CHAPTER 73

DESIGN CRITERIA RECOMMENDED FOR MARINE FENDER SYSTEMS

by

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U S A

A B S T R A C T

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

Pertinent information includes analytical treatment and experimental
investigation of the effects of berthing impact on the design of berthing struc-
tures, definition, function, and types of fender systems, advantages and disad-
vantages of various fender systems, cost-effectiveness and design procedures
for different marine environment and exposure conditions. The energy absorp-
tion characteristics, berthing velocity, and virtual mass of ship are discussed
in detail   Energy capacity requirements for marine fender systems are illus-
trated 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 struc-
tures to serve large vessels and construction barges in exposed seas, it is con-
sidered 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 effec-
tiveness because of physical and biological deterioration

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This paper summarizes the world-wide effective fender systems, investi-
gated at the Naval Civil Engineering Laboratory, Port Hueneme, California,
including the studies by contract (Lee, 1965a, b, 1966a, b, 1967, Risselada and
van Lookeren Compagne, 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 pro-
tecting 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 breast-
ing dolphins (pile clusters) or platforms independent of a dock and is a vari-
ant 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 Treat-
ment 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 prin-
ciples of conservation of angular momentum with respect to the point of contact,
and of conservation of kinetic energy. The first principle permits the evalu-
ation 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.)

$$M'U_o a \, \text{Sin} \, \beta + M'k^2\omega_o = M'(k^2+a^2) \, \omega \tag{1}$$

$$\omega = \frac{U_o a \sin \beta + k^2 \, \omega_o}{k^2+a^2} \tag{2}$$

Conservation of kinetic energy.

$$E_{eff} = \frac{1}{2}M'U_o^2 + \frac{1}{2}M'k^2\omega_o^2 - \frac{1}{2}M'(k^2+a^2) \, \omega^2 \tag{3}$$

Plan

Profile

(a) Fender system attached to dock

Plan

Profile

(b) Fender system detached from dock

Plan I

Plan II

(c) Breasting platform fender system
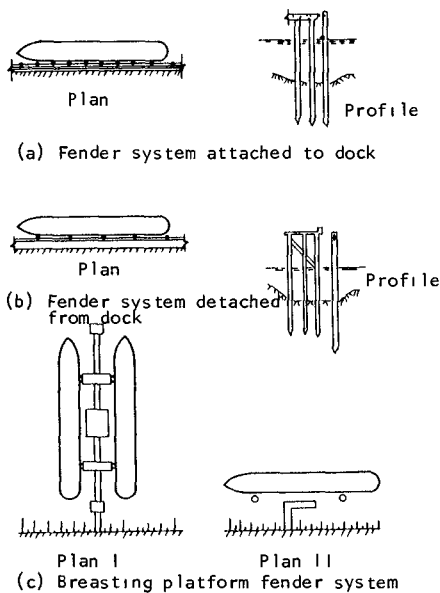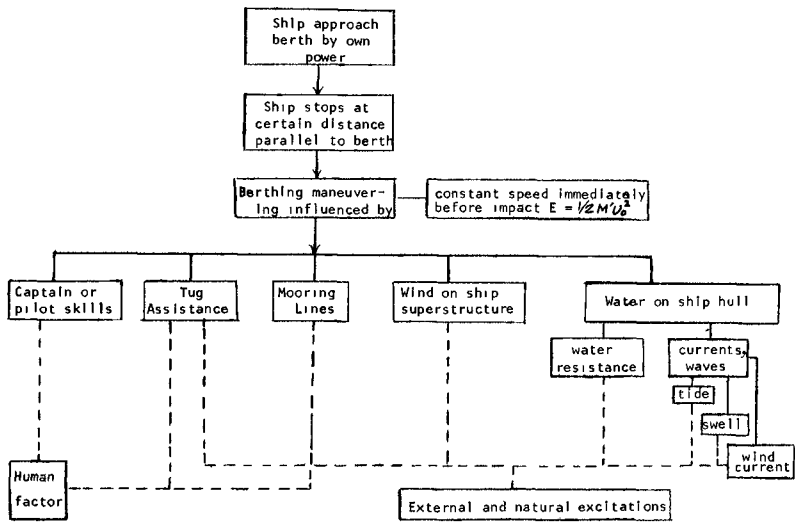
Fig 1   Definitions of fender systems from dock

