CHAPTER 73

DESIGN CRITERIA RECOMMENDED FOR MARINE FENDER SYSTEMS

by

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ABSTRACT

This paper summarizes the world-wide effectiveness of marine-fender systems. A design criteria is recommended as a result of an extensive research and development program executed at the U.S. Naval Civil Engineering Laboratory, Port Hueneme, California, under the sponsorship of Naval Facilities Engineering Command.

Pertinent information includes analytical treatment and experimental investigation of the effects of berthing impact on the design of berthing structures, definition, function, and types of fender systems, advantages and disadvantages of various fender systems, cost-effectiveness and design procedures for different marine environment and exposure conditions. The energy absorption characteristics, berthing velocity, and virtual mass of ship are discussed in detail. Energy capacity requirements for marine fender systems are illustrated in both graph and monograph forms. This paper is intended to provide guidelines to coastal engineers who may be involved in design of fender systems for waterfront and offshore structures.

INTRODUCTION

As the trend prevails toward the design and construction of offshore structures to serve large vessels and construction barges in exposed seas, it is considered necessary to assess and update the design criteria for marine fender systems.

A marine fender system is a protective installation designed to prevent direct contact between ship and dock so that mechanical damage caused by impact and abrasion can be reduced to a minimum. An ideal fender system offers a sensitive response that increases proportionally to the excitations induced by a berthing or moored ship. Such a system absorbs high energy with low load transmission at reasonable construction and maintenance costs. Cost-effectiveness is an important criteria to be considered, including the expected loss of effectiveness because of physical and biological deterioration.

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This paper summarizes the world-wide effective fender systems, investigated at the Naval Civil Engineering Laboratory, Port Hueneme, California, including the studies by contract (Lee, 1965a, b, 1966a, b, 1967, Risselada and van Lookeren Campagne, 1964; Thorn and Wilson, 1966).

Based on the method of construction, the fender systems can be categorized into three classes defined as follows:

1. A fender system attached to a dock is a system designed for directly protecting ship and dock by absorbing impact energy, thus reducing lateral ship thrusts (Figure 1a).

2. A fender system detached from a dock is a system for indirectly protecting a dock by absorbing lateral ship thrusts, tending to permit a lighter dock design (Figure 1b).

3. A breasting-platform fender system is a series of independent breasting dolphins (pile clusters) or platforms independent of a dock and is a variant of the detached fender system (Figure 1c).

ANALYTICAL TREATMENT AND EXPERIMENTAL INVESTIGATION

The mathematical treatment of berthing ships was not systematically presented until Prof. Vasco Costa published his paper in the Journal of Dock and Harbor Authority on "Berthing of Ships" in July 1964, and further discussed at the NATO Study Institution held in Lisbon in July, 1965, the Analytical Treatment of Problems of Berthing and Mooring Ships. Pertinent recommendations based on simplified analytical treatment have been made on how to maneuver a large ship to reduce berthing impact (Vasco Costa, 1968).

The complex nature of the berthing and mooring of ships can be well illustrated diagrammatically in the docking process of a ship (Figure 2). During the initial stage, the skills of the captain and pilot, together with the assistance given by the tugs and crew in mooring lines, all influence the berthing maneuvers.

Vasco Costa (1964, 1968) derived the dynamic equations based on the principles of conservation of angular momentum with respect to the point of contact, and of conservation of kinetic energy. The first principle permits the evaluation of the angular velocity (ω) with which the berthing ship will rotate about the point of contact. The energy equation will determine the effective kinetic energy to be absorbed by the fender system.

Conservation of angular momentum of kinetic moment with respect to point of contact  (See Figure 3.)

\[ M'Oa \sin \beta + M'k^2 \omega_o = M'(k^2 + a^2) \omega \]  \hfill (1)

\[ \omega = \frac{U_o \sin \beta + k^2 \omega_o}{k^2 + a^2} \]  \hfill (2)

Conservation of kinetic energy.

\[ E_{eff} = \frac{1}{2} M'O^2 + \frac{1}{2} M'k^2 \omega_o^2 - \frac{1}{2} M'(k^2 + a^2) \omega^2 \]  \hfill (3)
Fig. 1 Definitions of fender systems from dock

(a) Fender system attached to dock

(b) Fender system detached from dock

(c) Breasting platform fender system
A. STAGE I

Ship approach berth by own power

Ship stops at certain distance parallel to berth

Berthing maneuvering influenced by:

- Captain or pilot skills
- Tug Assistance
- Mooring Lines
- Wind on ship superstructure
- Water on ship hull

