Mechanical Engineering Systems
BSE At Havelock

(MAE 413-605 Design of Mechanical Systems)

Boat Winch Project 1

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I have neither given nor received any unauthorized assistance on this report.

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Abstract

In this project, students were asked to design two different anchor systems, one wedge anchor and one adhesive anchor, to properly restrain a boat winch. Teams calculated and selected the appropriate wedge anchor and adhesive anchor for the loads applied to the winch preventing failure with a factor of safety of 2. The previous winch anchors were subjected to excessive forces and failed, resulting in a catastrophic mishap. To prevent another failure, the team utilized design tools to select the best anchors possible for this application.

The applicable failure modes of each anchor type were determined and evaluated to include failure in tension, concrete failure, pullout, and shear. The wedge anchor selected was a 9 in. long Grade 105 galvanized steel stud anchor of 1 in. diameter, with 8 threads per inch. For the adhesive anchor, a Grade 105, 12 in. long, 1in.-8 UNC 2A threaded rod with Hilti HIT-RE 500 V3 adhesive was selected. These anchors are deemed to withstand the maximum forces applied to the winch at any given time.

Introduction

Objective

The objective of this project was to find two different types of bolts, an adhesive anchor and mechanical wedge, that would prevent the boat winch from pulling out of the ground and injuring the operator(s).

Background

A boat winch used to pull and lower boats in and out of the water was involved in an accident where the launch cable was left connected to the haul cable. This caused both cables on the winch to become rigid and pull in the same direction rather than one spooling in while the other spools out [1]. This mishap of the cables becoming rigid caused the winch to pull out of the cement and break into a wall causing an operator fatality.

This accident raised multiple questions. Why did the winch pull out of the cement? If the bolts were able to withstand the forces of the cables being rigid, would this accident still have happened?

Figure 1 below illustrates the winch after it had pulled out of the cement. The figure also shows the placement of the cables as well as the anchor bolt locations.

