systems usually are economical on a first-cost basis and adaptable to large tide ranges. Their disadvantages include high maintenance costs and limited protection. Many timber systems are being gradually replaced by more contemporary rubber units.

Camels are floating separators that may simply consist of a log or pile tethered to the pier or quay face or may be more substantial built-up timber, concrete, or steel pontoon structures (see Section 9.1). Camels may be integral parts of fender systems but are not necessarily energy absorbers. Caution should be exercised when using camels with springing pile fenders, as they may exert a concentrated load at the piles' midspan, resulting in frequent pile breakage. Therefore, camels used in this way should be long enough to distribute berthing and mooring loads over a sufficient number of piles.

Pneumatic floating fenders and foam floating fenders may double as fendering and camels to maintain a proper vessel standoff distance. Figure 5-13 shows a row of floating

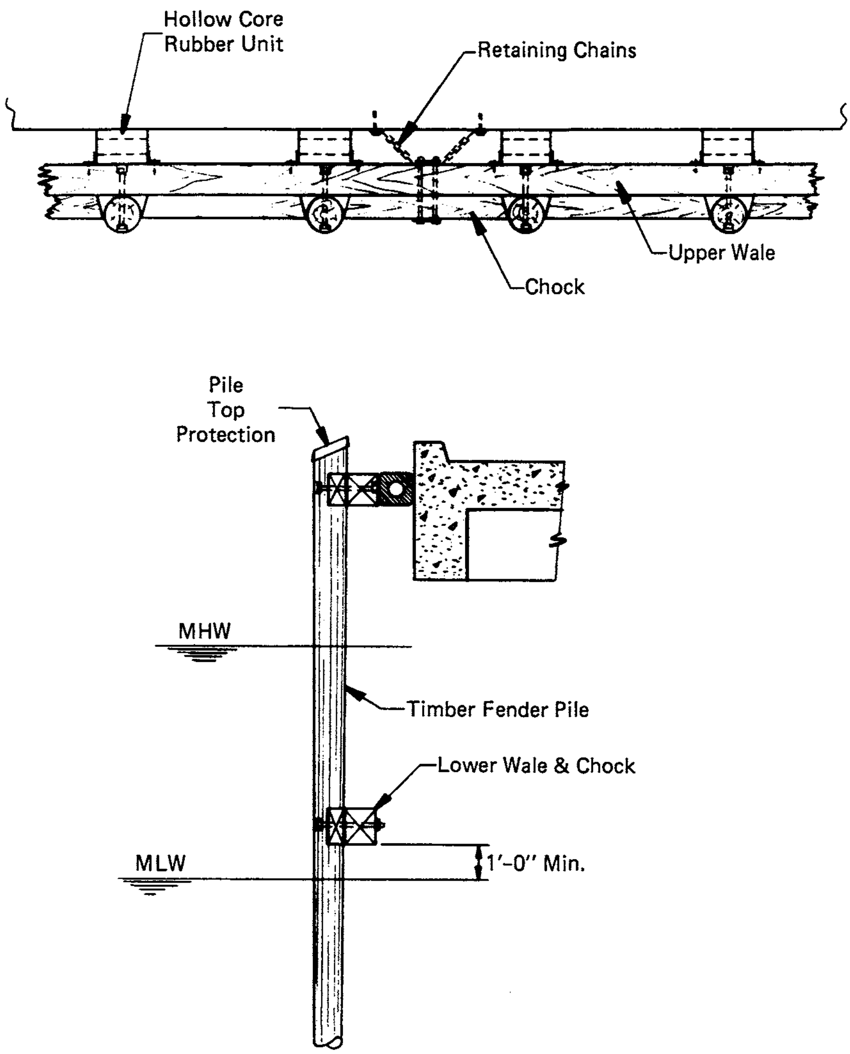

Figure 5-11. Timber fender pile system.