A. STAGE I

Ship approach berth by own power

Ship stops at certain distance parallel to berth

Berthing maneuvering influenced by — constant speed immediately before impact $E = \frac{1}{2}M'v_0^2$

Captain or pilot skills

Tug Assistance

Mooring Lines

Wind on ship superstructure

Water on ship hull

water resistance

currents, waves

tide

swell

wind current

Human factor

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

most important

important

less important

Energy Dissipation

Determine energy absorbed by fender, ship hull and berth deformations

Fender Design

decelerate

oscillate

stop

Fig. 2   Berthing Process

(a)   time at initial contact

(b)   time after initial contact

Fig. 3   Berthing impact instants

By substituting the value given in equation (2) into (3), we obtain

$$E_{ff} = \frac{1}{2}M'U_o^2\left(\frac{k^2+a^2 \cos^2\beta}{k^2+a^2}\right) + \frac{1}{2}M'\omega_o^2 \frac{k^2a^2}{k^2+a^2} - M'U_o\omega_o \frac{ak^2 \sin\beta}{k^2+a^2} \qquad (4)$$

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_o, (c) direction of velocity of translation, β, (d)ship velocity in rotational motion, ω_o, (e) radius of gyration of berthing ship, 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)

$$E_{eff} = \frac{1}{2} M'U_o^2 \frac{k^2+a^2 \cos^2\beta}{k^2+a^2} \qquad (5)$$

When $\beta = 90°, E_{eff} = \frac{1}{2}M'U_o^2 \frac{k^2}{k^2+a^2}$ (6)

where $\frac{k^2}{k^2+a^2}$ is an eccentricity coefficient

Special Case 2. Ship Motion with Rotation Only (without translation)

$$E_{eff} = \frac{1}{2}M'\omega_o^2 \frac{k^2 a^2}{k^2 + a^2} \tag{7}$$

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

$$V_o = \omega_o a \tag{8}$$

$$E_{eff} = \frac{1}{2} M' V_o^2 \frac{k^2}{k^2 + a^2} \tag{9}$$

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

Sway $$y + (\frac{a}{M'}) \, y + a\theta + h\phi = 0 \tag{10}$$

Yaw $$\ddot{\theta} - (\frac{k_e a}{M' K^2}) \, y = 0 \tag{11}$$

Roll $$\phi + (\frac{W h_m}{M' K^2}) \, \phi - (\frac{k_e h}{I_M' K^2}) \, v = 0 \tag{12}$$

By solving the above equations with given initial conditions, one can obtain the maximum overall deformation (y_{max}) of fender system, berting structure, and of 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 θ and ϕ 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 $E_{ff} = \frac{1}{2} M' \left[U_o + \frac{Ag}{\sigma D} \frac{\text{Sinh kd} - \text{Sinh ks}}{\text{Cosh kd}} \frac{\text{Sin kB/2}}{kB/2} \right]^2$ (13)

Closed-type structure $E_{ff} = \frac{1}{2} M' \left[U_o + \frac{2Ag}{\sigma D} \frac{\text{Sinh kt} - \text{Sinh ks}}{\text{Cosh kd}} \frac{\text{Sin}^2 kB/2}{kB/2} \right]^2$ (14)

