochemical reef structure developments (Young et al., 2012; Tortolero-Langarica et al., 2014; Lirman and Schopmeyer, 2016). The main purpose of these approaches has been to restore and rehabilitate coral reefs (Young et al., 2012; Tortolero-Langarica et al., 2014; Lirman and Schopmeyer, 2016). Traditional reef rehabilitation processes have been focused mostly on transplanting fragmented colonies (Rinkevich, 2005; Shafir et al., 2006a; Edwards and Gomez, 2007). Direct transplantation apply extra stress on the source reef and to the donor coral colony, especially if the source reef is already stressed and/or is in a state of decline (Rinkevich, 2005; Shafir et al., 2006a; Edwards and Gomez, 2007). Transplantation of corals also stress the transplants, which increases the risk of mortality (Rinkevich, 2005; Shafir et al., 2006a; Edwards and Gomez, 2007).

Reef gardening is an active reef restoration process to recover degraded coral reefs (Rinkevich, 2005; Edwards and Gomez, 2007). The reef gardening method consists of two steps: the first step is seeding (coral fragments, nubbins, or larvae) in nurseries until they grow in size, and the second step is to transplant the fragments to the degraded reef regions (Epstein et al., 2001). The restoration strategy has been successfully implemented in many coral reef ecosystems around the world such as the Red Sea (Eilat, Israel), Thailand, Singapore, Philippines, Tanzania, Malaysia, Seychelles, Caribbean and western Atlantic Ocean, Japan, Taiwan, and Hawaii (Shafir et al., 2006a; Putchim et al., 2008; Shafir and Rinkevich, 2008, 2012; Shaish et al., 2008; Levy et al., 2010; Horoszowski-fridman et al., 2011; Lirman and Schopmeyer, 2016; Rodgers et al., 2017).

Different models of nurseries have been designed such as frame/tables, rope/lines, cinderblock platforms, reef balls, floating structures, and larval seeding (Shafir et al., 2006a,b; Shaish et al., 2008). In Malaysia, for example, the coral nubbins (5–10 cm in length) of *Acropora formosa* were successfully

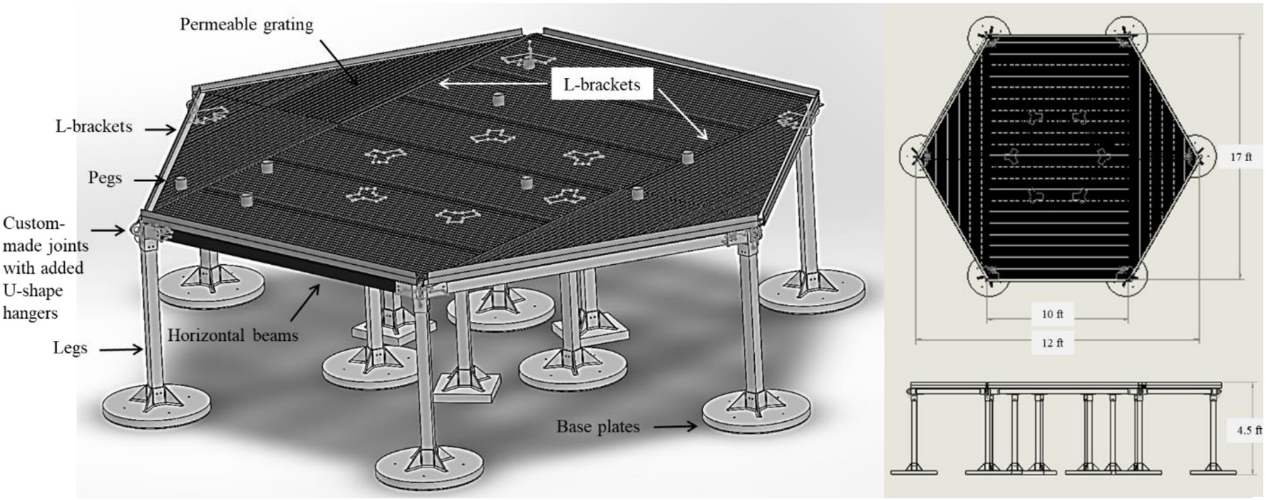

FIGURE 1 | Computer-Generated design of the coral nursery structure, with overall dimensions on the right.

