Increasing Crane Girder Capacity Using the Strut-and-Tie Method

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Introduction

Over recent decades, vessel size and the weight of the heaviest marine containers have increased, resulting in increased crane reactions to the wharves. The larger ships have greater drafts, which require deeper berths. So many of the Port of Oakland's existing wharves cannot carry the heavier crane loads and continue to meet the original design criteria.

This paper presents the strut-and-tie method of analysis and new criteria for determining the acceptable crane loads on the existing wharves. For most wharves, the new method of analysis increases the acceptable load.

Background

The current ACI 318-02 code recognizes both the linear elastic methods of analysis and the strut-and-tie method (STM) of analysis. The STM was originally proposed one hundred years ago by Ritter and Mörsch. Provisions for the STM were added to the 2002 edition of the ACI code. For many wharves, the STM predicts significantly higher girder strengths. Consequently, many of the existing wharves can be allowed to carry heavier cranes than allowed by ACI 318-89.

This paper discusses the STM and appropriate load factors, and develops other criteria that are needed to successfully apply the STM.

The *Model Code 1990* (CEB, 1993) presents two classes of limiting states of concrete structures: the serviceability limit states (SLS) and the ultimate limit states (ULS). The SLS are indirectly addressed by the ACI code through limits on strain under factored loads and limits on the amount and distribution of reinforcing steel. The *Model Code* provides methods of calculating crack size. The ULS criteria in the *Model Code* are parallel to the ACI Design Strength criteria.

This paper presents the criteria for evaluation of existing wharves that consider the serviceability and ultimate states and consider the balance between the cost of strengthening and the cost of the performance problems.

Acceptable Capacity and Its Implications

Assume the current ACI factored loads used to determine the required strength are the proper balance between the cost of new construction and the cost of performance problems. Then to maintain the balance, the load factors for evaluating existing structures should be less than those for new construction, since the cost of upgrading is considerably more than the cost of replacement. This concept is not new. For example, refer to ASCE/SEI 31-03, page 5-2. The proposed criteria are recommended for the evaluation of existing wharves and not for the design of new wharves.

Acceptable capacity is defined as the capacity that is a reasonable balance between the cost of strengthening and the cost of performance problems. Using the STM for the ultimate limit states increases the acceptable capacity of most wharves. This will decrease the cost of strengthening. Any method, however, that increases the acceptable load concomitantly increases the risk of repair costs, so the use of the STM will increase the risk of future cost due to performance problems.

The costs due to unexpected or inadequate performance are generally recognized as damage, but the costs of improving the strength of a structure are also damage. The costs of increasing strength are often not thought of as damage, since the costs of increasing strength are paid for initially and the amount is established before funds are committed. But it is just as uneconomic to spend too much on initial extra strength as it is to spend too much on later repairs. See Figure 1.