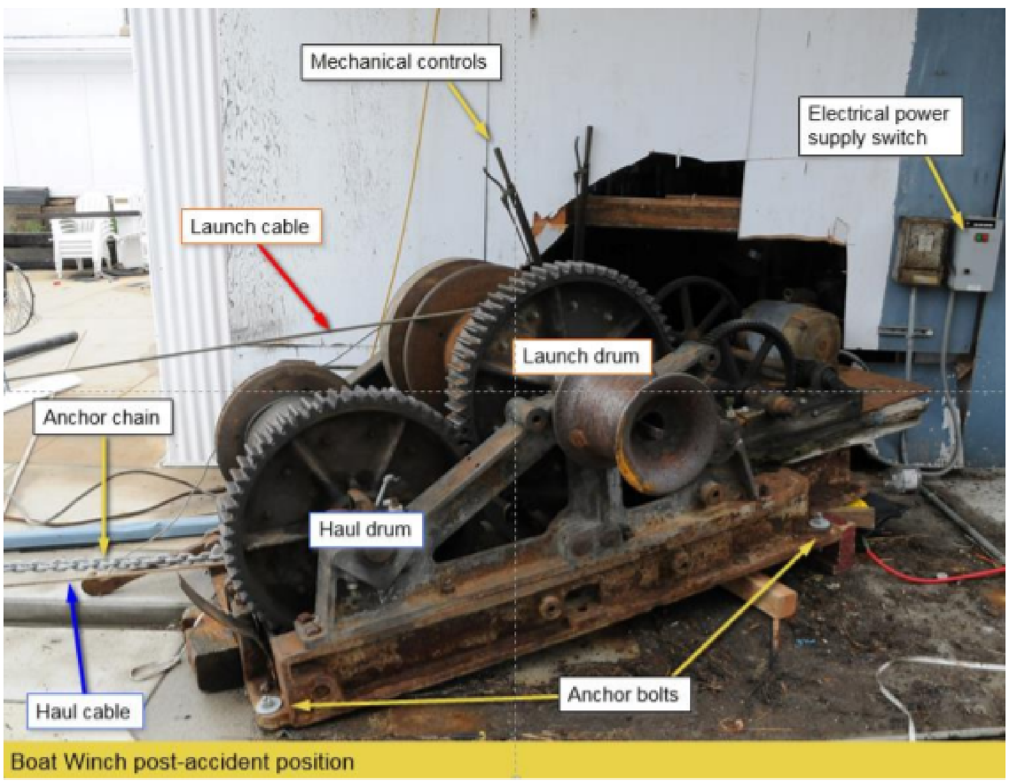

Figure 1: Boat Winch Post Accident

The boat winch is designed with four mounting holes for the winch frame to be anchored to the cement, one in each corner. The haul drum located at the front of the frame (see

Figure 1), is used to pull the boat out of the water. The launch drum, located directly behind the haul drum, is used to lower the boat into the water. When the cables became rigid, the front bolts were put in compression while the rear bolts were put in tension. All bolts experienced a shear force as the weight of the boat tried to pull the winch towards the water.

Design Analysis

The free body diagram shown below in Figure 2 was used in the analysis to determine the active forces and the reactions of the bolts. An x-y coordinate system was used to determine the sign of the forces with the positive y-axis pointing downward and the positive x-axis pointing to the left. The counterclockwise direction was taken for positive moments, and clockwise was used for negative moments. It was assumed that there was no friction acting between the winch and concrete, F_{sc} and F_c are both 7° below horizontal, F_{sc} and F_c are acting in the same direction, W was acting 45¼ inches (in.) off of R_f, and F_c was acting 44 in. off of R_f.

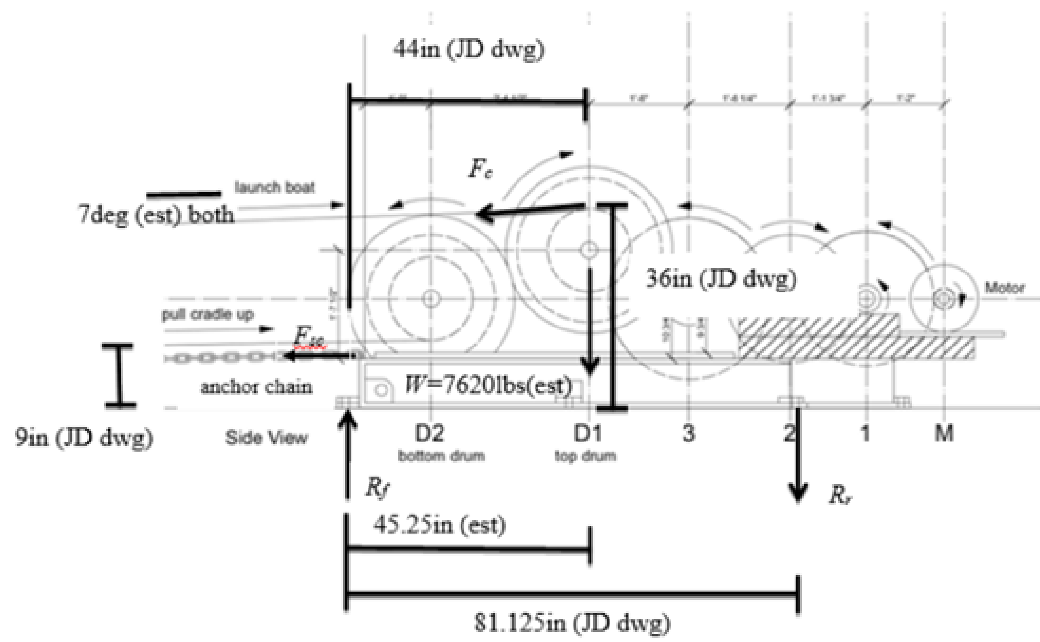

Figure 2: Free Body Diagram

The sum of the forces in the x and y direction were taken, and the sum of the moments at R_f were taken to determine the reaction forces of the bolts.