transferred to a substrate consisting of several rectangular frames (15-mm-diameter PVC pipes) with four parallel pipes across the frame. The whole structure was elevated about 35 cm from the bottom and the nubbins. The nubbins were tied vertically to the frames with plastic cable ties (Xin et al., 2016). In the Philippines, a novel mid-water nursery was introduced for branching and encrusting forms of corals (*Montipora*, *Pocillopora*, and *Echinophora*). This floating rope nursery was made from rope lines loaded with framed corals floated 2 m lower than surface buoys. The large fixed ropes were designed by angle bars forming a rectangle with its four legs secured inside the sandy substrate at 5-m intervals. Above these, the ropes with coral fragments were aligned (Levy et al., 2010). In the Philippines, a fixed and suspended nursery (2 m deep in a sandy lagoon) was found suitable for varied species with different shapes (branching, leaf-like, sub-massive), and with a different rate of growth. Both structures were modular structures, made of a 60 × 80 cm plastic mesh tray attached by cables to a 13-mm (0.5-inch) PVC pipe frame (Shaish et al., 2008). In a central Pacific park, *Pocillopora* spp. were transplanted to a natural substrate rather than an artificial substrate (Tortolero-Langarica et al., 2014). In another project, a floating mid-water coral nursery structure was successfully implemented in the northern shore of Eilat, Gulf of Eilat, and the Red Sea (Shafir et al., 2006a; Shaish et al., 2008).

It should be noted that in a degraded reef ecosystem, the non-fragmented corals are exposed to physical and biological damages; therefore, developing a suitable nursery for these corals could be the most effective method in rehabilitation. In this study, a novel Fiberglass Reinforced Plastics [FRP], 2019 reef rehabilitation platform was designed based on the gardening concept and applied to non-fragmented corals of south shore of O'ahu, Hawaii. The nursery was deployed in April 2018. This study was necessary because unlike Florida and the Caribbean, where their fragmentation nurseries rely on the relatively fast growth rates of their species, most coral species in Hawaii have much slower growth rates. Therefore, fragmenting larger corals may not result in increased growth rates over those previously reported that would yield untenable recovery times for fragmented corals in Hawaii. Using non-fragmented corals of different shapes allows for immediate replanting older corals that might otherwise take decades to regrow at reported rates. This work demonstrates the design, fabrication, assembly, and deployment of a coral nursery, with brief discussions about populating the nursery with corals.

MATERIALS AND METHODS

Design: Objectives, Constraints, and Functions

A coral nursery structure was designed to prepare a platform for coral restoration and transportation. In order to expose corals to sufficient amount of sunlight for their proper growth, the coral nursery structure needed to be installed at a depth of 12–21 m below sea level. Additionally, the structure needed to be located deep enough (at least 10 m) in the water to prevent any navigational hazards to local boating traffic. The structure had to be elevated about 1.5 m from the ocean floor to minimize sand scour from the bottom and to give divers easy access to the top of the structure for either initial attachments and/or later detachments of the corals. Three supports were needed to be embedded from the structure to the ground to restrict its lateral movements.

The size of the structure was 7.6 × 7.6 × 1.5 m (width, length, height). This structure was intended to be environmentally sustainable for 5 years with minimum maintenance. The coral nursery needed to be structurally rigid with reasonable integrity to secure large coral heads of up to 0.9 m diameter (longest axis). For a safe and durable design, the factor of safety in the analyses was intended to be greater than two to compensate for either peak dynamic (e.g., waves and currents) or static loads