where A = wave amplitude, l = wave length, $k = \frac{2\pi}{\ell}$ wave number. d = water depth. S = wave slope, B = ship beam, D = ship draft, $\sigma = \frac{2\pi}{T}$; 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 U S , 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 bio-
deterioration 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 un-
satisfactory. 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 absorp-
tion 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 com-
pression 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
between steel plates to form a series of "sandwiches" which are mounted
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 stiff-
ness 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 con-
stant 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 con-
crete blocks suspended from a heavily constructed wharf deck Impact energy
is absorbed by moving and lifting the heavy concrete blocks High energy
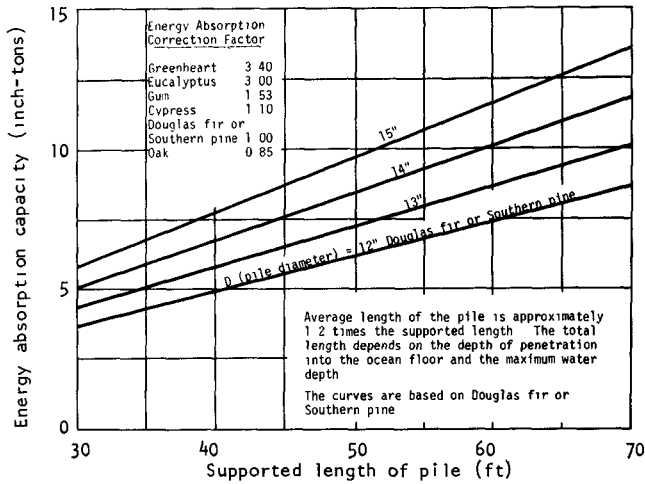
Fig. 4 Energy-absorption of timber fender piles
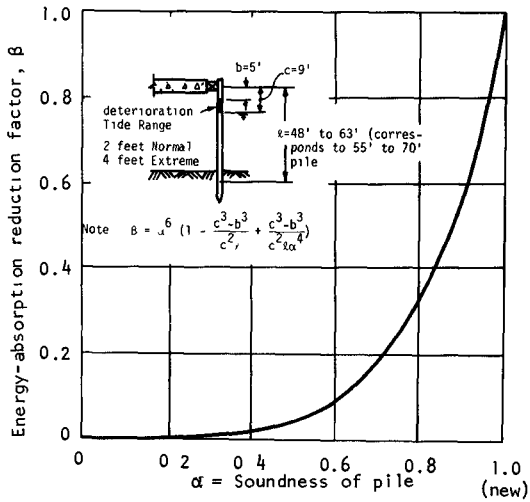
Fig. 5 Energy-absorption reduction due to bio-deterioration

| No Load | Light Load
Moored Ship | Heavy Load | Overload
Heavy Impact |
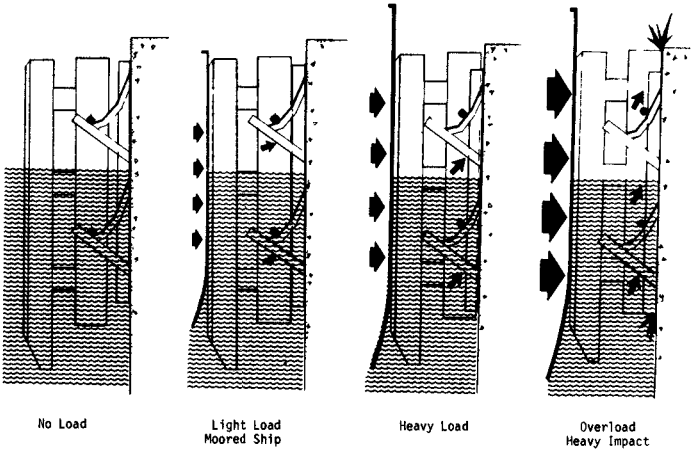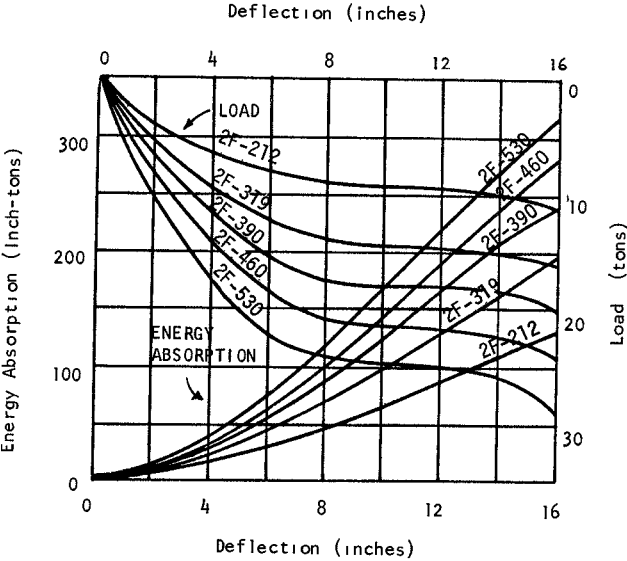
Fig. 6   Operation of modified retractable fender system