Constant speed immediately before impact $E = 0.5MV^2$

Wind current

Water resistance

Currents, waves

Swell

Tide

External and natural excitations

B. STAGE II

Ship made contract with fenders with berthing structure

Ship motion changes from constant speed to varied speed

- Sway
- Yawing
- Rolling
- Surging
- Heaving
- Pitching

Energy Dissipation

Most important

Determining energy absorbed by fender, ship hull and berth deformations

Energy degenerate

Fig. 2 Berthing Process
By substituting the value given in equation (2) into (3), we obtain

\[ E_{\text{eff}} = \frac{1}{2} M' U_o^2 \left( k^2 + a^2 \right) + \frac{1}{2} M' U_0^2 \omega_o^2 \left( \frac{k^2 - a^2}{k^2 + a^2} \right) - M' U_0^2 \omega_o^2 \frac{ak^2 \sin \beta}{k^2 + a^2} \]  

(4)

The general equation (4) is the energy absorbed by the fender system which is dependent on (a) virtual mass in sway motion, \( M' \), (b) ship velocity in translation motion, \( U_0 \), (c) direction of velocity of translation, \( \beta \), (d) ship velocity in rotational motion, \( \omega_o \), (e) radius of gyration of berthing impact, \( k \), (f) point of impact relative to center gravity of ship, \( a \). The above equations do not take into account the energy consumed in resisting ship motions by mooring lines between land and ship or between tugs and ship, if any. Furthermore, the above analytical treatment is based on two degrees of freedom motion - sway and yaw. Other motions such as surge, roll, heave, and pitch are ignored. Therefore, the energy absorbed by the fender so determined is on the conservative side. Assumption is made that virtual mass of ship remains unchanged for sway motion and for rotational motion about the center of gravity or about the point on impact, respectively.

Soon after the ship makes contact with the fender, the ship may move in a simple mode of motion, i.e., the two limited cases (a) translation without rotation, and (b) rotation without translation.

Special Case 1. **Ship Motion with Translation Only (without rotation)**

\[ E_{\text{eff}} = \frac{1}{2} M' U_o^2 \left( \frac{k^2 + a^2}{k^2 + a^2} \right) \cos^2 \beta \]

(5)

When \( \beta = 90^\circ \), \( E_{\text{eff}} = \frac{1}{2} M' U_o^2 \frac{k^2}{k^2 + a^2} \)

(6)

where \( \frac{k^2}{k^2 + a^2} \) is an eccentricity coefficient.
Special Case 2. Ship Motion with Rotation Only (without translation)

\[ E_{\text{eff}} = \frac{1}{2} M' \omega_o^2 \frac{a^2}{k^2 + a^2} \]  

(7)

In this case, the energy to be absorbed by fender can be expressed as a function of the velocity at the point of contact, which is

\[ V_o = \omega_o a \]  

(8)

\[ E_{\text{eff}} = \frac{1}{2} M' V_o^2 \frac{k^2}{k^2 + a^2} \]  

(9)

The motion of a berthing ship has been treated as a dynamic problem of three degrees of freedom by Hayashi and Shirai (1963) sway, yaw, and roll. The kinetic energy of the berthing ship is absorbed by the following modes (a) elastic deformation of fender system, berthing structure, and ship hull due to sway motion, (b) swing of ship due to yawing motion, and (c) heeling of ship due to rolling motion. The dynamic equations are

\[
\begin{align*}
\text{Sway:} & \quad \ddot{y} + \left( \frac{a}{M' K^2} \right) y + a \dot{\theta} + h \phi = 0 \\
\text{Yaw:} & \quad \ddot{\theta} - \left( \frac{k}{M' K^2} \right) \dot{y} = 0 \\
\text{Roll:} & \quad \ddot{\phi} - \left( \frac{k}{M' K^2} \right) \dot{\phi} + \left( \frac{1}{M' K^2} \right) v = 0
\end{align*}
\]  

(10) (11) (12)

By solving the above equations with given initial conditions, one can obtain the maximum overall deformation \( y_{\text{max}} \) of fender system, berthing structure, and ship hull at the point of contact. Then the effective energy to be absorbed by the fender systems can be determined. The overall effective spring constant, \( k_e \), consists of elastic characteristics of fender system, berthing structure, and ship hull. The values of \( \theta \) and \( \phi \) represent angle of yaw and angle of roll, respectively. The values of \( h \) and \( h_m \) represent the vertical distance from center of gravity of ship to point of contact between fender and ship, and the height of metacenter of the ship, respectively. Ship displacement is \( W \). The value of \( a \) is the distance between point of contact and center of gravity of ship along the longitudinal axis. \( K \) is the radius of gyration of the ship.

Water wave effect on berthing ship was studied by Wilson (1958). Wave effect would be minimum if berthing operation is made on a head sea, but the force will be considerable if berthing is in beam sea. The type of berthing structure is particularly important. For an open-type structure, waves will be transmitted without sensitive reflection but for a closed-type structure, a standing wave system will be formed to effect the berthing ship. Wilson derived formulas for berthing ship under wave action on impact with both open and closed type structures when impact is at the center of gravity of ship, during which sway motion is only concerned.
Open-type structure
$$E_{ff} = \frac{1}{2} M \left[ U_o + A g \sinh kd - \sinh ks \frac{\sin kD}{kD/2} \right]^2$$  \hspace{1cm} (13)

Closed-type structure
$$E_{ff} = \frac{1}{2} M \left[ U_o + 2A g \sinh kt - \sinh ks \frac{\sin^2 kD}{kD/2} \right]^2$$  \hspace{1cm} (14)

where $A$ = wave amplitude, $l$ = wave length, $k = \frac{2\pi}{l}$ wave number, $d$ = water depth. $S$ = wave slope, $B$ = ship beam, $D$ = ship draft, $\sigma = \frac{\pi}{d}$; $T$ = wave period, $g$ = gravitational acceleration. Unfortunately, yawing and rolling motions are not considered. However, this can easily be taken into account based on Vasco Costa's formulas.