$$\Sigma F_x \ : \ Fsc * cos7Fc * cos7 - Rfx - Rrx \ = 0 \tag{1}$$

$$\Sigma F_y \ : \ Fsc * sin7Fc * sin7 + W + Rry - Rfy = 0 \tag{2}$$

$$\Sigma MR_f \ :- (W * 45.25) - (Fcy * 44) + (Fcx * 36) + (Fscx * 9) - (Rry * 81.125) \ = 0 \tag{3}$$

Using the calculations shown above, the reaction forces at the bolts were solved. Since there are two bolts on the front and rear, the y reaction was divided by two and the x reaction was divided by four.

$$Rfy = \frac{17933.81\ lbf}{2} = 8966.905\ lbf \tag{4}$$

$$Rry = \frac{5439.01}{2} = 2719.505\ lbf \tag{5}$$

$$Rfx = Rfx = \frac{19850.9 lbf}{4} = 4962.725\ lbf \tag{6}$$

With the reactions solved, the grip length was calculated by:

$$L_t = L_e + T_s + T_n + T_w \tag{7}$$

Where:

L_t = Grip length
L_e = Embedment length
T_s = Steel Thickness
T_n = Nut Thickness
T_w = Washer Thickness

Table 1: Bolt Length

Total Length				
L_t (in)	L_e (in)	T_s (in)	T_n (in)	T_w (in)
6.875	4	2	0.75	0.125

The minimum bolt length required is 6⅞ in.

The bolt diameter was calculated by:

$$D = \sqrt{\frac{2E}{\pi S_y}} = \sqrt{\frac{2(17933.91)}{\pi(36300)}} = 0.8\ in. \tag{8}$$

Where:

D = Bolt diameter
F = Maximum bolt reaction force
S_y = Yield strength of bolt

Based on this calculation, a minimum bolt size of one inch was selected for both the wedge and adhesive anchors.

Failure Modes of Wedge Anchor Bolt

Figure 3 describes the different failure modes of the anchor bolt.

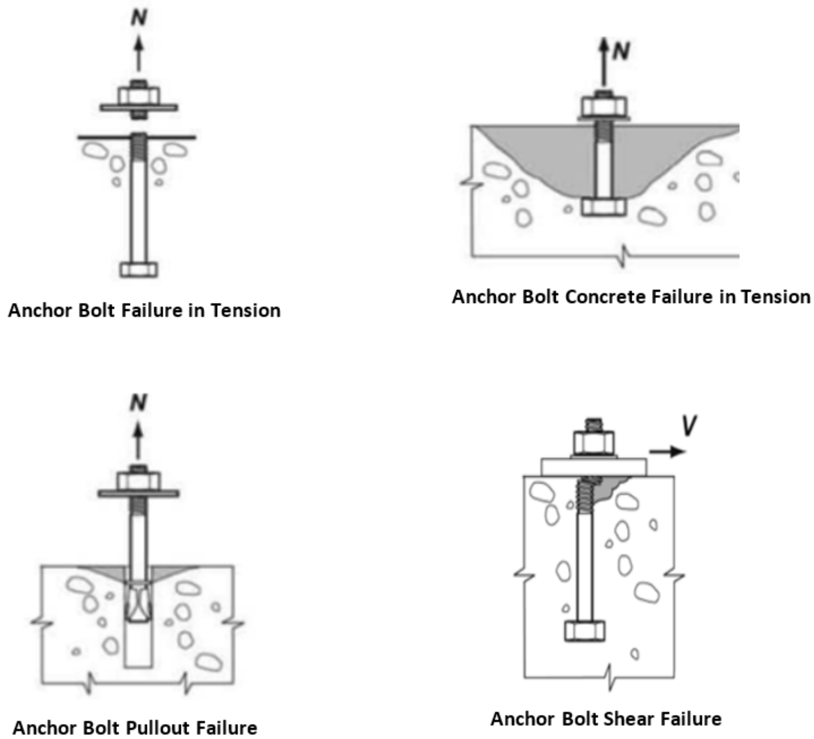

Figure 3: Anchor Bolt Failure Modes [5]