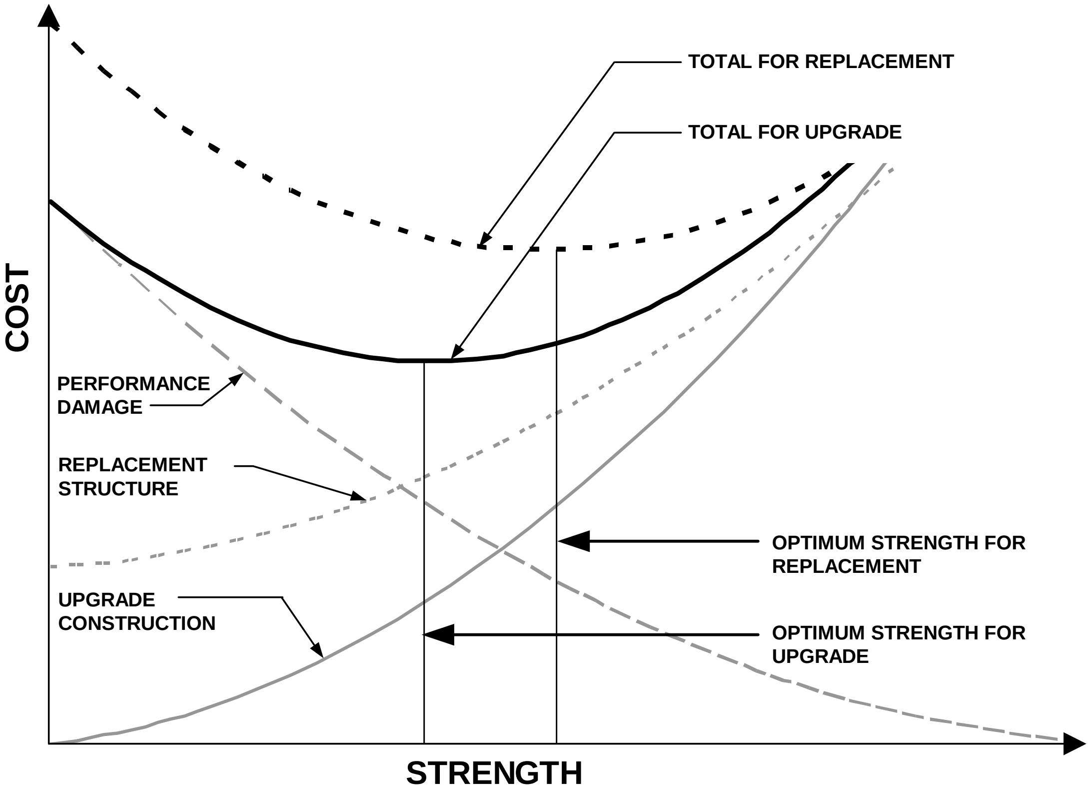


Figure 1: Economically Optimum Acceptable Capacity

The Proposed Criteria

All design is uncertain. The engineer uses judgment in addition to rules. To properly apply the criteria, the engineer needs to understand both the recommended criteria and the fundamentals that are the bases for the criteria. The proposed method requires more judgment than the application of code equations, but produces more cost-effective solutions.

The proposed method will make damage due to performance problems, even though unlikely, more likely. But the possible increase in costs due to performance problems will be offset by the reduction in the cost of strengthening. The proposed method would, in the long run, reduce costs.

The Applied Loads

The basic loads are the dead load of the wharf, the surface load due to operations on wharf, and a combination of the basic crane loads.

The dead load is the best estimate of the dead load of the structure and all fixed equipment. The surface load is the best estimate of the actual operating load on the wharf surface, not including the crane load. Restrictions may be placed on the operations to limit the surface load. For example, for a typical chassis operation, the load of the loaded chassis may be used. The effect of averaging the weight of multiple chassis may be included. Actual operating lanes may be used rather than filling all the space between the crane legs with chassis. In most cases, no surface load is applied to the portion of the surface outboard of the waterside crane rail.

Recommended load factors are shown in Table 1.

The Service Limit States Load, SLS

The SLS load is the best estimate of the actual load applied during normal operations. The combination resulting in the maximum load should be used to check the service limit states.

The crane load should include the normal operating loads. The crane dead load may be calculated or may be determined with more reliability by weighing the crane. The normal crane operating conditions should be used. For example, the crane does not normally operate in a significant wind; the lateral inertia forces are much less than the design loads used for sizing the crane members; impact and other inertia forces are reduced as they are transmitted to the wharf structure.

The crane weighing procedure should be in accordance with and under the review of a qualified engineer. The procedure should produce redundant results so the measurements can be verified.