Deflection (inches)

Deflection (inches)

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.
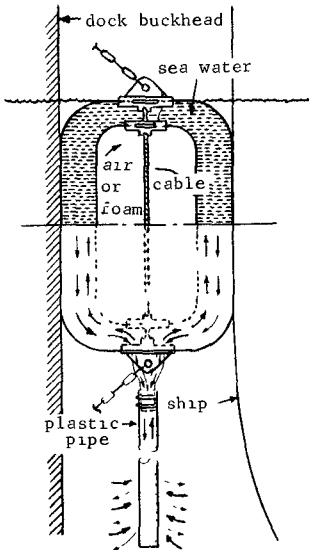
Fig 7   Load-deflection and energy-absorption characteristics
          of Lord flexible fender

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

Fig 8 A new concept of hydraulic - pneumatic fender

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

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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" finder 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 de-
formable torsion and a mechanism transforming the berthing impact into the
shock absorber
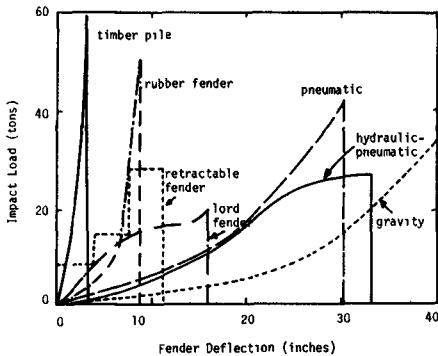
Fig 9   Load-deflection characteristics
          of various fender systems

To assist the practicing en-
gineers in the selection of the
desirable type of fender system,
Table 1 is prepared summarizing
major advantages and disadvan-
tages 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 Labora-
tory's technical reports   (a)
"A Study of Effective Fender
Systems for Navy Piers and Wharves,"
R-312, March 1965, and (b) "Re-
view of 'Report on the Effective
Fender Systems in European Countries'
by Risselada and van Lookeren
Campagne," R-376, October 1965
(Lee, 1965 a, 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, parti-
cularly cost-effectiveness characteristics.

Table 1. Comparison of Various Types of Fender Systems

Fender System	Advantages	Disadvantages
Standard Pile, timber	1. Low initial cost 2. Timber piles are abundant in U S 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)

Fender System	Advantages	Disadvantages
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 Rubber-in-compression	1. Simplicity and adaptability. 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 Rubber-in-shear	1. Capable of cushioning berthing impact from lateral, longitudinal, and vertical directions. 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 I Comparison of Various types of Fender Systems (Continued)

Fender System	Advantages	Disadvantages
Rubber Fender Systems Lord Flexible Fender	1 High energy-absorption and low terminal-load characteristics	1 Possible destruction of bond between steel plates and rubber 2 Possible fatigue problems
Rubber Fender Systems Rubber-in-torsion	1 Capable of resisting impact load from all directions	1 Possible destruction of the bond between steel casting and rubber 2 Possible fatigue problems.
Gravity-Type Fender Systems	1 Smooth resistance to impacts induced by moored ships under severe wave and swell action 2 High energy absorption and low terminal load can be achieved through long travel for locations where excessive distance between ship and dock is not a problem	1 Heavy berthing structure is required 2 Heavy equipment is required for installation and replacement 3 High initial and maintenance costs 4 Excessive distance between dock and ship caused by the gravity fender is undesirable for general cargo piers and wharves
Pneumatic Fender System	1 Suitable for both berthing and moored ships. 2. Fixed tire-wheel type is feasible for pier-corner protection.	1 Use in fixed dock-fendering is limited to bulkhead-type structures. 2 High maintenance cost
Hydraulic and Hydraulic-pneumatic Fender	1. Favorable energy-absorption characteristics for both berthing and moored ships	1 High initial and maintenance cost.