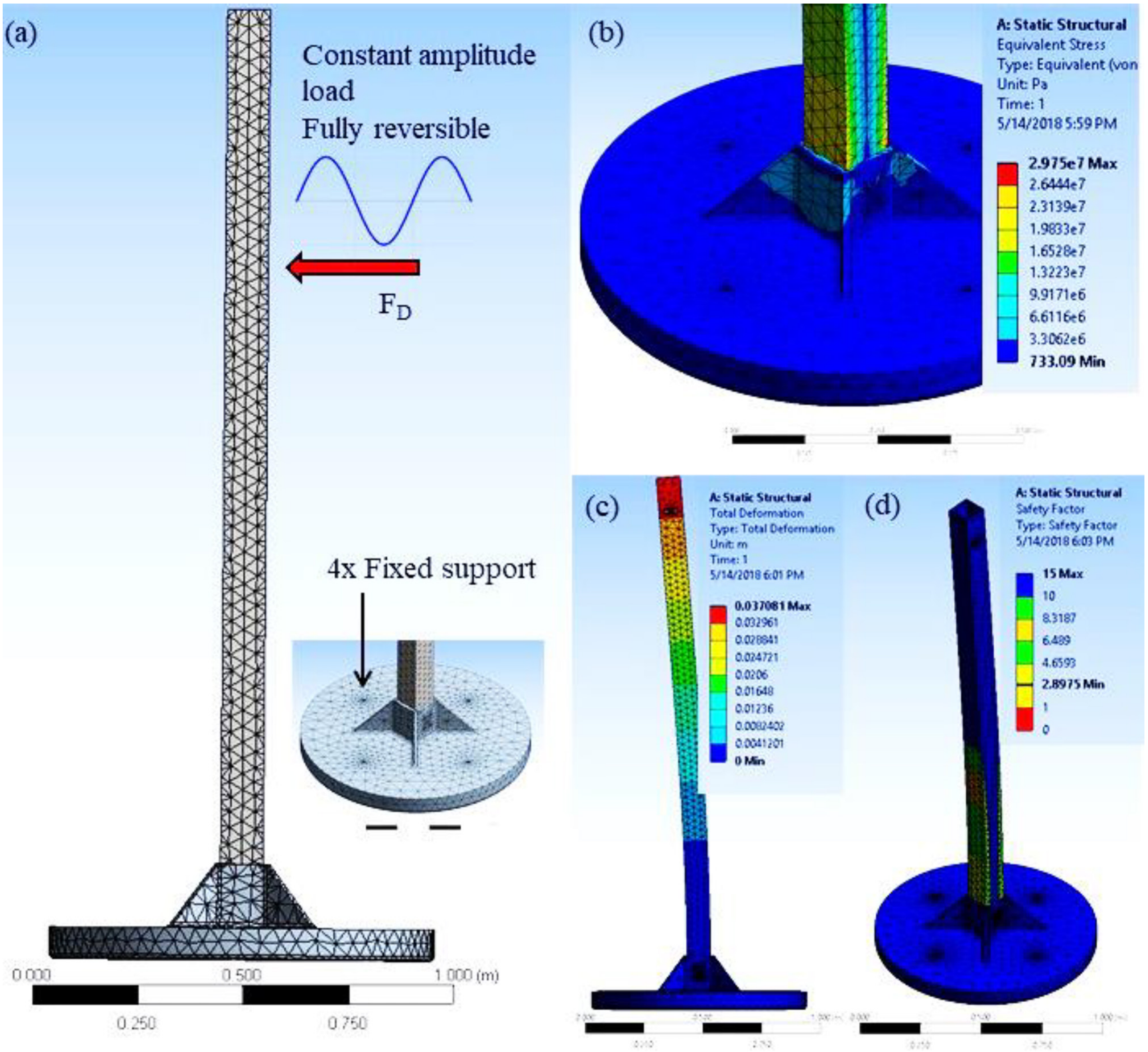

FIGURE 2 | Finite element model of a single leg subject to horizontal drag force: **(a)** the generated mesh, **(b)** the maximum equivalent von-Mises stress, **(c)** total deformation, and **(d)** the factor of safety for extreme case of 1,815 N of drag force.

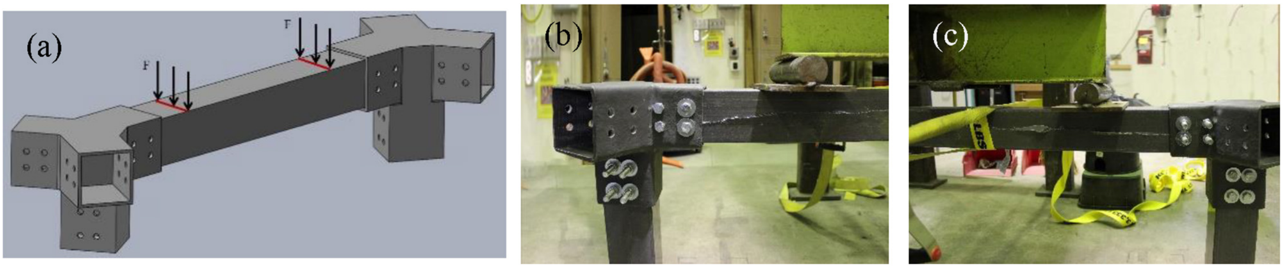

FIGURE 3 | Compression test with an FRP horizontal beam supported at its two ends. **(a)** The schematic view of the experimental setup, **(b)** front, and **(c)** back view of the propagated cracks.

TABLE 1 | Fatigue analyses of the coral nursery structure.