The mathematical treatments of the berthing ships described above are quite complicated for practicing engineers. Major difficulties are due to the fact that the dynamic equations involve several undefined parameters such as hydrodynamic masses, wave forces, vertical moments of inertia of ship, and ship velocity in translation and rotational motions. When the fender system is having non-linear elastic characteristics and the effects of natural excitations from winds, waves, and currents are taken into account, the situation becomes worse, if not hopeless, for mathematical solutions. Keeping these factors in mind, and being realistic in dealing with berthing problems involving human factors also, it is considered feasible to design fender systems by a semi-theoretical and semi-empirical approach which will be discussed in this paper. In view of the fact that semi-empirical approach seems satisfactory only when proper engineering judgement is achieved, pertinent information is furnished in this paper on the relative merits of different fender types, the choice of design berthing velocity, hydrodynamic mass, cost-effectiveness, and other factors as related to local marine environment and navigation conditions.

Model experiments and full-scale observations or measurements have been used to supplement the mathematical treatment. Statistical approach has also been used for the purpose of finding ways to improve berthing operations in Great Britain, the British Petroleum Company (Saurin, 1963 and 1965) and the Hydraulic Research Station, Wallingford (1961, 1962) are the major contributors, berthing forces of large tankers are assessed to establish a realistic design criteria based on semi-empirical approach. In France, the Port of LeHare conducted model experiments on the berthing energy of ships with both translation and rotation motion of ship due to wind effects (Giraudet, 1966). In the US, this author conducted full-scale investigations of berthing impacts and evaluations of a Hydraulic-pneumatic floating fender (Lee, 1966a). In Norway, field measurements were made of berthing forces of a ferry boat (Tryde, 1965). In Japan, Shiraishi (1962) conducted field tests from which an approximate solution of berthing impact force was recommended.

**GENERAL TYPES OF FENDER SYSTEMS**

**Standard pile-fender systems.** This type of fender system employs piles driven into the ocean bottom along a wharf face. Impact energy is absorbed by deflection and limited compression of the pile. Energy absorption capacity is dependent on size, length, penetration, and material of the pile. It is
determined on internal strain-energy characteristics (Figure 4). The energy absorption capacity is very limited; it declines rapidly as a result of biodeterioration and mechanical damage (Figure 5). Steel piles are occasionally used for fendering in water depth greater than 40 feet or for locations where very high strength is desirable. Regular reinforced concrete piles are unsatisfactory. In some cases, prestressed concrete piles with rubber buffers at deck level have been used with success.

Retractable fender systems: This type of fender retracts under impact, thereby absorbing energy by action of gravity and friction. Energy absorption depends on (a) effective weights, (b) the maximum amount of retraction of the system, and (c) the angle of inclination of the supporting brackets.

The use of composite inclined planes of supporting brackets and proper selection of the maximum retraction are the most feasible means for attaining design energy-absorption capacity (See Figure 6). Deterioration of timber frames does not materially reduce energy-absorption capacity, nor is capacity dependent on internal strain energy as with timber piles.

Rubber fender systems: Rubber fender systems consist of rubber-in-compression, rubber-in-shear, and rubber-in-bending buffers. These resilient units are normally installed behind standard fender piles so as to increase the energy absorption capacity.

Energy absorption of the rubber-in-compression system is achieved by a compression of the rubber tubes or solid blocks in axial or radial directions. The capacity may be increased by using multiple layers; thus also keeping the resistance force to dock or ship at a reasonably low level.

The rubber-in-shear system consists of a series of rubber pads bonded firmly as buffers between a pile-fender system and a pier. The improved version of the so-called "Raykin" buffers have been designed to have a 100 percent overload capacity. This type of fender is most suitable for berths designed for servicing large tankers because of its high energy absorption capabilities. It is capable of resisting direct and glancing impacts. Because of its stiffness and lack of suitable responsiveness to widely varying amounts of impact, it is unfit for servicing vessels varying widely in size at a berth.

The rubber-in-bending system, so-called "Lord" flexible fender, consists of an arch-shaped rubber block bonded between two steel plates. Impact energy is absorbed by bending and compression of an arch-shaped rubber column. When an impact force is applied, it will build up a relatively high load with small deflection, buckle at a further small deflection, and maintain a virtually constant load over the range of buckling deflection (Fig 7).

