Effect of Keying Flaps on a Multiline Ring Anchor in Soft Clay

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ABSTRACT

The multiline ring anchor (MRA) was devised as a cost-effective means for securing floating offshore wind turbines (FOWTs) to the seabed. FOWTs occurring in arrays create the possibility for attaching mooring lines from multiple units to a single anchor. Additionally, the deep embedment of the MRA into relatively strong soil permits high load capacity to be achievable with a small and lighter anchor, thereby reducing anchor material, transport, and installation costs. However, since the MRA is shorter than a conventional caisson, features such as wing plates and keying flaps are needed to achieve parity in load capacity with a caisson having a comparable diameter. Preliminary studies show that attaching wing plates to MRA in soft clay is highly effective in enhancing its horizontal load capacity, but only marginally effective in improving vertical load capacity. This motivated the current study investigating the use of keying flaps to further enhance vertical load capacity. Two-dimensional finite element analyses were conducted to understand how keying flaps impact the failure mechanism of the stiffeners and provide reliable evaluations of the uplift resistance of the MRA. The results show that the thickness of the stiffener, flap length, and flap angle can affect the failure mechanism and bearing factors. For the optimal design of the stiffener, a comparative study was carried out to compare the effects of keying flaps and thickness of the stiffener. The studies show that introducing keying flaps can have comparable load capacity with thicker stiffeners and that it can be an economical solution for achieving high vertical load capacity while containing material and fabrication costs.

INTRODUCTION

In the United States, about 80 % of the electricity demand is consumed in coastal areas (Musial et al. 2016). Compared to land-based renewable energy resources, the offshore wind is stronger, more consistent, and has fewer aesthetic issues, in addition to its proximity to population centers. Since a major portion of potential offshore wind resources exists at water depths of greater than 60m, this leads to a need for cost-effective floating offshore wind turbine (FOWT) systems (Musial et al. 2018). Despite the improvement of the floating technologies, the capital cost of the support system still remains a primary obstacle. To overcome this deficit, a cost-effective, novel, networked multiline ring anchor (MRA) system has been developed. The MRA includes an embedded ring anchor in which up to six mooring lines can be attached (Figure. 1). Optional wing plates and keying flaps can be attached to improve the load capacity (Figure. 2). Since the MRA can significantly reduce the required number of anchor footprints, the multiline potential can allow significant reductions in site investigation, material, and fabrication costs (Lee et al. 2020). Additionally, since the currently envisioned sites for FOWTs typically include heterogeneous soil profiles, many existing anchors were precluded from utilizing them into the seabed (Aubeny 2017; Diaz et al. 2016). In contrast, the MRA can be installed in any soil condition due to its specific features (Lee and Aubeny 2020). Although installable in any soil type, the current study focuses on performance in soft clay. Additionally, for versatile use in all types of mooring systems such as catenary, semi-taut, or taut, there is a need to develop further for the MRA to achieve parity with a suction caisson of comparable diameter under vertical loading. Introducing keying flaps can be one solution to improve this parity in performance. Thus, this study conducted two-dimensional finite element analyses to understand how keying flaps affect the failure mechanism of a stiffener and to provide reliable evaluations of the increase in uplift resistance attributable to keying flaps.

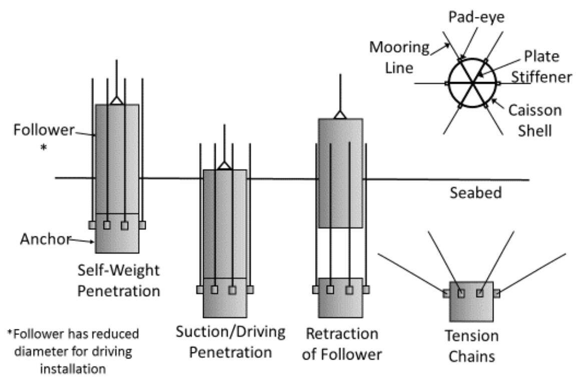


Figure 1. The installation procedure of the MRA. (Lee and Aubeny 2020)