Table 1: Service and Ultimate Load Combinations

	Load Factors				
Limit State	Service	Ultimate			
Combination name	S1	U1	U2	U3	U4
Basic Load					
Crane Loads:					
Dead Load					
Calculated	1.10	1.15	1.15	1.15	1.15
Weighed	1.00	1.08	1.05	1.05	1.05
Trolley Load	1.00	1.10	1.00	1.00	1.00
Lifting System	1.00	1.10	1.00	1.00	1.00
Lifted Load	1.00	1.30			
Impact—vertical	0.50	0.50			
Lateral Inertia		1.00			
Stall Torque			1.00		
Earthquake				0.75	
Storm Wind					1.00
Wharf Loads:					
Dead Load	1.20	1.25	1.15	1.15	1.15
Superimposed Live Load	1.00	1.00	0.50	0.50	0.50

The Ultimate Limit State Load, ULS

The ULS load should be used when checking the ultimate limit states. The combination resulting in the maximum load should be used. Recommended load factors are shown in Table 1.

Concrete Crane Rail Girder Capacity

Under the limit states, SLS and ULS, the structure should perform in accordance with the criteria outlined below.

SLS Capacity

When subjected to the SLS loads, the structure shall not suffer "local damage such as excessive cracking or excessive compression stresses, producing irreversible strains and microcracks" (CEB, 1993).

Strains are usually calculated using linear elastic analysis in accordance with ACI 318. Concrete structures are not linearly elastic. Portions of the structure are cracked and portions are uncracked. ACI 318 recognizes this and specifies when to consider sections cracked and uncracked. ACI 318 allows some plastic redistribution of forces.

The forces in the crane girder and piles are dependent on the relative stiffness of the girder and the piles. Usually, the supporting piles are not linearly elastic.

Since the strains depend, to a great extent, on the stiffness of the girder relative to the piles, it may be worthwhile to perform a load test to measure the actual deflection of the girder and the actual strains in the piles. The deflections could be measured using laser equipment. The pile strains could be measured using two strain gages on each pile. The testing would also be useful in determining the structure's behavior under the ULS loads.

The criteria for allowable strains and crack size will need to be established. The limits may vary from wharf to wharf, depending on the expected life and local conditions. The *Model Code* method could be used. No specific recommendations for strain and crack size limits are made here.

ULS Capacity

When subjected to the ULS loads, "the structure shall not lose static equilibrium" (CEB, 1993). Some damage may be acceptable due to the ULS, but the wharf should not collapse. The expected damage should be evaluated much as the damage due to earthquakes is evaluated. The evaluation methods are well known. The engineer should make an estimate of what damage may occur and how it could be repaired.

The ability of the structure to maintain static equilibrium may be determined by using the methods in the body of the ACI 318-02 code or the STM specified in ACI 318-02 Appendix A: Strut-and-Tie Models.

The STM is also presented in a number of texts and papers and described in detail in the *Model Code*. Three excellent texts that explain STM are Muttoni, Schwartz, and Thürlimann; Reineck; and MacGregor.

The Lower and Upper Bound Limit State Theorems, discussed in the *Model Code* and Muttoni et al., require the identification of a statically admissible stress field and a kinematically admissible velocity field. When the girder strength is determined using the STM, the upper and lower bounds are the same. Only one analysis is required.

All elements of the wharf may be included in the analysis, for example, the confining effect of the concrete surrounding the girder. The surrounding structure will confine the girder and increase its capacity. This effect is usually neglected, but may be significant, especially for the ULS.

The STM will predict the wharf's ability to maintain static equilibrium, but will not predict the damage due to incompatible deformations. The majority of the damage due to incompatible deformations is expected to occur in the girder between the last pile carrying the wheel loads and the adjacent "unloaded" pile. Both the STM and elastoplastic analysis may be used to predict the damage to the girder.

Pile Capacity

The structural and geotechnical engineer using conventional methods should determine the pile capacity for both the SLS and ULS. If the necessary performance cannot be determined analytically, a load test may be justified.

Load Test

The relative stiffness of the girder and piles may be determined by a non-destructive load test, as described above. The strength of an isolated pile may be determined by load testing an individual pile in accordance with ASTM D 1143-81, “Standard Test Method for Piles Under Static Axial Compressive Load.”

The overall performance of the structure may be verified in accordance with ACI 318-02, Part 6, Chapter 20, “Strength Evaluation of Existing Structures.” The loading, according to ACI 318-02, will be 1.23 times the SLS load. The acceptance criteria of section 20.5 should be used. Since the girder span is not defined, the repeat test provisions, equation (20-3), should be used.