Rubber-in-torsion fender is a rubber-and-steel combination fabricated in a cone-shaped compact bumper form, molded into a specially-cast steel frame and bonded to the steel. It absorbs energy by torsion, compression, shear, and tension. However, most energy is absorbed by compression (Lee, 1965a).

Gravity type fender systems. Gravity fenders are normally made of concrete blocks suspended from a heavily constructed wharf deck. Impact energy is absorbed by moving and lifting the heavy concrete blocks. High energy
MARINE FENDER SYSTEMS

Energy Absorption Correction Factor

- Greenheart: 3.40
- Eucalyptus: 3.00
- Red gum: 1.53
- Cypress: 1.10
- Douglas fir or Southern pine: 1.00
- Oak: 0.85

Average length of the pile is approximately 1.2 times the supported length. The total length depends on the depth of penetration into the ocean floor and the maximum water depth.

The curves are based on Douglas fir or Southern pine.

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Fig. 4 Energy-absorption of timber fender piles

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Fig. 5 Energy-absorption reduction due to bio-deterioration

\[ \alpha = \text{Soundness of pile (new)} \]

\[ \beta = 0.5 \left( 1 - \frac{c}{c'} + \frac{3c}{c'\alpha} \right) \]

Deterioration Tide Range
- 2 feet Normal
- 4 feet Extreme
- 4 feet Normal plus 2 feet Extreme

Note: \( \alpha = \frac{s}{55'} \) (corresponds to 55' to 70')
Fig. 6  Operation of modified retractable fender system

NOTE  The part number 2F-212 is defined as a "Lord" rubber fender having an energy-absorption capacity of 21,200 foot-pounds at full deflection of 16 inches.

Fig 7  Load-deflection and energy-absorption characteristics of Lord flexible fender
absorption is achieved through long travel of the weights. The movements may be accomplished by (1) a system of cables and sheaves, (2) a pendulum, (3) trunnions, or (4) an inclined plane. The type of gravity fender suited to a given situation depends on tidal conditions, energy-absorption requirements, and other load environmental factors such as exposures to wind, waves, and currents. For example, heavy vertically-suspended gravity fenders are commonly used in exposed locations with large tidal ranges.

Pneumatic fender systems. Pneumatic fenders are pressurized and airtight rubber devices designed to absorb impact energy by compression of air inside a rubber envelope. These pneumatic fenders are not applicable to fixed dock-fender systems but are feasible for use as ship fenders or shock absorbers on floating fender systems. A proven fender of this type is the pneumatic tire-wheel fender. This system consists of pneumatic tires and wheels capable of rotating freely around a fixed or floating axis. Energy-absorption capacity and resistance load depend on the size and number of tires used and on initial air pressure when inflated.

Hydraulic and hydraulic-pneumatic fender systems. This system consists of a cylinder full of oil or other fluid so arranged that when a plunger is depressed by impact, the fluid is displaced through an invariable or variable orifice into a reservoir located at a higher elevation. When the ship impact is released, the high pressure inside the cylinder forces the plunger back to its original position, and the fluid flows back into the cylinder by gravity. The system is non-floating. Its most common use is in locations of severe wind, wave, swell, and current conditions.

Hydraulic-pneumatic floating fender system. This system consists of a floating rubber envelope filled with water, or with water and air, which absorbs energy by viscous resistance and/or by compression of air. This fender seems to meet certain requirements of the ideal fender but is considered expensive in combined first and maintenance costs.

A new patented (Figure 8) concept has been developed by this writer to overcome the existing deficiencies of both pneumatic and hydraulic fenders by combining the pneumatic and hydraulic principles within a single marine fender. As shown in Figure 8, the system employs a pair of inflatable rubber bags, one being an exterior bag and the other being a smaller interior bag which is located within the exterior bag. The interior bag which is sealed when in use, may contain air or foam cushion and is sufficiently smaller than the exterior bag so as to define a chamber therebetween for containing water. A conduit means may be connected to the exterior bag so as to communicate the water chamber with the exterior body water. The marine fender will absorb high impact loading without bursting because of pressure relief caused by the escaping water through the conduit means. After berthing, the fender will provide even improved cushioning over the pneumatic type fenders since the water discharge effect will minimize the high...
rebounding effect of the pneumatic bag. It is expected that the new fender is particularly feasible for use as separators between ships or small crafts. It is sensitive to both berthing and moored vessels.

Torsion fender system. This is a new concept developed by Mr. Turner and Prof. Baker of the Cambridge University Engineering Laboratories. The so-called "Cambridge" fender has been tested with success in both laboratory and field installations. It employs the principles of energy absorption by plastic deformation of metals. The system consists of a plastically deformable torsion and a mechanism transforming the berthing impact into the shock absorber.

To assist the practicing engineers in the selection of the desirable type of fender system, Table 1 is prepared summarizing major advantages and disadvantages of various fender systems described above. Load-deflection characteristics are compared in Figure 9.