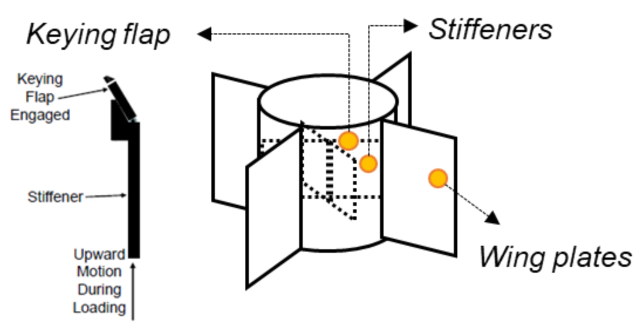


Figure 2. Strategies for enhancing load capacity

KEY ISSUES FOR STIFFENER ON MRA

Comparison to a suction caisson: The mechanisms of the uplift resistance of the MRA can be best illustrated through the comparison to a conventional suction caisson (SC). Although two anchors are similar, differences in the uplift resistance between two anchors can be significant. As an example, Figure 3 shows the reverse end bearing is a component of the uplift resistance of the SC, which does not develop for the MRA. Due to a relatively shorter length and deeply embedded condition, the MRA also cannot have additional side resistance extending to the surface, which is shown in the case of the SC. Side resistance along the interior cylindrical surface of the MRA can partially offset these effects; however, the axial capacity of the MRA must still be enhanced through other means to achieve parity with a SC of similar diameter. Preliminary findings from rigorous analytical calculations on the effects of wing plates and stiffeners currently in progress show that the axial capacity can be improved by increasing diameter, installing wing plates, or introducing keying flaps. Although various alternatives to improve the uplift resistance, this study focuses on understanding the effects of keying flap.

Optimal design for the stiffener: O'Neill et al. (2003) and Murff et al. (2005) studied the performance of thin plate anchors under vertical and horizontal loading. To this end, the authors presented a two-dimensional finite element (2-D FE) study in which the effects of thickness aspect ratio (length to thickness ratio, L_{pl}/t_{pl}) is evaluated. According to their studies, increases in thickness of the plate are expected to increase bearing factor and axial capacity. Likewise, the uplift resistance of the stiffener can likely be improved by increasing the thickness of the stiffeners t_{stf}. On the other hand, thicker stiffeners mean that the capital costs like material and fabrication costs, which are dependent on the total dry weight of the anchor, will increase with increasing t_{stf}. Thus, this study conducted 2-D FE analyses to understand the effect of the keying flaps on uplift resistance and demonstrate it by comparison to the effect of t_{stf} on uplift resistance. The optimal design of the stiffener can be suggested through this study.