Two Case Studies

Two case studies have been used to illustrate the application of the concepts described in the paper above. Both case studies are investigations where existing crane girders were checked for additional capacity because of increased wheel loads from new larger cranes. The loading geometry is based on the typical crane wheel spacing for the cranes at the terminal. Two load positions were investigated to address the fact that the loads are movable. Both case studies used a strut width of 152.4 mm. This value was used as a preliminary strut width, and kept for the final model because compression in the struts was not the limiting factor. In addition to the STM analysis, an elastic analysis was performed for both crane girders and evaluated based on conventional capacity (ACI 318-02 Chapters 10 and 11).

The Computer Aided Strut-and-Tie (CAST) program created by Professors Tjhin and Kuchma at the University of Illinois at Urbana-Champaign was used to analyze the girders. Although this program is still under development, it is quite useful for performing a strut-and-tie analysis. The program allows the user to quickly build a strut-and-tie model. The program does the tedious calculations required for the method. The program has built-in elements consistent with ACI 318-02 and allows the user to create their own elements types.

Port of Oakland Berth 68 Extension Waterside Crane Girder

The first case study is an evaluation of the waterside crane rail girder at Berth 68 Extension at the Port of Oakland in Oakland, California. This wharf structure was constructed in 1995. An elevation of a typical interior span and cross section are shown in Figure 2. The specified minimum concrete strength is 27.5 MPa (4000 psi), and ASTM 615 Grade 60 reinforcing was used. Figure 3 shows two strut-and-tie models for two different wheel load positions. Only the typical interior span was analyzed because the cranes cannot load the end spans of this crane girder.

The capacity based on the elastic analysis was limited by shear, and resulted in an allowable wheel load of 961 kN/m (65.9 kips/ft). The STM analysis resulted in an allowable wheel load of at least 1500 kN/m (103 kips/ft) with tension in the top reinforcing as the limiting factor. The STM analysis of the Port of Oakland crane girder showed a higher allowable wheel load, approximately 150% increase, compared with the elastic analysis. For crane rail girder analysis, frequently the piles control the girder capacity. Using strut-and-tie in this case eliminates the girder flexure or shear as the element controlling the capacity.

For this example, the STM results in a higher capacity than the elastic analysis.

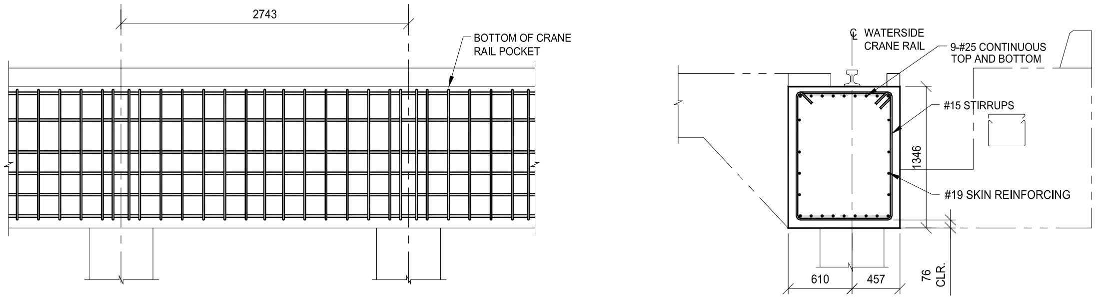
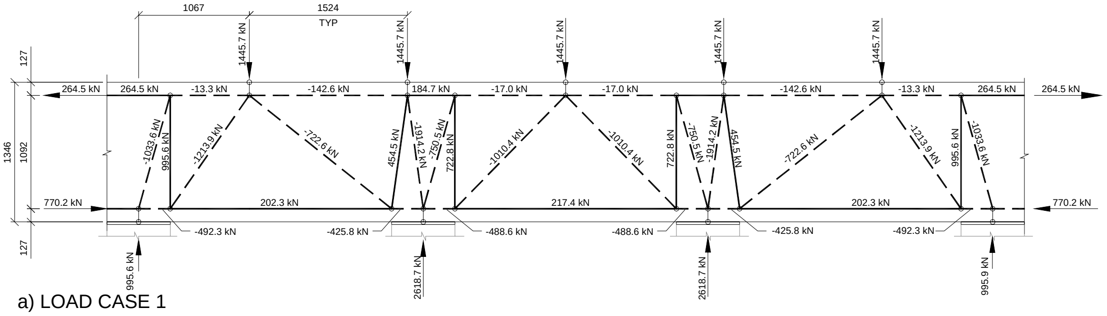