For case histories and detailed comments on each system, see U.S. Naval Civil Engineering Laboratory’s technical reports (a) "A Study of Effective Fender Systems for Navy Piers and Wharves," R-312, March 1965, and (b) "Review of 'Report on the Effective Fender Systems in European Countries' by Risselada and van Lookeren Campagne," R-376, October 1965 (Lee, 1965a, b).

DESIGN CRITERIA RECOMMENDED FOR MARINE FENDER SYSTEMS

General. A variety of factors affect the proper selection of a fender system. These include local marine environment, exposure of harbor basins, class and configuration of ships, speed and direction of approach of ship when berthing, available docking assistance, type of berths, and even skills of pilots or ship captains. It is considered impractical to standardize fender designs since local conditions are rarely identical. Previous local experience in the application of satisfactory fender systems should be considered, particularly cost-effectiveness characteristics.
<table>
<thead>
<tr>
<th>Fender System</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Standard Pile, timber             | 1. Low initial cost  
2. Timber piles are abundant in US and most world regions | 1. Energy absorption capacity is limited. It declines as result of biodeterioration  
2. Susceptible to mechanical damage and biological deterioration. 
3. High maintenance cost if damage and deterioration is significant |
| Standard Pile, steel              | 1. High strength  
2. Feasible for difficult seafloor conditions. | 1. Vulnerability to corrosion  
2. High cost |
| Standard Pile, reinforced concrete| 1. Insignificant effects of biodeterioration                                 | 1. Energy-absorption capacity is very limited. 
2. Corrosion of steel reinforcement through cracks |
| Standard Pile, prestressed concrete| 1. Resistance to natural and biological deterioration  
2. Better energy-absorption characteristics than reinforced concrete piles. | 1. Limited strain-energy capacity, if rubber buffers are not provided. |
| Timber Hung System                | 1. Very low initial cost  
2. Less biodeterioration hazard                                              | 1. Low energy-absorption capacity  
2. Unsuitability for locations with significant tide and current effects |
Table 1. Comparison of Various Types of Fender Systems (Continued)

<table>
<thead>
<tr>
<th>Fender System</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Retractable Fender System | 1. Effects of biological deterioration on energy absorption-capacity are negligible.  
2. No heavy equipment is required for fabrication and replacement  
3. Low maintenance cost, minimum time loss during replacement | 1. Loss of effectiveness due to corrosion and/or damage to supporting brackets.  
2. High initial cost for use at open-type piers. |
| Rubber Fender Systems  
2. Effectiveness at reasonable cost. | 1. High concentrated loading may result, frictional force may be developed if rubber fenders contact ship hull directly  
2. Higher initial cost than standard pile system without resilient units. |
| Rubber Fender Systems  
2. Most suitable for dock-corner protection.  
3. High energy-absorbing capacity for serving large ships of relatively uniform size.  
4. Favorable initial cost for very heavy duty piers. | 1. 'Raykin' buffers tend to be too stiff for small vessels and for moored ships subject to wave and surge action.  
2. Steel plates are subject to corrosion  
3. Bond between steel plate and rubber is a problem.  
4. High initial cost for general cargo berths. |
<table>
<thead>
<tr>
<th>Fender System</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubber Fender Systems</td>
<td>1 High energy-absorption and low terminal-load characteristics</td>
<td>1 Possible destruction of bond between steel plates and rubber</td>
</tr>
<tr>
<td>Lord Flexible Fender</td>
<td></td>
<td>2 Possible fatigue problems.</td>
</tr>
<tr>
<td>Rubber Fender Systems</td>
<td>1 Capable of resisting impact load from all directions</td>
<td>1 Possible destruction of the bond between steel casting and rubber</td>
</tr>
<tr>
<td>Rubber-in-torsion</td>
<td></td>
<td>2 Possible fatigue problems.</td>
</tr>
<tr>
<td>Gravity-Type Fender Systems</td>
<td>1 Smooth resistance to impacts induced by moored ships under severe wave</td>
<td>1 Heavy berthing structure is required</td>
</tr>
<tr>
<td></td>
<td>and swell action</td>
<td>2 Heavy equipment is required for installation and replacement</td>
</tr>
<tr>
<td></td>
<td>2 High energy absorption and low terminal load can be achieved through long</td>
<td>3 High initial and maintenance costs</td>
</tr>
<tr>
<td></td>
<td>travel for locations where excessive distance between ship and dock is not</td>
<td>4 Excessive distance between dock and ship caused by the gravity fender is undesirable for general</td>
</tr>
<tr>
<td></td>
<td>a problem</td>
<td>cargo piers and wharves</td>
</tr>
<tr>
<td>Pneumatic Fender System</td>
<td>1 Suitable for both berthing and moored ships.</td>
<td>1 Use in fixed dock-fendering is limited to bulkhead-type structures.</td>
</tr>
<tr>
<td></td>
<td>2. Fixed tire-wheel type is feasible for pier-corner protection.</td>
<td>2 High maintenance cost</td>
</tr>
<tr>
<td>Hydraulic and Hydraulic-</td>
<td>1 Favorable energy-absorption characteristics for both berthing and moored</td>
<td>1 High initial and maintenance cost.</td>
</tr>
<tr>
<td>pneumatic Fender</td>
<td>ships</td>
<td></td>
</tr>
</tbody>
</table>
Design Procedures

1. **Examine local marine environment and exposure conditions.** Local natural environment and the degree of protection of harbor basins are important factors in fender system selection. A classification of marine environments and navigation conditions is shown in Table 2. Designers may determine local navigation conditions based on local marine environment.