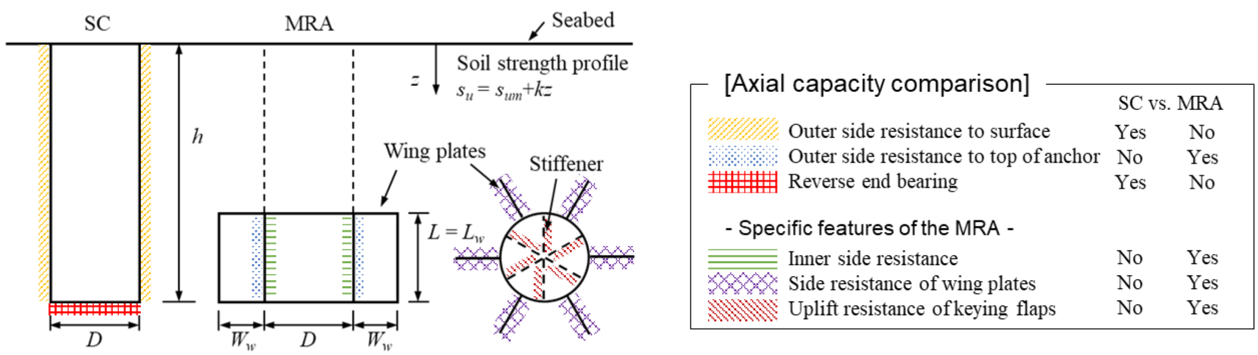


Figure 3. Axial capacity comparison between the suction caisson and MRA in clay

FINITE ELEMENT STUDIES

The soil model considered linearly elastic-perfectly behavior beneath a Tresca yield surface and associated flow rule. A Poisson's ratio is taken as μ = 0.49 to approximate the undrained loading condition. A uniform undrained shear strength profile is assumed, with s_u set to 1 kPa since only relative changes in resistance are of interest. Noting that the elastic response does not affect the ultimate load capacity, as shown by Chen (1975) and Aubeny (2017), Young's modulus assumed as a ratio E/s_u=800. All FE simulations considered full bonding between soil and anchor. The soil also can be considered weightless due to the deep embedment depth of the anchor without gapping effects.

The dimensions of the stiffener are shown in Figure 4, a 1-m length of the stiffener L_{stf} with keying flaps lengths L_{fl} varying 0.1m to 0.3m. The angle between the flap and axial direction of the stiffener θ_{fl} varies from 0° to 90°. To understand the effects of the keying flaps on the axial capacity, L_{fl} and θ_{fl} are considered in the parametric study. A typical thickness of the stiffener t_{stf} and flap t_{fl} assumed as the same thickness t_{stf}=t_{fl}=0.05m, while a ratio of L_{stf}/t_{stf} can vary from 20 to 7 to estimate the effects of the thickness of the stiffener. Element dimensions vary from 1/250 of L_{stf} near the boundary to 1/20 of L_{stf} in regions far from the stiffener (Figure 5).

Since the stiffener without keying flap has the same geometric configuration as the thin plate anchor, upper bound estimates for a simple plate anchor provide acceptable reference solutions to validate the FE model. Two bearing factors based on loading directions were given through the FE simulations to compare with that of a thin plate anchor. In the horizontal loading case, the FE computed lateral bearing factor is N_p=11.64, about 0.2% less than the exact solution for a plate with the same aspect ratio of length to thickness L_{pl}/t_{pl}=20, calculated by Aubeny (2017). However, the validation for the vertical loading case involves ambiguity, since the existing upper bound solution consistently exceeds the FE calculations (Aubeny 2017; Murff et al. 2005; O'Neill et al. 2003). In this case, recourse is made to comparing the the FE computed vertical bearing factor N_a=3.1 to a semi-empirical solution suggested by O'Neill et al. (2003). This comparison shows the current FE prediction to exceed the O'Neill et al. value by 12.73%. FE calculations under various aspect ratios also show a similar level of agreement with upper bound solutions.

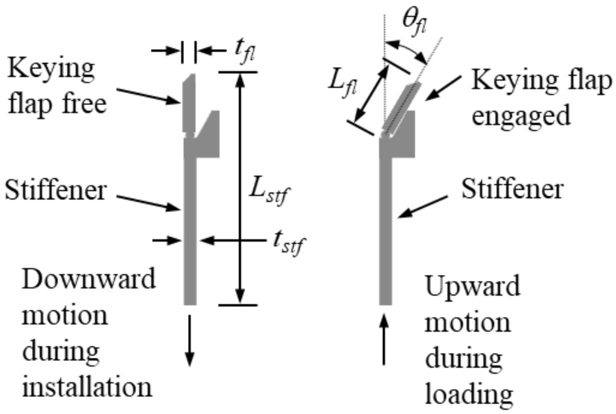


Figure 4. Dimensions of the stiffener and keying flap

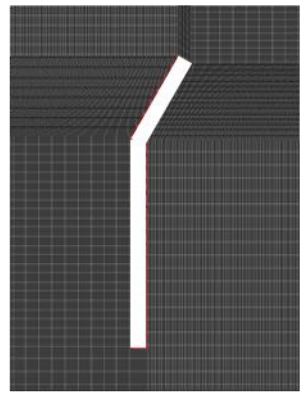


Figure 5. 2-D FE mesh

PARAMETRIC STUDY

Description: In order to understand how the stiffener with or without keying flap alter the collapse mechanism and axial bearing factor, the current study estimated the following parameters (Figure 4).