Figure 2: Details at Waterside Crane Rail Girder at Berth 68



a) LOAD CASE 1

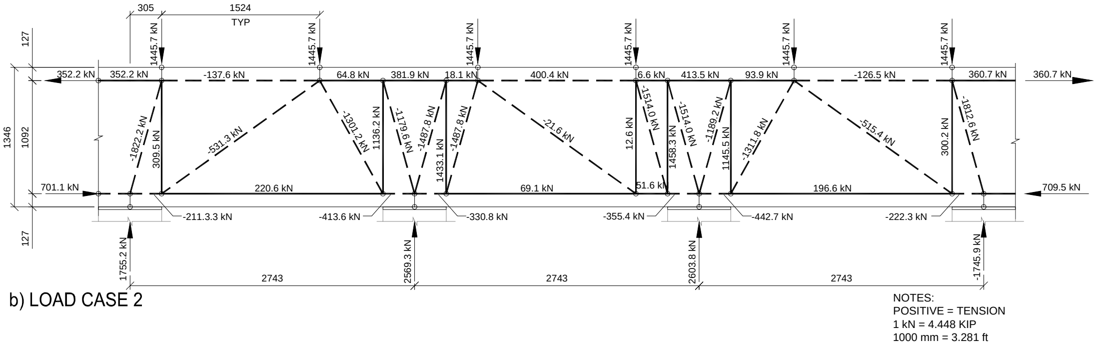


Figure 3: Strut-and-Tie Model at Berth 68

Virginia Port Authority, Portsmouth Marine Terminal, Phase I (PMT) Landside Crane Girder

The second case study is an evaluation of the landside crane rail girder at Phase I at the Portsmouth Marine Terminal. By 2005, this wharf will be receiving three new cranes. An elevation of a typical end span and cross section are shown in Figure 4. The specified minimum concrete strength is 24.1 MPa (3,500 psi), and ASTM 615 Grade 40 reinforcing was used. Figure 5 shows two strut-and-tie models, which represent the crane girder with different wheel positions. Only the end span of the crane girder was analyzed because the moments at an end span are larger than an interior span.

The capacity based on the elastic analysis was limited by shear, and resulted in an allowable wheel load of 408 kN/m (28 kips/ft). The STM analysis resulted in an allowable wheel load of 393 kN/m (27 kips/ft) with tension in the bottom longitudinal reinforcing, with Load Case 2 as the limiting factor. The STM analysis of the Portsmouth crane girder resulted in slight decrease in the allowable wheel loads.

At the girder end span, the bottom longitudinal reinforcing was terminated before the end of the span. When using the STM, the reinforcing must be anchored beyond the nodal zone for it to be effective. Since some the reinforcing was cut off, less reinforcing was available for flexure, which resulted in a lower calculated girder capacity. With the insight revealed in the STM analysis, a designer can see that if the longitudinal reinforcing had continued into the support, the girder capacity would be much higher. The cost of this reinforcing is minimal compared with the total construction cost.