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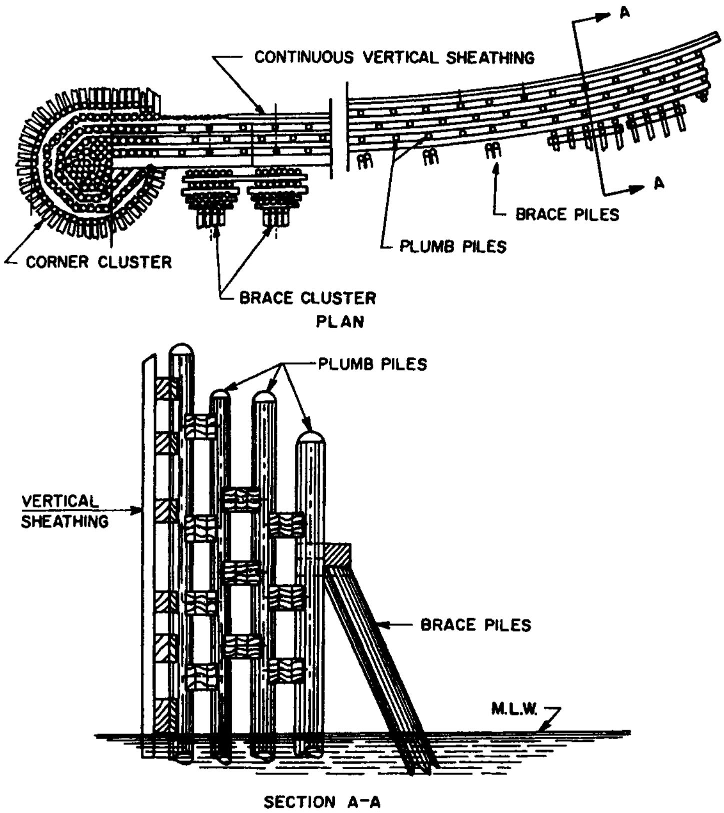

Figure 5-12. Timber fender rack for ferry slip. [From ref. (4).]

units alongside a rigid timber pile fender system. Such units also are used as separators between vessels and are available in a large range of sizes and energy absorption capacities. Pneumatic-type fenders also are available as fixed units to be mounted on the quay face.

Hanging or draped fender units consisting of hollow-core rubber sections or pneumatic or foam-filled rubber units sometimes are employed at solid-face quays.

Rotating fenders typically consist of either a pneumatic tire or a foam-filled doughnut rubber unit mounted on a vertical shaft. The tire or cylinder is free to rotate, thus reducing friction, and to absorb energy by its deformation. Such fenders are ideally suited to applications where vessels frequently are warped about them. The pneumatic tire types are primarily used at the entrances to locks and drydocks. They are generally less tolerant of vertical motions.

Considered mostly obsolete today are mechanical-type systems consisting of springs and linkages, and/or gravity systems consisting of suspended weights or buoyancy units.

Hydraulic fenders may be preset to a given reaction-force level. Bruun (43) has advocated their use at exposed locations because of their energy absorption efficiency and nonrecoiling characteristics. The fact that they do not immediately return to their original position after impact may be a problem at certain locations. Others have noted that hydraulic units are likely to require greater than average maintenance (2).

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Figure 5-13. Pneumatic-type floating fenders alongside pier. (Photo courtesy of Seaward International, Inc.)

At most major marine terminals today, however, high-energy-capacity *resilient rubber units* are employed. There are a wide variety of shapes and sizes of elastomeric units on the market today. Figure 5-14, from reference (3), illustrates some of the more common generic types. The elastomer is of either a natural rubber or a synthetic rubber, the properties of which can be varied to obtain different characteristics. Rubber units may be worked in direct (bending) compression of hollow cross-sections, bending via buckling-column action or in shear or torsion. Shear fenders are more difficult to construct and are more likely to break than other rubber-fender types.

Padron and Han have presented the results of a study of fender system problems in U.S. ports (44), based upon a study conducted for MarAd (45) that is of interest to those evaluating alternative fender types with particular regard to maintenance costs and problems. Their findings are summarized in Table 5-2, and the most prevalent types are illustrated in Fig. 5-15. Padron and Han found that timber systems generally had greater main-