- The thickness of the stiffener, t_{stf}
- Flap length, L_{fl}
- The angle between the flap and axial direction of the stiffener, θ_{fl}

The axial bearing factor of the stiffener: An axial bearing factor for the stiffener can be defined as a function of the length of the flap L_{fl} and flap angles θ_{fl}. Nevertheless, this study adopts a non-dimensional classical definition of a bearing factor because of the following reasons. Firstly, the conventional type of formulation can have the advantage of providing a clear picture of how the imposed keying flaps improve the uplift resistance. Secondly, the classical type of definition has the advantage of direct comparison to existing solutions for the thin plate, which has the same thickness effects as the stiffener. Thus, a non-dimensional equation for the axial bearing factor N_a is as follows:

$$N_a = \frac{V}{s_u L_{stf}} \tag{1}$$

where V is the ultimate vertical resistance of the stiffener with or without keying flap, s_u is the undrained shear strength of soil, and L_{stf} is the length of the stiffener.

Effect of thickness of the stiffener: In the case of a typical stiffener, likewise a thin plate, the uplift resistance comprises frictional resistance along the sides and end bearings at the top and tip. The aspect ratios L_{stf}/t_{stf} vary from 20 to 7 to understand how the thickness t_{stf} impact on the stiffeners, which have the same length L_{stf}. Since the sensitivity of t_{stf} to uplift resistance can be represented as an axial bearing factor N_a, as shown in Figure 6, the FE results show that N_a increases with decreasing L_{stf}/t_{stf}. This is a direct consequence of the increase in thickness t_{stf}. This means vertical load capacity increases as the thickness of the stiffener increases.

Effect of flap length: In comparing the cases of L_{fl}/L_{stf}=0.1 and L_{fl}/L_{stf}=0.2, the increase of the flap length L_{fl} increases the uplift resistance V (Figure 6). On the other hand, the uplift resistance V for the case of L_{fl}/L_{stf}=0.3 has similar values as that of the case of L_{fl}/L_{stf}=0.2, even though it has longer L_{fl}. A possible explanation for this trend might be related to the horizontal force imbalance generated by the keying flaps, illustrated in Figure 7. This issue is discussed further in this paper in the discussion of future research needs. Nevertheless, FE results confirm that L_{fl} is one of the key parameters to evaluate the vertical load capacity of the stiffener.

Effect of flap angle: As the flap angle θ_{fl} increases, shown in Figure 6, the axial bearing factor N_a also increases by up to 50%. A more pronounced increasing trend of N_a occurs for longer flap lengths L_{fl}, such as L_{fl}/L_{stf}=0.2 and L_{fl}/L_{stf} =0.3. Increasing the flap angle leads to progressively greater bearing resistance. While the stiffener without keying flaps typically is dependent on side resistance, particularly the adhesion between soil and pile, the keying flaps alter the collapse mechanism of the stiffener in a manner that is largely independent on adhesion factor α. Bearing resistance, as opposed to friction, is generally less sensitive to soil disturbance during plate installation.