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

1/ Berthing velocity normal to dock
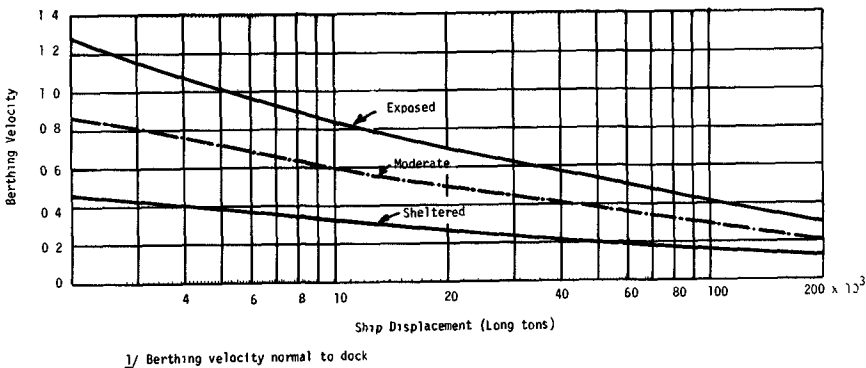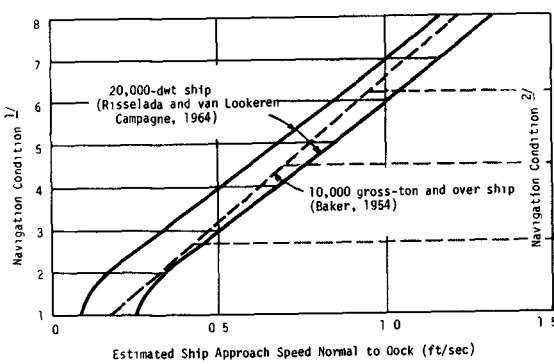
Fig. 10   Berthing velocity vs. ship displacement.

Table 2. Classification of Marine Environments and Navigation Conditions (Based on Risselada and van Lookeren Campagne, 1964)

Navigation Condition	Harbor Basin	Marine Environment — Description	Example of Harbor Tidal/Current Conditions
1	Sheltered	No or little current up to 0.31 ft/sec Tide range up to 3 ft. No strong winds	Mediterranean ports
2	Sheltered	Some current up to 0.31 ft/sec Tide range. 1 ft (normal), 10 ft (maximum). No strong winds	Baltic ports
3	Moderately sheltered	No or little current up to 0 31 ft/sec Tide range up to 3 ft Fresh gale winds up to 40 knots	Mediterranean ports
4	Moderately sheltered	Moderate current up to 0 7 ft/sec. Tide range 10 ft (normal), 20 ft (maximum) Strong gale winds up to 47 knots	Rotterdam Lisbon N W Germany
5a	Moderately sheltered	Considerable current up to 0 8 ft/sec Tide range 16 ft(normal), 27 ft(maximum) Strong gale winds up to 47 knots	Le Havre
5b	Slightly sheltered	Moderate current up to 0.7 ft/sec Tide range 10 ft (normal), 20 ft (maximum) Strong gale winds up to 47 knots	Rotterdam Lisbon N W. Germany
5c	Exposed	No or little current up to 1 0 ft/sec. Tide range 1 ft (normal), 10 ft (maximum). Strong gale winds up to 47 knots	Baltic ports
6a	Slightly sheltered	Great Current up to 1 0 ft/sec. Tide range 20 ft (normal), 33 ft (maximum) Strong gale winds up to 47 knots	British Atlantic ports
6b	Exposed	Considerable current up to 0 8 ft/sec Tide range 16 ft (normal), Strong gale winds up to 47 knots	Le Havre
7	Exposed	Great current up to 1 2 ft/sec Tide range 20 ft (normal), 33 ft (maximum) Storm winds up to 63 knots. Waves up to 3 feet.	British Atlantic ports
8	Very exposed	Great current up to 1.3 ft/sec (maximum) Tide range 20 ft (normal), 33 ft Storm winds up to 63 knots. Waves 3 ft or greater	British Atlantic ports