	Coefficient of drag (C_D)	Wave velocity (m/s)	Drag force (N)	Deformation (m)	Max equivalent von-Mises stress (MPa)	Lowest factor of safety	Life
Fiber Reinforced Plastic (FRP)							
Case 1	1.17	1	90	0.002	1.47	15	10^6
Case 2		1.5	204	0.004	3.30	15	10^6
Case 3		2.5	566	0.012	9.27	9.29	10^6
Case 4	1.5	1	116	0.002	1.90	15	10^6
Case 5		1.5	261	0.005	4.28	15	10^6
Case 6		2.5	726	0.015	11.90	7.24	10^6
Case 7			1,815	0.037	29.70	2.9	
Aluminum							
Case 8	1.17	2.5	566	0.002	9.23	8.95	10^8
Case 9	1.5	2.5	726	0.003	11.80	6.98	10^8
Structural steel							
Case 10	1.17	2.5	566	0.0008	9.28	9.29	10^6
Case 11	1.5	2.5	726	0.001	11.90	7.24	10^6

(e.g., coral weight, divers' weight, and equipment). The factor of safety is defined as the ratio of the nursery's absolute strength to actual applied load. To obtain an upper limit of loading weight applied on the coral nursery, the higher limit of aragonite was multiplied to estimated coral volume. The volume of corals was estimated as a hemisphere with the largest axis diameter of each coral. This method greatly overestimated the weight of encrusting and branching corals. This overestimation along with a factor of safety of greater than 2 ensured the structural safety of the nursery in this work.

The structure was purposed to hold around 430 kg m^{-2} of coral heads. To help keep the corals in proper orientation, some pegs were designed to attach to the top of the structure. The pegs were also to prevent the corals from falling off the nursery platform onto the seafloor. The pegs were made from polyvinyl chloride (PVC).

Computer-Generated Design

The designed structure for the coral nursery structure is shown in **Figure 1**. This single-tier, hexagonal benthic structure was chosen for its ease of access and stability. The symmetrical shape of the structure was selected to resist the dynamic forces applied in any magnitude and direction. The single-tier platform was supported by 18 horizontal beams. The platform sat on 12 legs (six at the peripheral side and six at the center). These legs were distributed at specific points to prevent the top face from buckling or bending. Custom-designed joints were included to accommodate assembly of the structure. The joints were rigidly formed at predetermined angles for ease of assembly, as well as introducing more strength to the structure. The legs were sitting on a base plate that was either in a circular or a square shape. These plates helped prevent the structure from sinking into the sand. To hold the legs properly, the plates were reinforced by four angular gussets. The square shape base plates were used at the center to leave enough space between all base plates. In case of misalignment between the legs due to irregular bottom topography, this space provided easy access to divers to fit all six inner legs and footings together. A permeable grating was included on the top face of the structure for coral attachment. Six L-bracket pieces (5 cm in height) were attached around the frame to prevent corals from falling over the edge of the platform. Four additional L-brackets were included under and across the grates to level and align the grates on the top face of the structure, as well as to prevent the grates from buckling. The L-brackets were epoxied directly to the grates.

Pegs were designed to connect to the grates by sliding onto their cross sections. The pegs were reinforced with zip-ties. This design was appropriate to secure various sizes and shapes of corals to the platform.

Material Selection and Detailed Considerations

To select a suitable material for the coral nursery structure, several factors were considered. The material needed to work under water within a temperature range of 24–30°C, at around three times atmospheric pressure, and with minimal impact to the environment. Also, the material needed to be non-corrosive, light, and mechanically and chemically durable for a lifetime of 5 years.

Fiberglass Reinforced Plastic, a thermoset plastic resin reinforced by glass fibers, was chosen for its strength and non-corrosiveness. Compared to other conventional materials such as 361 stainless steel, 6061 aluminum, and concrete, FRP offered a low weight-to-strength ratio (FRPs). FRP could be easily molded into custom shapes with a lower cost of manufacturing and maintenance. Properties of FRP are anisotropic and depend on orientation of fibers in plastic based on manufacturing process (Strongwell, 2019). The density of FRP varies in accordance with percentage of fibers in the plastic (Moldedfiberglass, 2019). Therefore, to define the exact properties of the material, a dog-bone-shaped sample was obtained from Fibergrate (with outer rectangular tabs of 25.4 × 6.35 × 76.2 mm and a middle section of 12.7 × 6.35 × 50.8 mm) and used in a tensile test with