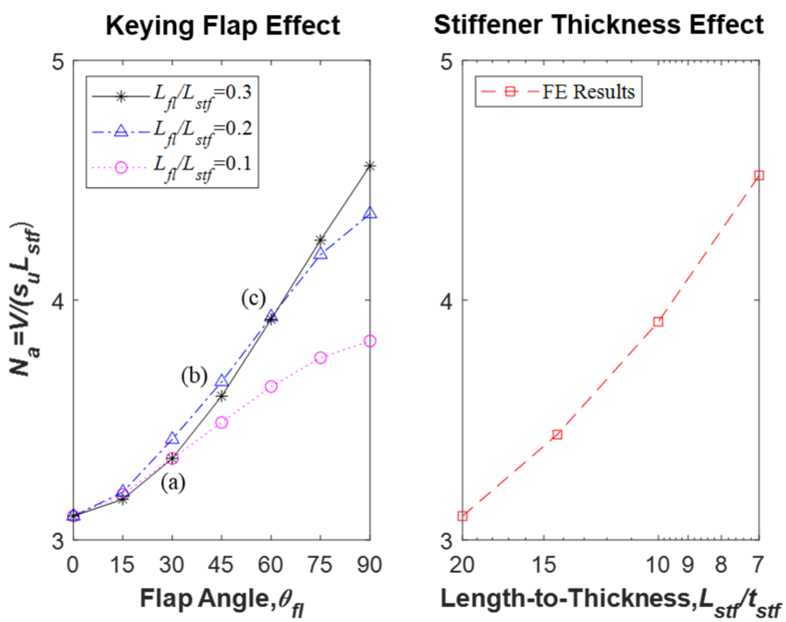
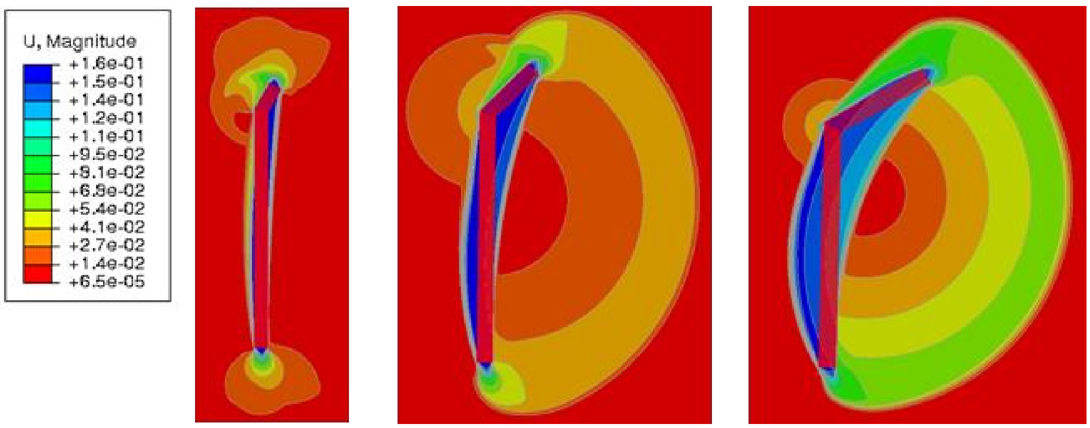


Figure 6. Effect of L_{fl}, θ_{fl} and t_{stf} on the stiffener

OPTIMAL DESIGN OF KEYNG FLAPS

Since the capital costs of the anchor have an impact on the decision to initiate a project, the optimal anchor design can be critical (Bhattacharya 2014). Preliminary findings from the study on cost analysis currently in progress show that material and fabrication costs account for at least approximately 40 percent out of total capital cost. Thus, indicative cost analyses for each case can be instructive in deciding the best approach for enhancing vertical capacity, a thicker stiffener or a keying flap. The cost quantification assumed that material and fabrication costs are dependent on unit steel cost of bulk and unit fabrication cost of bulk, respectively (O'Loughlin et al. 2015; SteelBenchmarker 2020). These costs are not necessarily accurate in absolute terms for a particular project, but they can provide useful comparisons for evaluating the merits of each alternative. Table 2 indicates that introducing keying flaps can be a more economical solution with comparable load capacity compared to the thicker stiffener. While introducing keying flaps or thickening the stiffener can improve the axial bearing factors up to a certain level (e.g., N_a=3.91), the material and fabrication cost for the thicker stiffener almost doubles compared to keying flap stiffener. Thus, a stiffener with a keying flap should be considered a cost-effective means to improve uplift resistance.