Estimated Ship Approach Speed Normal to Dock (ft/sec)

1/ Navigation conditions (Risselada and van Lookeren Campagne, 1964)

2/ Navigation conditions (Baker, 1954)

1 Good approach and sheltered
2 Difficult approach but sheltered
3 Moderate approach but exposed
4 Good approach but very exposed
5 Difficult approach and very exposed

Fig 11   Ship approach speeds recommended

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

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

$$M_h = C_h \, M = 2 \, (D/B) \, M \tag{15}$$

Thus, the virtual mass

$$M' = M + M_h = (1 + 2 \, D/B) \, M = C_m M \tag{16}$$

where

M_h = hydrodynamic mass M' = virtual mass or effective mass

C_h = hydrodynamic coefficient C_m = virtual mass coefficient

M = ship mass D = draft of ship

B = 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-tons 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)
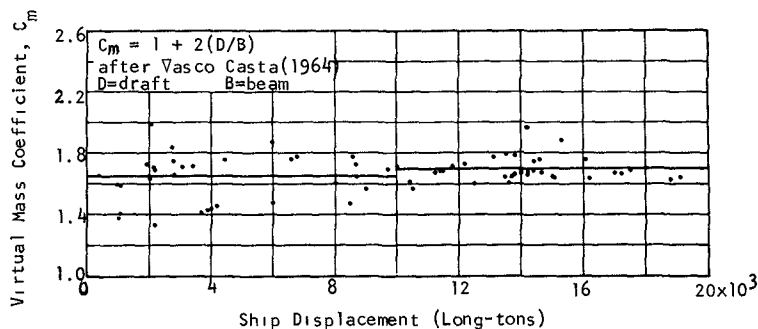
Fig 12   Virtual Mass Coefficient versus Displacement
(Thron, 1966)

5   Determine the kinetic energy (E) of berthing ship

$$E = \frac{M' V^2}{2} \qquad\qquad \text{or} \qquad\qquad E = 0\ 209\ C_m WV^2 \qquad (17)$$

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

$$E'_{eff} = CE = 0.209\ C\ C_m\ WV^2$$

$$C = C_e\ C_g\ C_d\ C_c \qquad\qquad\qquad (18)$$

where

E'_{eff} = kinetic energy to be absorbed by fender system in inch-tons
C = berthing coefficient
C_e = eccentricity coefficient

C_g = ship geometric coefficient

C_d = ship deformation coefficient

C_c = berth configuration coefficient

Eccentricity coefficient, C_e, is expressed as $\quad C_e = \dfrac{k^2}{a^2 + k^2}$