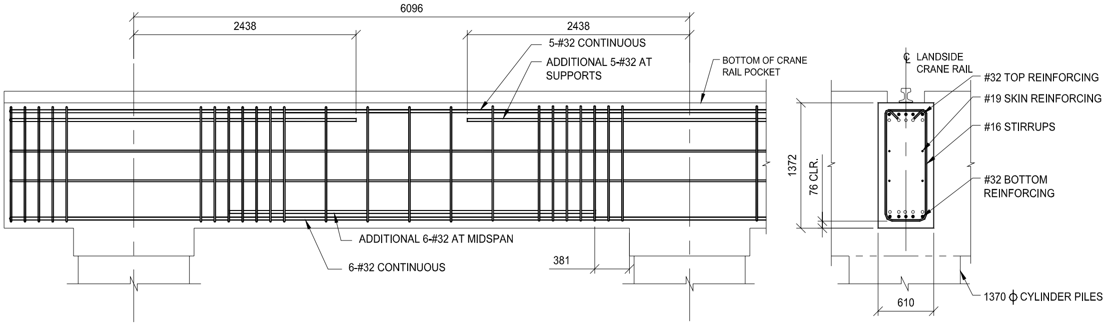
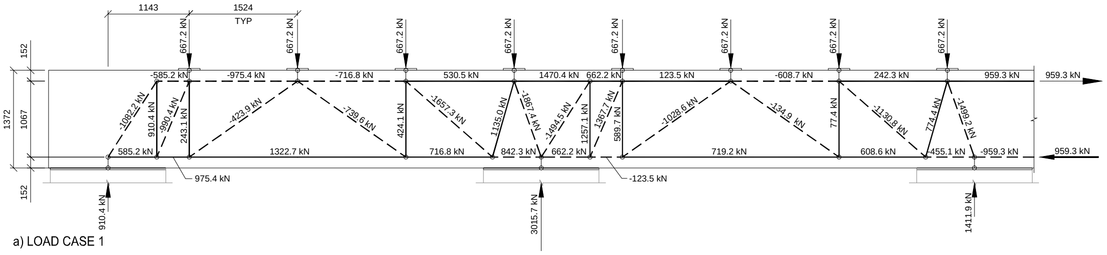
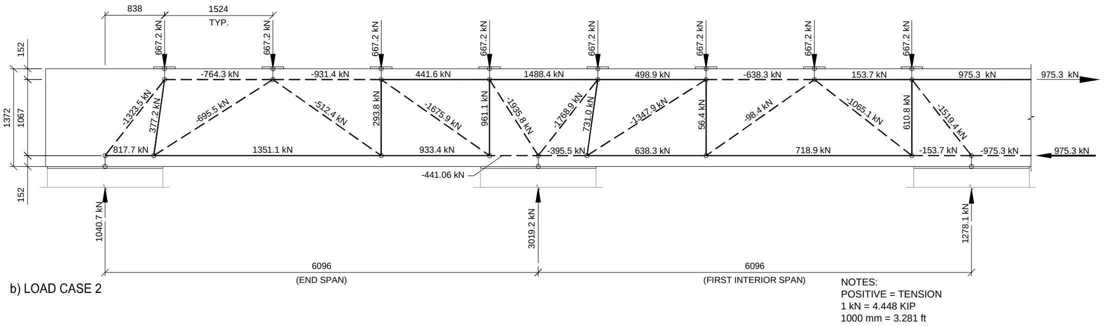


Figure 4: Details at Landside Crane Rail Girder at PMT



a) LOAD CASE 1



b) LOAD CASE 2

Figure 5: Strut-and-Tie Model at PMT

Conclusion

The proposed method for the determination of the acceptable capacity of a crane girder will make better use of the available funds, but will require more study by the engineer. The risk of damage due to performance problems, although small, will be increased. The engineer and the owner should discuss the alternatives before the STM is accepted.

If the STM is used to determine the acceptable capacity, the engineer should make a thorough investigation of performance under SLS. If the engineer or owner chooses the not use the STM, the STM should still be applied, since STM is a valuable tool for understanding how crane girders function. It gives insight into the limit state through showing a possible load path at failure. Often a minimal amount of reinforcing and improved anchorage details will increase the ULS by fifty percent or more.

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