(a) L_{fl}/L_{stf}=0.1, θ_{fl}=30° (b) L_{fl}/L_{stf}=0.2, θ_{fl}=45° (c) L_{fl}/L_{stf}=0.3, θ_{fl}=60°

Figure 7. 2-D FE failure mechanism

Table 1. Computed FE values considering the effects of keying flap and thickness of the stiffener

Axial bearing factor, $N_a=V/(s_u L_{stf})$					
Keying flap effect				Stiffener thickness effect	
Flap angle	L_{fl}/L_{stf}=0.1	L_{fl}/L_{stf}=0.2	L_{fl}/L_{stf}=0.3	L_{stf}/t_{stf}	FE
0°		**3.10**[1)]		100	2.33
15°	3.19	3.20	3.17	33.3	2.75
30°	3.34	3.42	3.34	**20**	**3.10**[2)]
45°	3.49	3.66	3.60	14.3	3.44
60°	3.64	3.93	3.92	10	3.91
75°	3.76	4.19	4.25	7	4.52
90°	3.83	4.36	4.56	6.7	4.64

[1)] The same as the condition of L_{stf}/t_{stf}=20
[2)] The same as the condition of θ_{fl}=0°

Figure 7 (b) and (c) show asymmetric collapse mechanisms for stiffeners with keying flaps, which induce unbalanced horizontal forces with a concomitant tendency to rotate the anchor. In actuality, these forces are transmitted to the anchor which, if the anchor is sufficiently large, can be resisted with minimal rotation. However, the possibility exists that the horizontal forces may be large enough to adversely affect anchor performance. Y-shaped flaps may rather need to be considered to estimate the keying flap effects. These have been identified as future research needs for the optimal design of the keying flaps.

Table 2. Indicative cost analysis for the stiffeners on an MRA

Conditions	Typical stiffeners without keying flap	Stiffeners with keying flaps	Thicker stiffeners
Dimensions[1)]	L_{stf}:1m, t_{stf}: 0.05m	L_{stf}:1m, t_{stf}: 0.05m L_{fl}: 0.2m θ_{fl}: 60°	L_{stf}:1m, t_{stf}: 0.1m
Axial bearing factor[2)], N_a	3.10 (100%)	3.93 (127%)	3.91 (126%)
Total dry weight[3)]	3.53 tons (100%)	3.89 tons[4)] (110%)	7.07 tons (200%)
Material cost (Unit price: $620/ton)	$2,190 (100%)	$2,409 (110%)	$4,380 (200%)
Fabrication cost (Unit price: $2,500/ton)	$8,831 (100%)	$9,714 (110%)	$17,663 (200%)

[1)] Three stiffeners are located inside of the anchor having a 3-m diameter.
[2)] N_a is based on computed FE values
[3)] Dry unit weight of the steel assumed as 7.85 tons/m^3
[4)] Marginal dry weights were considered for the hinge of the flaps and assumed as 10% additional weight.
% Indicates value relative to typical stiffeners for each case

CONCLUDING REMARKS

This study presents the potential benefit of keying flaps on the MRA to improve vertical load capacity. Two-dimensional FE analyses were carried out to understand how keying flaps can alter the collapse mechanism and to estimate the effects of the keying flap on the stiffener. Key findings are as follows:

- Uplift resistance V increases with increasing the thickness of the stiffener t_{stf} (Fig. 6).
- Uplift resistance V increases as the flap angle θ_{fl} increases (Fig. 6). The trend of increasing load capacity V also occurs with increasing flap length L_{fl} but has shown slight increases of V under L_{fl}/L_{stf}=0.3. This has been identified as a future research work to provide a reliable evaluation of uplift resistance.
- Introducing keying flap on the stiffener can be a more cost-effective means to improve the vertical load capacity.

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