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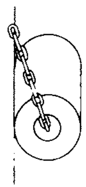
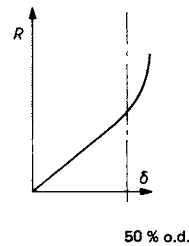
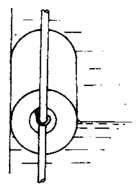
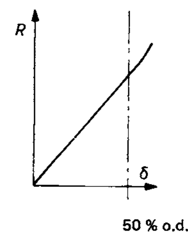
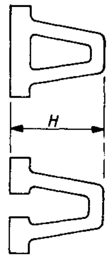
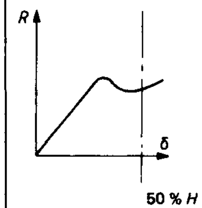
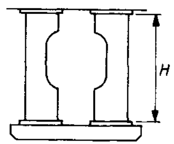
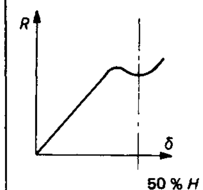
Elastomeric units: types and characteristics

Type	Shape and mounting	Approximate size range	Energy range	Reactive force range	Performance curve	Remarks
Hollow cylindrical	May be horizontal, vertical, catenary or diagonal 	mm Outside diameter of fender = 100 to 3000 Generally the inside diameter of the fender is half the outside diameter	t·m/m 0.1 to 110	t/m 4 to 210		Generally simply suspended against berthing face. Type of suspension dependent on size of fender; may be chains or rods
Cylindrical floating		Outside diameter of fender = 500 to 2500	2 to 50	20 to 90		Relative density about 0.97. Energy absorption about 75 % of hollow cylinder. Suspension by anchored cables

NOTE 1. R is the reactive force of the fender.
NOTE 2. If the chain or rod forms a substantial percentage of the bore of the cylindrical fender, the performance curve will be affected.

Figure 5-14. Elastomeric fender units: types and characteristics. [From British Standards Institution, BS 6349 (3).]

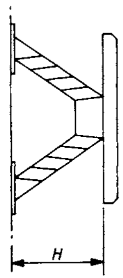
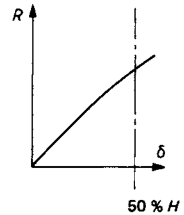
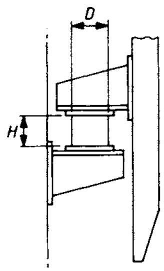
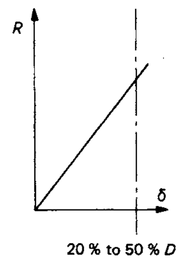
. . *(continued)*

Type	Shape and mounting	Approximate size range	Energy range	Reactive force range	Performance curve	Remarks
V-shaped	 Closed leg; Open leg	mm H = 150 to 1300	t·m/m 0.3 to 60	t/m 6 to 110		Large variety of rubber grades made with single base plate (closed leg) or double base plate (open leg); also with resin board facing to decrease surge friction. It is also possible to use multiple units with a fender frame
Buckling column		H = 400 to 2500	3 to 160	20 to 180		Large variety of rubber grades. It is used with a fender frame. Reaction R at least 30 % less than for V-shaped fenders. Fenders may need to be supported by piles

NOTE. R is the reactive force of the fender.

Figure 5-14 Continued. Elastomeric fender units: types and characteristics. [From British Standards Institution, BS 6349 (3).]

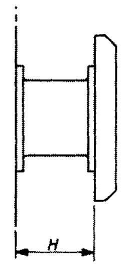
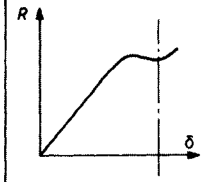
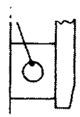
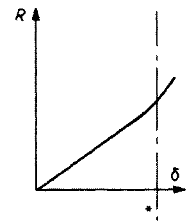
(continued)

Type	Shape and mounting	Approximate size range	Energy range	Reactive force range	Performance curve	Remarks
Shear fender multi-bonded		mm $H =$ 500 to 1650	t·m 1 to 50	t 30 to 100		May be mounted horizontally or vertically or grouped with fender frame. Will probably require facing panel to be supported
Shear fenders single unit		$D =$ 400 to 550 $H =$ 190 to 270	1 to 3	10 to 30		Can be mounted in vertical pairs

NOTE. D is the diameter of the fender.
R is the reactive force of the fender.

Figure 5-14 Continued. Elastomeric fender units: types and characteristics. [From British Standards Institution, BS 6349 (3).]