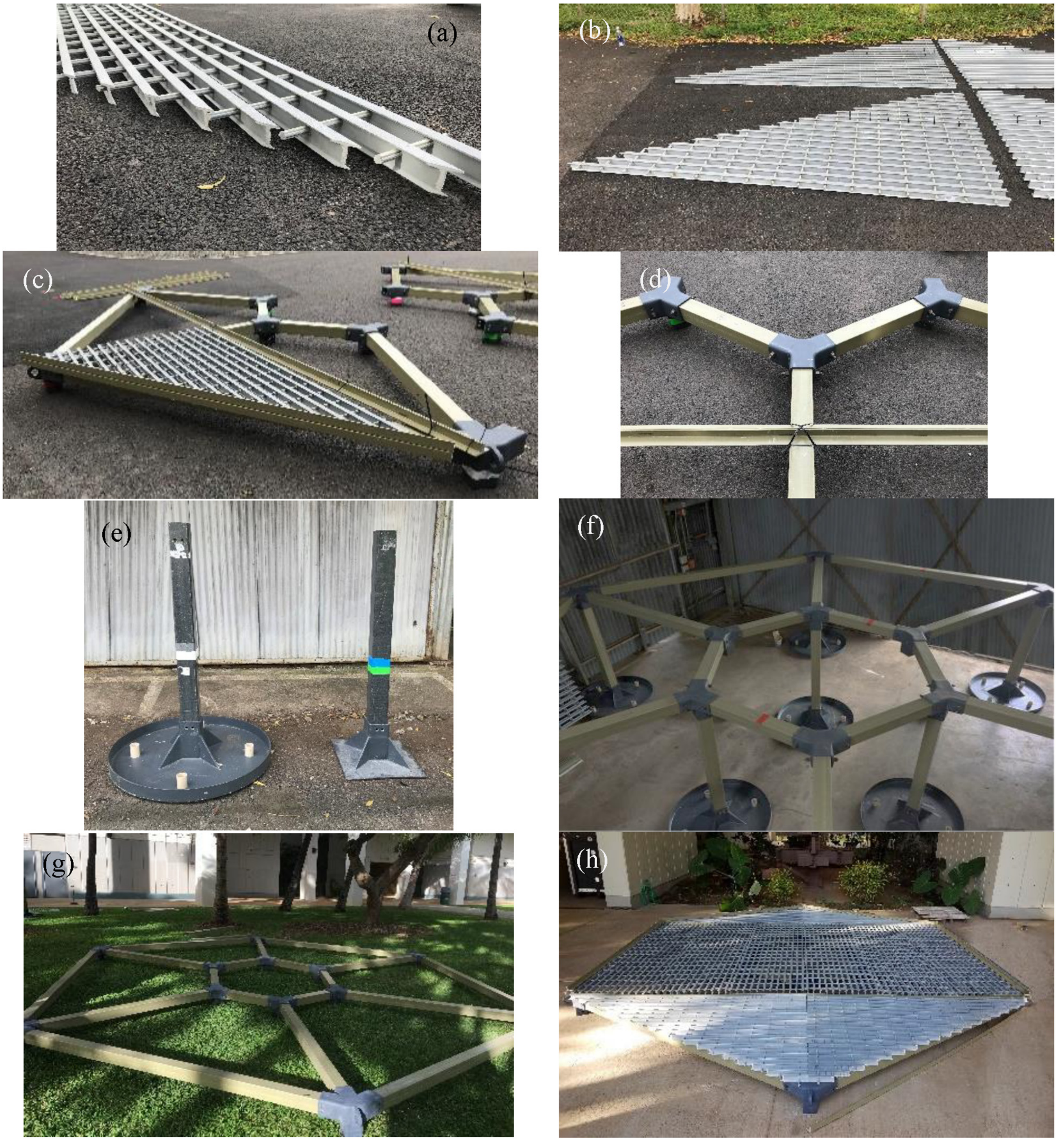

FIGURE 4 | The fabricated components of the coral nursery structure: **(a)** the grates with I-shaped cross section, **(b)** sample grating plates, **(c)** top face covered by the grates, **(d)** horizontal beams attached by the costume made joints, **(e)** legs marked with colorful labels for assembly, **(f)** assembled legs and horizontal members, **(g)** the hexagonal platform, and **(h)** top face of the platform covered with grates.

an Instron machine. A gradually increasing tensile force was applied on both ends of the sample until it experienced a brittle fracture at its tapered portion. The measured elastic modulus was 14 GPa, with a yield strength of 275.5 MPa. Maximum tensile strength was recorded at 294 MPa (sample failed at 23,780 N of tensile force). The FRP's measured density was 1,840 kg m^{-3}. These properties were included in the finite element analyses, described in the section "Finite Element Evaluations of the Design" to evaluate the safety and durability of the structure.