2. **Determine the displacement tonnage of ship.** The fender capacity for any ship depends not only on its size, but also on its frequency of arrival. Average size of ships using the berth (i.e., one-half to two-thirds the maximum) should be selected for design. Displacement tonnage is used in measuring the size of ship. For design of general-cargo piers and wharves, 20,000 long-tons may be considered as design displacement.

3. **Determine the berthing velocity, V.** Berthing velocity is determined with due consideration of (a) the size of the vessel, (b) the berthing method (broadside, approach with angle to dock face, with or without tug assistance, (c) navigation condition, and (d) type of dock. Figure 10 shows the range of berthing velocity which may be selected for design ships up to 200,000 long-tons displacement.

![Figure 10: Berthing velocity vs. ship displacement.](image-url)
Table 2. Classification of Marine Environments and Navigation Conditions
(Based on Risselada and van Lookeren Campagne, 1964)

<table>
<thead>
<tr>
<th>Navigation Condition</th>
<th>Marine Environment Description</th>
<th>Example of Harbor Tidal/Current Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Sheltered</td>
<td>No or little current up to 0.31 ft/sec. Tide range up to 3 ft. No strong winds</td>
<td>Mediterranean ports</td>
</tr>
<tr>
<td>2 Sheltered</td>
<td>Some current up to 0.31 ft/sec. Tide range up to 3 ft. No strong winds</td>
<td>Baltic ports</td>
</tr>
<tr>
<td>3 Moderately sheltered</td>
<td>No or little current up to 0.31 ft/sec. Tide range up to 3 ft. Fresh gale winds up to 40 knots</td>
<td>Mediterranean ports</td>
</tr>
<tr>
<td>4 Moderately sheltered</td>
<td>Moderate current up to 0.7 ft/sec. Tide range up to 10 ft (normal). 20 ft (maximum). Strong gale winds up to 47 knots</td>
<td>Rotterdam, Lisbon, N W. Germany</td>
</tr>
<tr>
<td>5a Moderately sheltered</td>
<td>Considerable current up to 0.8 ft/sec. Tide range up to 16 ft (normal). 27 ft (maximum). Strong gale winds up to 47 knots</td>
<td>Le Havre</td>
</tr>
<tr>
<td>5b Slightly sheltered</td>
<td>Moderate current up to 0.7 ft/sec. Tide range up to 10 ft (normal). 20 ft (maximum). Strong gale winds up to 47 knots</td>
<td>Rotterdam, Lisbon, N W. Germany</td>
</tr>
<tr>
<td>5c Exposed</td>
<td>No or little current up to 0.3 ft/sec. Tide range up to 1 ft (normal). 10 ft (maximum). Strong gale winds up to 47 knots</td>
<td>Baltic ports</td>
</tr>
<tr>
<td>6a Slightly sheltered</td>
<td>Great current up to 1.0 ft/sec. Tide range up to 20 ft (normal). 33 ft (maximum). Strong gale winds up to 47 knots</td>
<td>British Atlantic ports</td>
</tr>
<tr>
<td>6b Exposed</td>
<td>Considerable current up to 0.8 ft/sec. Tide range up to 16 ft (normal). Strong gale winds up to 47 knots</td>
<td>Le Havre</td>
</tr>
<tr>
<td>7 Exposed</td>
<td>Great current up to 1.2 ft/sec. Tide range up to 3 ft (normal). 33 ft (maximum). Storm winds up to 63 knots. Waves up to 3 feet.</td>
<td>British Atlantic ports</td>
</tr>
<tr>
<td>8 Very exposed</td>
<td>Great current up to 1.3 ft/sec. Tide range up to 20 ft (normal). 33 ft (maximum). Storm winds up to 63 knots. Waves 3 ft or greater</td>
<td>British Atlantic ports</td>
</tr>
</tbody>
</table>
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If the fender system is designed for ships of 20,000 long-ton displacement, berthing speed recommended is shown in Figure 11.

If the fender system is designed for ships of 20,000 long-ton displacement, berthing speed recommended is shown in Figure 11.