(concluded)

Type	Shape and mounting	Approximate size range	Energy range	Reactive force range	Performance curve	Remarks
Hollow cylindrical· axially loaded		mm D = 300 to 3500	t·m 0,4 to 700	t 4 to 600	 40 % to 50 % H	Large variety of rubber grades available
Rectangular square and 'D' hollow	Suspension system  or 	mm Cross-sectional dimensions vary from 150 x 125 to 305 x 305	t·m/m 1 to 4	t/m 30 to 90		*Large variation in performance in relation to deflection limits

NOTE. D is the diameter of the fender.
R is the reactive force of the fender.

Figure 5-14 Continued. Elastomeric fender units: types and characteristics. [From British Standards Institution, BS 6349 (3).]

Table 5-2. Ranking of Fender System Problems and Fender System Types by Prevalence/Severity of Fender System Problems*

Rating of severity of fender system problems as percentage of total wharf length

Description of fender system problem (1)	Timber fender systems							Rubber fender systems				Summation	Rank of fender system problem (14)
	A 34.3 (2)	B 9.1 (3)	C 4.9 (4)	D 3.3 (5)	E 5.9 (6)	F 1.2 (7)	G 14.1 (8)	H 22.9 (9)	I 2.1 (10)	J 1.7 (11)	K 0.5 (12)		
High berthing energy	5	4	5	5	5	4	5	1	1	1	1	380.9	1
Wear	4	3	5	5	3	3	3	1	1	2	2	298.5	2
Deterioration by marine organisms	4	4	4	4	4	4	2	1	1	3	1	293.6	3
Securing lines to fender system	4	4	4	1	3	3	—	—	—	—	—	217.8	4
Performance adversely affected	2	2	2	2	3	3	3	1	1	2	1	195.7	5
Snagging by vessels	1	1	1	1	3	3	3	1	3	3	3	151.0	6
Corrosion of steel components	1	1	1	1	1	1	1	2	2	3	3	129.4	7
Summation	720.3	172.9	107.8	62.7	129.8	25.2	239.7	160.3	18.9	23.8	5.5		
Rank of fender system type	1	3	6	7	5	8	2	4	10	9	11		

Note: Summations are the sum of the products of wharf length and rating for each row or column.
*From ref. (44).

tenance problems than rubber systems, chief among them being damage due to high-energy berthings, wear, and attack by marine organisms. Rubber fender units, when properly sized and installed, may have practical design lives of 15 to 20 years or more, depending upon the level of activity at the berth (39, 46). Replacement of deteriorated systems with contemporary resilient fenders can play an important role in the upgrading of existing facilities (47).

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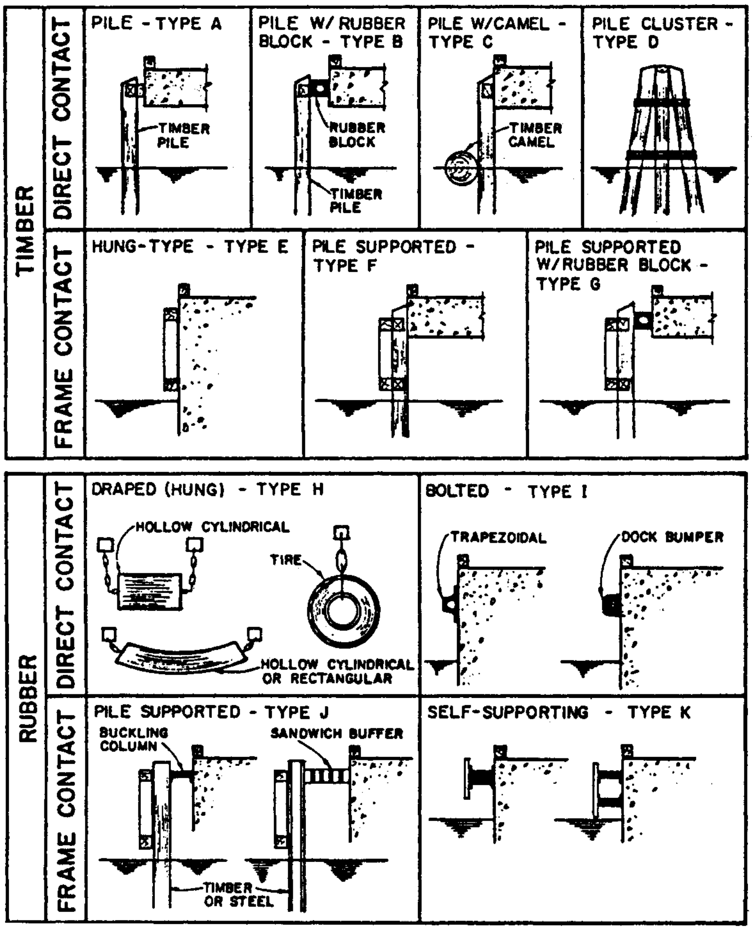

Figure 5-15. Prevalent types of timber and rubber fender systems. [From ref. (44).]