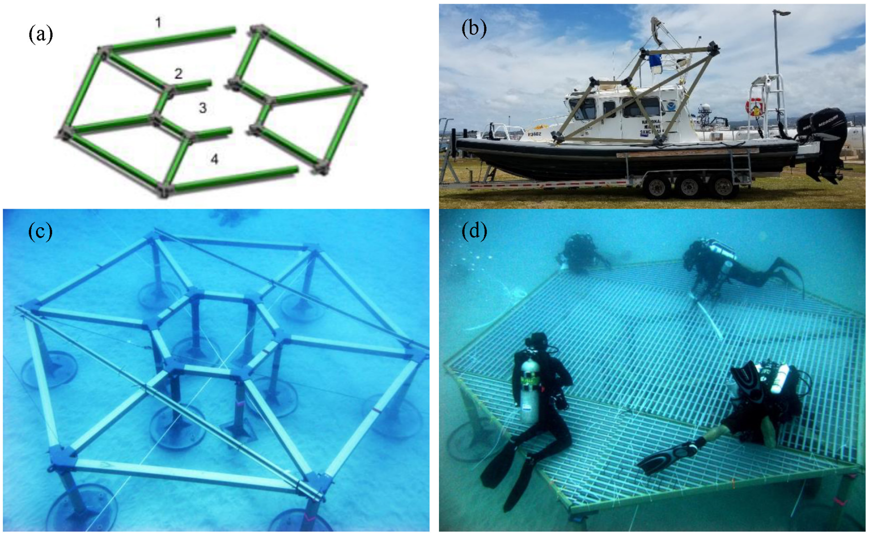

FIGURE 5 | (a) The pre-assembled halves, and installation method under water, **(b)** NOAA 36 ft vessel R/V Hihimanu of the Papahanaumokuakea National Marine Monument with pre-constructed nursery top surface secured to side, and **(c,d)** the deployed coral nursery structure underwater.

The grating was manufactured by Fibergrate. The published values from the manufacturer for the maximum recommended load is 9.58 kN m^{-2} (Load Tables - Fibergrate Molded Gratings, 2019), which is greater than our calculated maximum loading of 4.26 kN m^{-2}.

Finite Element Evaluations of the Design

Finite element analysis of the structure was implemented for the coral nursery design. Based on the amount of stress that the FRP withstands, the analyses ensured structural stability of the design. The structure was under static forces as well as dynamic underwater forces. The hydrostatic forces were applied from the corals sitting on the grates, additional to the weight of the structure itself supported by the legs. Considering buoyancy, the amount of vertical forces was almost negligible for buckling of grating or legs. However, the oscillating drag forces were likely to cause fatigue and eventually structural failure. For this reason, Finite Element Analysis (FEA) was performed on a single leg and by projecting all the forces from other members for fatigue analyses. The drag force (F_D) was calculated using:

$$F_D = 0.5 \times C_D \times \rho \times A \times V^2 \quad (1)$$

where C_D is coefficient of drag, ρ is seawater density, V is wave velocity, and A is the cross-sectional area. With Reynolds (Re) number in the order of magnitude of 10^6, and by assuming the overall geometry was either a thin annular disk or a rectangle, the coefficient of drag (C_D) was found to be 1.17 and 1.5, respectively.

Fatigue analyses were also performed with the applied force ranging from 90 to 726 N on the cross-sectional area of the leg, depending on the velocity of hitting waves. Wave oscillation velocity at the depth of 18–21 m on the south shore of O'ahu is roughly 0.5 m s^{-1} in average conditions; between 1 and 2 m s^{-1} during a swell event, and up to approximately 2.5 m s^{-1} in the case of a tsunami. Six case studies were developed to study each scenario with different wave strength and coefficient of drag. The study was repeated with the two worst-case scenarios for aluminum and structural steel for comparison. An additional study was performed with a force of 1,815 N applied horizontally to the leg to make sure that each leg could tolerate unexpected shocking forces applied from external objects as well. The mesh, generated in ANSYS on the 3D model of the leg, is shown in **Figure 2a**. The model consists of 23,283 elements and 43,036 nodes. Mesh refinement was applied to the edges connecting the leg to the base plate. The Goodman mean stress theory with fully reversible cyclic loads was used for fatigue analyses. **Figures 2b–d** show the equivalent von-Mises stress, total deformation, and safety factor, respectively, for the extreme case of 1,815 N of force.