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4. **Determine the effective mass or virtual mass of a vessel.** When a ship approaches a dock, the berthing impact is induced not only by the mass of moving ship, but also by the water mass moving along with the ship. The latter is generally called the "hydrodynamic" or "added" mass. In determining the kinetic energy of a berthing ship, the effective or virtual mass (a sum of ship mass and hydrodynamic mass) should be used. The hydrodynamic mass does not necessarily vary with the mass of the ship but is closely related to the projected area of the ship at right angles to the direction of motion. Other factors such as the form of ship, the water depth, the berthing velocity, the acceleration and deceleration of the ship would have some effect on the hydrodynamic mass. Taking into account both model and prototype experiments, the hydrodynamic mass can be estimated as

\[ M_h = C_h M = 2 \left( \frac{D}{B} \right) M \]  \hspace{1cm} (15)

Thus, the virtual mass

\[ M' = M + M_h = (1 + 2 \frac{D}{B}) M = C_M M \]  \hspace{1cm} (16)
where

\[ M_h = \text{hydrodynamic mass} \quad M' = \text{virtual mass or effective mass} \]

\[ C_h = \text{hydrodynamic coefficient} \quad C_m = \text{virtual mass coefficient} \]

\[ M = \text{ship mass} \quad D = \text{draft of ship} \]

\[ B = \text{beam of ship} \]

Adopting Vasco Costa's formula, a graph (Figure 12) of \( C_m \) versus vessel size (long tons) has been plotted, using dimensions of some 70 U S Naval vessels in the 2,000-20,000 long-ton class. The virtual mass coefficient as predicted by Vasco Costa's formula is adequate for ships berthing at moderate to high speed. Caution should be exerted when design speed is low (Lee, 1966a).

\[ C_m = 1 + 2 \left( \frac{D}{B} \right) \]

Figure 12: Virtual Mass Coefficient versus Displacement (Thron, 1966)

5. Determine the kinetic energy \((E)\) of berthing ship

\[ E = \frac{M'}{2} V^2 \quad \text{or} \quad E = 0.209 C_m W V^2 \]  

(17)

where

\( E \) = kinetic energy of berthing ship in inch-tons

\( W \) = ship displacement in long-tons

\( V \) = berthing velocity normal to dock in feet per second.

6. Determine effective berthing energy of ship to be absorbed by fender system

\[ E'_{\text{eff}} = C E = 0.209 C_m W V^2 \]

\[ C = C_e C_g C_d C \]  

(18)

where

\( E'_{\text{eff}} \) = kinetic energy to be absorbed by fender system in inch-tons

\( C \) = berthing coefficient

\( C_e \) = eccentricity coefficient
C = ship geometric coefficient
C_d = ship deformation coefficient
C_c = berth configuration coefficient

Eccentricity coefficient, C_e, is expressed as
\[ C_e = \frac{k^2}{a^2 + k^2} \]
where a = distance between the point of impact and the center of gravity of the ship
k = ship radius of gyration about the axis - frequently 0.20 to 0.29 times the ship length

The value of C_e varies from 0.14 to 1.0

Geometric coefficient, C_g, depends upon the geometric configuration of the ship at the point of impact. It varies from 0.85 for an increasing convex curvature to 1.25 for concave curvature. Generally, 0.95 is recommended for the impact point at or beyond the quarter points of the ship and 1.0 for broadside berthing in which contact is made along the straight side.

Deformation coefficient, C_d, corrects the energy reduction effects due to local deformation of the ship's hull and deflection of the whole ship along its longitudinal axis. The energy absorbed by the ship depends on the relative stiffness of the ship and the obstruction. The deformation coefficient varies from 0.5 for a nonresilient fender to nearly 1.0 for a very flexible fender.

Berth configuration coefficient, C_c, provides for the water cushion effect between pier and ship. It is recommended that 0.8 be used for a closed wharf, 0.9 for a semi-closed type, and 1.0 for an open pier.

The berthing coefficient, C_b, is frequently assumed to be 0.5 where insufficient information is available to allow evaluation of individual coefficients. A higher coefficient must be used if broadside berthing is always involved.

7. Nomograph. A published nomograph (Fig 13) is reproduced on the following page to facilitate the determination of the energy-absorption requirement of a fender system.

8. Compare the energy-absorption capacity requirements determined from (7.) above or with Figure 14 on the following page if the fender system is designed for ships up to 20,000 long-ton displacement for a specific navigational condition.

9. Select the final energy-absorption capacity of the fender system, taking into account frequency of berthings, probability of accidents, and expenses that may be involved in the construction, repair or replacement of the main berthing structure, the fender system, and the ships. Cost-effectiveness should be studied in order to determine the feasibility of selecting a high-energy absorption fender system, particularly as compared with existing systems. An example is given in Appendix A.
Fig. 13 Nomograph = Energy absorption requirements for marine fender systems
(Courtesy of Lord Mfg Co.)

Fig. 14 Energy-absorption capacities recommended for fender design
OTHER RECOMMENDATIONS PERTINENT TO FENDER TYPE SELECTION

Selection of a fender system for a given installation is based on the following factors. Pertinent recommendations are given as follows:

1. **Exposure conditions**  In exposed locations or in areas subject to seiche, a resilient system such as a rubber fender system, should be used. In sheltered basins, a standard timber-pile system, a hung system, or a retractable system is generally used.