5.6 FENDER SYSTEM DESIGN

The design of marine fender systems usually begins with a determination of the fender energy absorption requirements and allowable reaction, and ascertaining if there are any standoff restrictions. If there are no standoff restrictions, there will usually be a choice of multiple fender types and sizes that can be employed. Some may prove impractical and some clearly will be too costly. If there are maximum standoff limitations, some types of fenders may be incapable of meeting the energy and reaction requirements with the restricted deflection space available. In some cases, no fender may be theoretically capable of meeting an application's specified energy and reaction limits. If so, the best approach is to reevaluate all assumptions and see if something can change.

When maximum standoff is limited, buckling-type fender elements will often be the only type capable of absorbing the necessary energy without exceeding the permitted reaction. This is because of the greater area (energy absorption) under their reaction/deflection curves.

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Other fender type selection factors are introduced in Section 5.5, and Table 5-3, from reference (3), which lists additional design considerations for specific facility types.

The need to consider a fender's performance while the vessel is moored cannot be overemphasized. This is especially true at exposed locations and for larger vessels subject to dynamic forces (48–50). The fender load/deflection properties should be compatible with the elasticity of the mooring lines at open-sea berths (49), and berthing/mooring design requirements should be integrated.

Since most modern fenders currently employ rubber energy-absorbing elements, it is important to understand that all rubber devices exhibit a characteristic called hysteresis. This might better be thought of as intermolecular friction. This characteristic is strain-rate dependent. Therefore, the performance of rubber devices, even within a linear region of a reaction/deflection curve, cannot be modeled correctly with a spring constant. Because of hysteresis, rubber devices incorporate both a deflection-based (spring) component and a deflection-rate-based (damper) component. The net result is that not only is deflection reaction increased in response to strain rate, but recoil reaction is decreased in response to the rate of recoil. Depending on the rubber compound, this difference can be as much as 50% or more.

Because at this time virtually no information is in print giving rubber fender reaction versus recoil deflection characteristics, great caution should be exercised when attempting to incorporate fender performance into mooring simulations. For further information on variables affecting rubber fender performance, see reference (51).

Some engineers recommend that the ultimate capacity of a fender unit and its supporting structure should be on the order of twice the nominal design energy level, subject to site-specific studies, which may determine that a higher or lower figure is warranted (3). However, common practice over the last 15 years in the United States and Canada when using rubber fenders has been to design fenders to meet design energy requirements without exceeding allowable reaction and without any further, explicit factor of safety. The design energy should be based on an educated guess at a design berthing velocity, which should be approximately a 98% to 99% berthing velocity.

Design berthing velocity and nominal berthing velocity will vary widely depending on berthing frequency, exposure, and known hazards. For instance, from a purely engineering standpoint, high-frequency ferries should probably have design berthing velocities that are four times nominal, whereas oil tankers will have greater margins of safety than any ferry, even with design berthing velocities that are equal to their nominal berthing velocities. This is because with the schedule sensitivity of high-frequency ferries, there will be "accidents" occurring on a regular basis. Tanker operators, on the other hand, are so aware of the risks and the owners so averse to them that they will take all necessary precautions to provide safe berthing conditions. Obviously, selecting an appropriate design berthing energy is a highly subjective exercise and one in which the inexperienced designer may want to ask for recommendations from fender manufacturers.

Any overload factors depend to some degree upon the type of fender system, its mode of failure, and the consequences of such a failure. Steel pipe pile dolphins, which absorb energy via bending deflection, often are designed to be at up to 80% of the yield stress in the steel under nominal design conditions, corresponding to a factor of safety of approximately 1.5 on the design energy at the yield of the steel (1). This illustrates a

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