Populating With Corals

Two SCUBA divers spent 5 days collecting detached and loose corals from nearby areas and transporting them to the structure. Divers visually examined coral colonies and determined whether they were loose or not. When corals were determined to be detached from the substrate, they were collected and placed in plastic baskets harnessed to underwater scooters. Once the baskets were full, scooters were used to transport the corals onto the structure. Corals were chosen opportunistically as those with greater than 50% tissue mortality were not selected for the nursery for effective rehabilitation.

RESULTS

Material Testing

During the bending test on the Instron compression machine, fracture was observed after 8,555 kg of vertical force and

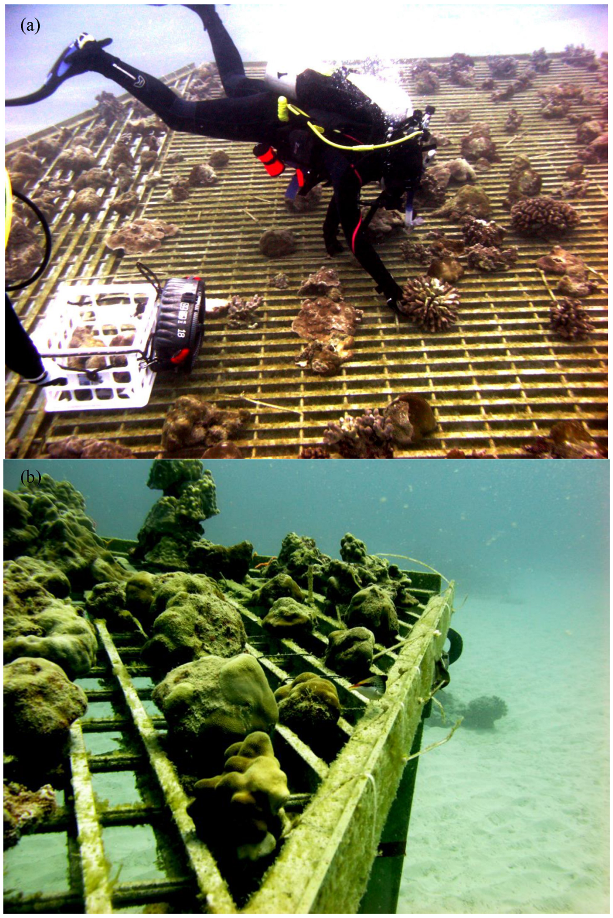

FIGURE 6 | (a) Diver unloading corals onto coral structure. The transport basket and harnessed underwater scooter can be seen in the bottom left of the photo, and **(b)** corals slotted into the spaces between the grating without the need for extra supports.

displacement of 53 mm, with cracks propagated at the pins (**Figure 3**). **Figures 3b,c** show the front and back views of the cracks. The bending test proved the strength of the FRP under vertical loading conditions. However, additional epoxy was applied to the holes to reinforce the connection points.

Finite Element Validation

Table 1 lists the maximum deformation, equivalent von-Mises stress, factor of safety, and lifetime of the structure for 11 case studies developed with different forces applied horizontally to the leg, and with three different materials (i.e., FRP, aluminum, and structural steel). It was shown that even under severe conditions (F_D = 726 N) with a wave velocity of 2.5 m s^{-1}, the FRP will work at a high cyclic fatigue life ($>10^5$), and with a factor of safety of higher than 7.24. It was also shown that with 1,815 N of shocking force, FRP will work at a factor of safety of 2.9. This factor of safety is acceptable from an engineering point of view, especially for structures that do not involve risks to human lives. Structural steel showed a close trend to FRP because of similar material properties. Aluminum, however, showed lower factor of safety with a higher fatigue life.

Manufacturing and Fabrication

Figure 4 shows the fabricated components of the coral nursery structure. **Figures 4a,b** show the grating plates that were formed from I-shaped beams connected by rebars. The grating plates were cut into right angles to cover the top face of the platforms (shown in **Figure 4c**). **Figure 4d** shows the square beam members connected by the custom-designed joints, firmly attached by screws and nuts made of FRP. The legs were marked with colorful tapes (**Figure 4e**) to help divers in assembly process (**Figure 4f**). The top face of the platform without and with gratings is shown in **Figures 4g,h**, respectively.

Assembly, Transportation, and Deployment

The coral nursery structure was installed at the southern part of Reef Runway, Sand Island, O'ahu. This area has minimal fishing and diving activity due to its proximity to Honolulu International Airport. To facilitate transportation and easy deployment of the structure via normal boats, the structure was made in pieces (**Figure 5a**) and shipped unassembled. The structure was designed to be assembled and installed by certified divers underwater adhering to guidelines and rules.