Anchor Bolt Failure in Tension

The anchor bolt will fail in tension if the tensile stress on the bolt is greater than the yield strength [1]. In all failure mode calculations, a force of 17,934 pounds (lbs) was used.

$$N_y > S_y \tag{9}$$

$$N_y = \frac{F_{fy}}{A_{se}} \tag{10}$$

$$A_{se} = \frac{\Pi}{4}\left(d_a - \frac{0.9743}{n_t}\right)^2 \tag{11}$$

Where:

- N_y is the tensile stress
- S_y is the yield strength
- F_{fy} is the force in the y direction
- A_{se} is the effective cross sectional area

N_y was calculated to be 29,621 pounds per square inch (psi), which is less than the 63,570 psi for which the bolt is rated. Therefore, the bolt will not yield.

Anchor Bolt Concrete Failure in Tension

The concrete will crack at a 45 degree angle in a cone shape section. To calculate the failure force, the force that is required to separate the concrete over the total surface area of a Right Circular Cone is used [6].

$$F_{ry} > F_c \tag{12}$$

$$F_c = S_c * \Pi * 1.4142 * H^2 \tag{13}$$

Where:

- F_{fy} is the force applied to the bolt
- F_c is the failure force required to pull out the concrete
- S_c is the concrete strength
- H is the embedment length

The concrete is assumed to be 4,000 psi compressive strength which means it has 400 psi in tensile strength [7].

The embedment length did not need to be solved since concrete anchors are installed at a minimum of 4 in. By inputting these parameters in Equation 13, the force required to rip out the concrete is 28,419 lbf. Since the applied force is around 18,000 lbf, the concrete will not rip out.

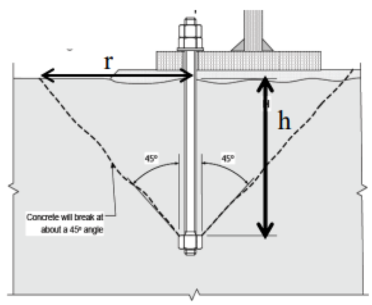

Figure 4: Anchor Bolt Concrete Failure [6]

Anchor Bolt Pullout Failure

The anchor bolt will fail if it is pulled out of the concrete. As per the ACI source, the pullout strength should not exceed [6]:

$$F_p = 1.4 * 17933.81\ lbf \tag{14}$$

It will take 25,106 lbf to pull the anchor out of the concrete. This is more than the 17,934 lbf that was calculated. No cracking of the concrete was assumed in the analysis.

Anchor Bolt Shear Failure

The anchor bolt will fail if the shear stress is greater than the yield strength. Since there are 4 anchors, the shear is distributed equally on all anchors. Since there is a safety factor of 2, the divided shear is then multiplied by 2.

$$\tau_s > 0.6 * S_y \tag{15}$$

$$\tau_s = 2 * (\frac{R_{fx}}{4}) * A_{se} \tag{16}$$

Where:

τ_s is the shear stress on the bolt
A_{se} is the effective area
R_{fx} is the shear force

The shear stress was calculated to be 16,393 psi, this is less than the yield strength which was 45,407 psi, so the bolt will not yield.

Anchor Bolt Details

A Grade 105 steel stud anchor of galvanized steel of 1 in. diameter, 9 in. length, with 8 threads per inch should be chosen. A hole with a diameter of ⅞ in. should be drilled 5 in. in 4,000 psi concrete and 4 in. of the anchor should be embedded.

Failure Modes of Adhesive Anchor Bolt

Steel Strength in Tension

The adhesive anchor bolt experiences the same failure in tension as the wedge anchor bolt. The one inch diameter threaded rod selected has a tensile strength of 56,785 lbf and needs to be able to withstand 17,934 lbf [8].

Pullout Strength in Tension

The adhesive anchor bolt fails when the bolt/adhesive is pulled out of the concrete. This usually occurs due to poor adhesion between the adhesive used and the existing concrete. This mode of failure can also be caused by poor adhesion between the adhesive and the bolt, although this failure mode is less common. The adhesive must be able to withstand 17,933 lbf. The adhesive selected is rated to withstand 26,640 lbf of pullout [9].