2. **Berthing ship versus moored ship**
   
   (a) For locations where berthing operations are hazardous, stiff fender systems with high energy-absorption characteristics are advisable.

   (b) For locations where the behavior of the already moored ship is the governing factor, soft fenders with soft mooring ropes are feasible in minimizing mooring forces and ship motion.

   (c) Where berthing operations and the behavior of moored ships seem to pose problems of equal importance, it is best to choose a fender of intermediate type that can act stiffly during berthing and softly when the ship is moored. Hydraulic-pneumatic fender systems meet such requirements.

3. **Acceptable lateral load to docks**  At berths for vessels up to 20,000 long-ton displacement, the acceptable lateral loading to dock should be kept within 3,000 to 3,500 pounds per linear foot of berth. Special tanker berth may be acceptable for higher lateral loading.

4. **Acceptable hull loads**. For vessels from 15,000 to 20,000 tons, hull pressure of 35 psi is acceptable in general, with overloads of up to 50 psi as an upper limit.

5. **Maximum allowable distance between moored ships and dock face**  The maximum limit is 4 to 5 feet for general cargo berth. No problem exists if the fender system is for a tanker berth involving fuel supply only.

6. **Pier type as related to fender system selection**
   
   (a) Open pier. Any type of fender system may be applicable.

   (b) Solid pier  This type has little resilience. Consider use of resilient or retractable fenders to minimize vessel damage.

7. **Miscellaneous factors related to fender system selection**
   
   (a) Resistance to tangential forces

   (b) Reliability in operation.

   (c) Cost of maintenance.

   (d) Evaluation of systems that have given satisfactory service at or near the proposed installation.
(e) Resistance to longitudinal component of berthing force

(f) Ease and economy of replacement

(g) Available docking assistance

(h) Skills of pilots and captains during docking

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REFERENCES


Biological deterioration and mechanical damage by berthing and moored ships have significant effects on energy-absorption capabilities of conventional timber piles. The fender effectiveness depreciates hyperbolically as the treated and untreated piles are attacked by molluscan and crustacean borers such as *Teredo*, *Bankia*, and *Limnoria*. Therefore, most timber fender systems in existence are weakened, having a lower energy-absorption capacity than originally designed. Considerable efforts and money would have to be expended to maintain the existing systems to an acceptable level in order to meet their performance requirements. In some cases, annual cost or capitalized cost seems considerably higher than generally realized. To evaluate the cost-effectiveness characteristics, Lee (1966b) conducted on-site investigations and subsequent technical and economical analyses of existing timber fender systems at 10 representative United States Naval stations and shipyards, covering a total of approximately 200,000 linear feet of berth. Discussions included cost-effectiveness aspects, relative merits of creosoted versus untreated fender piles of Douglas fir, Southern pine, oak, gum, cypress, and eucalyptus, extent, cause, and possible solution of fender problems, distribution of fender damage by biological deterioration and ship damage to sound or weakened piles, and physical factors such as marine environment, berth usage, and other navigation conditions as related to above.

Cost Effectiveness Analysis Criteria. In formulating criteria to evaluate cost-effectiveness of an existing fender system in a particular environment, effectiveness and cost must be considered on a long-term basis. Therefore, the initial values are not necessarily the control factor. The most effective fender system must meet not only service requirements initially, but also maintain its effectiveness during a substantial life. The most economical fender system must offer the lowest combined initial and maintenance costs over an extended period. An ideal fender is a system which is most effective and most economical over its lifetime. A fender's effectiveness is measured by (a) system serviceability, (b) system reliability, and (c) system availability. Lack of proper record would prevent a meaningful evaluation of the serviceability and availability of existing fender systems. Therefore, reliability may be the yardstick in evaluation of the effectiveness of the existing fender systems. Reliability is determined from energy-absorption capacities with the consideration of the biological deterioration and physical damage to piles. Comparative economics of pile fender systems is determined by annual cost and/or capitalized cost methods involving an assess of the related factors such as initial construction costs, maintenance and replacement costs, and physical life of the system. Indirect costs such as demurrage costs resulting from repairing accidental damage to berthing ships or dock, and obsolescence costs are not normally considered due to unavailability of such data. The method of economic analysis is described elsewhere (Garbaccio et al, 1966, Lee, 1966b).

Energy-absorption capacity of a fender system is determined from the summation of the total initial strain energy of the total fender piles in action over a 150-foot berth length which represents the normal contact.
length of a 20,000-ton cargo transport. Effectiveness can be reduced to as much as 28% and as low as 99% of the original capacity, depending on the efforts exercised in fender maintenance and replacement (Fig 15). The fender effectiveness can be determined from a well-kept pile deterioration and replacement record. The annual cost can be computed from cost data collected over an extended period. The life of existing fender systems should be determined from actual pile replacement records. As shown in Fig 15, it seems apparent that the fender life is closely related to berth usage and to the extent of mechanical damage by ships

Fig 15 Cost-effectiveness of fender systems at Pearl Harbor