Primary assembly of portions of the structure was done above water. The top section of the structure was built above water in two halves (**Figure 5b**). Once both sides were constructed, the halves were transported to the location by a boat. Legs, footings, and the grates were transported on the deck of the vessel and down in the forward cabin. Once at the location, the halves were lowered to the ocean floor and bolted together. The bolts were sealed with a marine epoxy curable underwater. Once the two halves of the framework were brought together,

TABLE 2 | List of coral colonies attached to the nursery.

	P. compressa	*P. lobata*	*P. meandrina*	*P. damicornis*	*M. capitata*	*P. varians*	*P. grandis/eydouxi*
Size class (cm)							
A (5–10)	13	8	0	3	9	0	0
B (10–20)	40	174	33	0	101	1	1
C (20–40)	2	18	5	0	6	0	0
D (40–80)	0	0	0	0	0	0	1
E (>80)	0	0	0	0	0	0	0

the four connecting beams marked with red tape were finally bolted together. This provided an adequate amount of space to line up the sections accordingly and bolt the entire structure together. Once the two halves were joined, one side of the structure was lifted for the legs to be added. The opposite side was then lifted to add the remaining legs. Once the legs were attached, the last step was to place the grates on the frame. Once the frame was fully assembled, the 10-piece grating was placed on top of the frame. Three Danforth style anchors (each providing roughly 1,810 kg of holding force) were used to secure the structure in the sand using rope and 3 m of anchor chain. Ropes were secured to opposing U-shaped hangers molded into the joints and the ropes run under the nursery with anchors secured in the sand roughly 6 m away from the nursery providing ample scope (**Figure 5c**). The deployed coral nursery structure underwater is shown in **Figure 5d**. The deployment took 3 days, during which the structure was transported by a 9-m boat to the location and installed underwater by five divers in about 8 h.

Populating the Nursery

A total of 415 coral colonies of various species and size classes were collected and placed on the nursery (**Figure 6a**). As shown in **Figure 6b**, the pegs were not used to date to hold the corals in place, since the grating appeared to provide ample space to slot protrusions from the coral into the grating by itself. The corals were ensured to get stuck well between the grates for stability in rough weathers. Pegs were only used for the areas that the space was not large enough for the corals. Corals were censused using longest axis measurements for each colony and visually identified (**Table 2**).

There was a wide range of estimates for coral densities in the literature. Actual coral skeletal density could vary widely depending on species, growth rate, environmental variations, and other factors. Skeletal density of corals (Hughes, 1987) should theoretically be constrained to an upper limit of 2.94 g cm^{-3}, which was the density of solid aragonite $CaCO_3$ (Hughes, 1987). Additionally, coral morphology differed greatly between lobate, branching, and encrusting corals, making it difficult to estimate for the overall volume of the coral. Treating all the corals as equal density hemispheres of solid aragonite yields a total weight (highest estimate) of 1,726 kg. Taking the buoyant force of water into account, the summation of weight that the structure feels underwater was 1,139 kg. The corals were placed roughly equidistant from each other to prevent interspecific competition between colonies. Assuming an equal load of the platform, the average highest estimate for static load on the platform was 47.36 kg m^{-2}. This was well within a safe loading weight for the structure.

CONCLUSION AND FUTURE WORK

The first step for rehabilitation of damaged coral colonies on the island of O'ahu in Hawaii was presented in this work. A durable and feasible coral nursery was designed, built, assembled, and deployed for efficient restoration of corals. The design of the coral nursery was demonstrated to be structurally safe and environmentally friendly. The unique design of the nursery featured several branches connected by custom-made joints to break external forces similar to a truss, and thereby can tolerate very strong underwater wave currents. This design can be used in other areas worldwide where large colonies of corals need to be restored and rehabilitated. The FRP material, used in this work, is an appropriate choice for other nurseries as well because of its high corrosion resistance and stiffness. In future work, this method will be further adapted to be able to be assembled underwater and on uneven floors. The ongoing work will involve monitoring coral colonies that have been attached to it for rehabilitation to evaluate the effectiveness of the methods.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this manuscript will be made available by the authors, without undue reservation, to any qualified researcher.

ETHICS STATEMENT

No humans were used in this work. Detachment, transportation, and installation of corals were done by experts and with care.

AUTHOR CONTRIBUTIONS

BK designed, analyzed, and fabricated the coral nursery. MP commented on the design and development and deployed the structure at its cite.

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