Steel Strength in Shear

The adhesive anchor bolt/adhesive will fail in shear the same as the wedge anchor bolt. The system must be able to withstand up to 80,000 lbs of shear force, or 20,000 lbf per bolt. The threaded rod selected is rated at 29,530 lbf of shear, and the adhesive selected is rated at 57,375 lbf of shear [8][9].

Adhesive Anchor Details

For the adhesive anchor, the Hilti HAS-B-105 HDG, 12 in. Grade 105 galvanized threaded rod was selected. The thread specification for this rod is 1in.-8 UNC 2A. A 1¼ in. hole will be drilled into the concrete, and the rod will be embedded 8¾ in. The adhesive chosen is Hilti HIT-RE 500 V3 with a cure time of 30 minutes to attain full strength.

Conclusion

As a result of the findings, the wedge anchor, Grade 105 Galvanized Steel Stud Anchor, 9 in. long of 1 in. diameter, with 8 UNC per ASTM F1554 is recommended. A hole with a diameter of ⅞ in. should be drilled 5 in. into 4,000 psi concrete and 4 in. minimum of the anchor should be embedded. For the Adhesive anchor, a Grade 105 threaded rod, 12 in. long, 1in.-8 UNC 2A threaded rod with Hilti HIT-RE 500 V3 adhesive is recommended. For optimal results, embed the threaded rod into a predrilled hole with a diameter of 1¾ in. at a depth of 8¾ in.

If a rigid system occurs again, the bolts recommended will withstand the forces subjected on the system, and will prevent the winch from pulling out of the concrete and ultimately save a life.

References

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Appendix A: Data Collection Sheet With Calculations and Notes

Material Properties		
Material	Yield Strength (psi)	Tensile Strengh (psi)
Grade 105 Galvanized Steel	105000	125000
Shear Per bolt (lbs)	Tension Front Per Bolt(lbs)	Tension back Per Bolt (lbs)
4962.725	8966.905	2719.505

Stresses on Bolt			
Diameter (in)	Tensile Area (in^2)	Ny (psi)	Ts (psi)
0.250	0.013	1389767.561	769165.528
0.375	0.050	356313.786	197201.524
0.500	0.112	159709.647	88391.152
0.625	0.199	90219.427	49931.856
0.750	0.310	57888.162	32038.148
0.875	0.445	40268.724	22286.687
1.000	0.605	29621.270	16393.864
1.250	0.999	17948.208	9933.419

Bolt Analysis: 1 in diameter 8 Threads per inch

Yeild Failure	
Tensile Stress in bolt > Yield Strength	
Bolt Stress (psi)	Bolt Yield Stregth (psi)
29621.270	63570.87431
Will Not Fail in Yeild	

Shear Stress in bolt > Yield Strength	
Bolt Stress (psi)	Bolt Yield (psI)
16393.864	45407.76736
Will Not Shear	

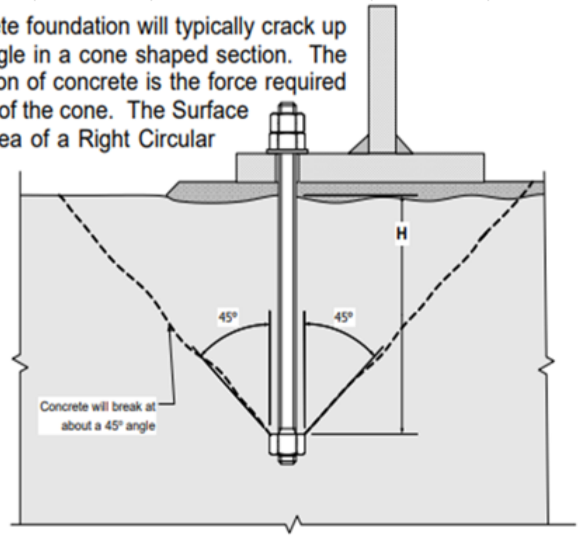
As a comparison, an anchor bolt set in a concrete foundation will typically crack up and out from the bottom of the bolt at a 45° angle in a cone shaped section. The force required to pull up this cone shaped section of concrete is the force required to separate concrete over the total surface area of the cone. The Surface Area of a Cone (SACone) = Lateral Surface Area of a Right Circular Cone with 45° Sides:

SACone = π x 1.4142 x H^2

The force required to pull the concrete apart is the Shear Strength of concrete (800 psi) times the Surface Area of the Cone.

Force lbs = 800 psi x SACone in^2

Force lbs = 800 x π x 1.4142 x H^2



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Concrete Failure			
Embodiment Lengh H (in)	SACone (in^2)	Concrete Strength (psi)	Failure Force Fc (lbs)
4	71.049408	400	28419.7632

TABLE D.4.1.1 — REQUIRED STRENGTH OF ANCHORS, EXCEPT AS NOTED IN D.3.3

Failure mode	Single anchor	Anchor group*	
		Individual anchor in a group	Anchors as a group
Steel strength in tension (D.5.1)	$\phi N_{sa} \geq N_{ua}$	$\phi N_{sa} \geq N_{ua,i}$	
Concrete breakout strength in tension (D.5.2)	$\phi N_{cb} \geq N_{ua}$		$\phi N_{cbg} \geq N_{ua,g}$
Pullout strength in tension (D.5.3)	$\phi N_{pn} \geq N_{ua}$	$\phi N_{pn} \geq N_{ua,i}$	
Concrete side-face blowout strength in tension (D.5.4)	$\phi N_{sb} \geq N_{ua}$		$\phi N_{sbg} \geq N_{ua,g}$
Bond strength of adhesive anchor in tension (D.5.5)	$\phi N_{a} \geq N_{ua}$		$\phi N_{ag} \geq N_{ua,g}$
Steel strength in shear (D.6.1)	$\phi V_{sa} \geq V_{ua}$	$\phi V_{sa} \geq V_{ua,i}$	
Concrete breakout strength in shear (D.6.2)	$\phi V_{cb} \geq V_{ua}$		$\phi V_{cbg} \geq V_{ua,g}$
Concrete pryout strength in shear (D.6.3)	$\phi V_{cp} \geq V_{ua}$		$\phi V_{cpg} \geq V_{ua,g}$

*Required strengths for steel and pullout failure modes shall be calculated for the most highly stressed anchor in the group.

Appendix B: Hand Calculations

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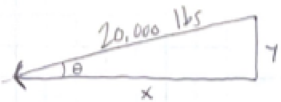
Assumptions: F_{sc} at 7°

F_{sc} and F_c = 20,000 lbs and pull same direction

F_c is acting 44 in aft of R_f

W is acting 45.25 in aft of R_f



$\theta = 7°$

$$\boxed{\begin{aligned} F_c(x) &= \frac{\cos(7°)}{20{,}000} = 19{,}850.9 \text{ lbs} \\ F_c(y) &= \frac{\sin(7°)}{20{,}000} = 2437.4 \text{ lbs} \end{aligned}}$$

$F_c = F_{sc}$

$$\Sigma F_x = 0: \quad F_{c_x} + F_{sc_x} - R_{f_x} - R_{r_x} = 0$$

$$\Sigma F_y = 0: \quad F_{c_y} + F_{sc_y} + W + R_{r_y} - R_{f_y} = 0 \rightarrow \boxed{R_{f_y} = 17933.81 \text{ lbs}}$$

$$\Sigma M_{@R_f} = 0: \; -W(45.25\text{in}) - F_{c_y}(44\text{in}) + F_{c_x}(36\text{in}) + F_{sc_x}(9\text{in}) - R_{r_y}(81.125\text{in})$$

$$\rightarrow \boxed{R_{r_y} = 5439.01 \text{ lbs}}$$

Appendix C: Bolt Drawings