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 <u>convex</u> curvature to 1 25 for <u>concave</u> 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, 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   <u>Nomograph</u>. 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.   <u>Compare the energy-absorption capacity requirements</u> 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   <u>Select the final energy-absorption capacity of the fender system,</u> 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
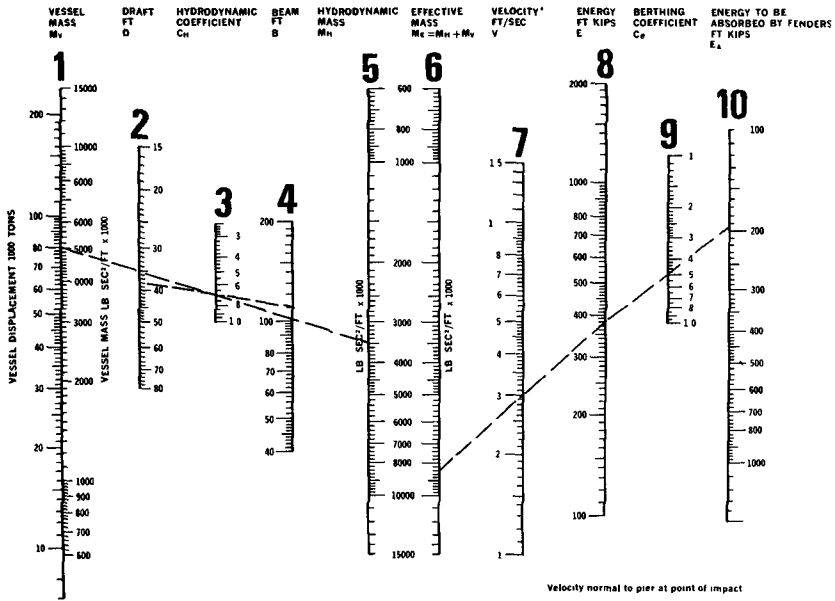
Fig. 13   Nomograph — Energy absorption requirements for marine fender systems
(Courtesy of Lord Mfg Co.)
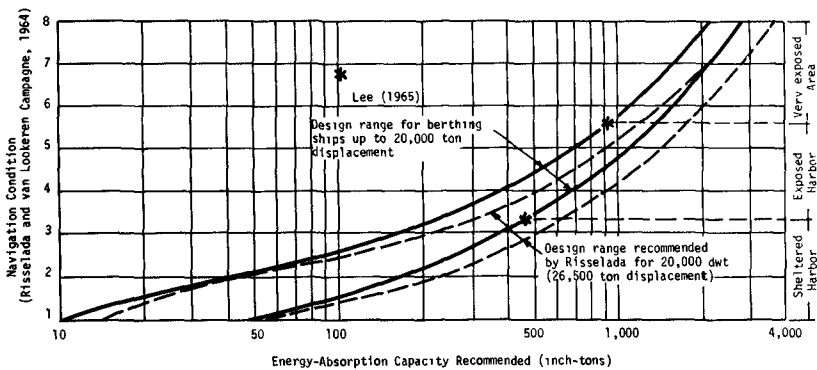
Fig. 14   Energy-absorption capacities recommended for fender design

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

ACKNOWLEDGEMENTS

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APPENDIX A

EFFECTS OF BIOLOGICAL DETERIORATION AND PHYSICAL DAMAGE ON THE
EFFECTIVENESS OF TIMBER FENDER SYSTEMS

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 hyperboli-
cally 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 approxi-
mately 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 eucalyp-
tus, 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, birth
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 construc-
tion 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, 1966 b)

    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
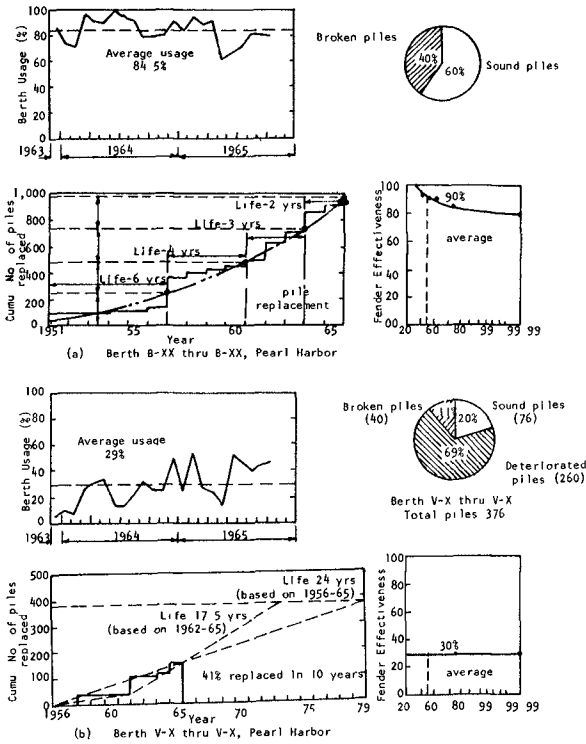
Fig 15 Cost-effectiveness of fender systems
              at Pearl Harbor