- E and R vary directly with fender-element length. If two fenders are otherwise identical, a 1,500-mm-long fender has 150% the E and R of a 1,000-mm-long fender.
- Rated R is directly proportional to H for a given rubber compound and fender-element length.
- Rated E is proportional to the square of H for a given rubber compound.
- Rated E is proportional to rubber volume. Any two fenders of the same design and rubber compound have rated Es in direct proportion to their volumes of rubber, regardless of differences in element heights and/or lengths.
- Fender element cost varies (approximately) directly with rubber volume. Costs per unit volume are usually very close for fender heights within two sizes of each other, regardless of rubber compound.
- Fender efficiency (E/R, not R/E) varies directly with H. All fender elements of the same H have the same E/R. Compound and length have virtually no effect.
- Use a fender with E/R greater than or equal to the specified E divided by the specified R. No fender with a lower E/R can meet the specification. Usually, rated E/R needs to be 5% to 15% greater than the nominal specification to allow for the effects of angle berthing and bow flare.
- Contact panel area varies inversely with hull pressure.
- Contact panel cost usually varies (roughly) directly with overall panel area. Panel area is based on overall dimensions, including any bevels on the top, bottom, or sides.
- For barge or ferry service, increase ultrahigh-molecular-weight polyethylene (UHMW) thickness by 1/4 to 1/2 in. (6 to 12 mm).

Where loss of a single fender for even a few hours can have serious financial or political consequences, fenders should be designed for easy repair and/or removal/installation. A good example would be a rubber buckling-type fender with panel and weight restraint that can be removed or installed without a wrench, requiring only removal of a locking pin and lifting (or the reverse when installing).

In the vast majority of instances, fenders should be designed with the understanding that they from time to time become hooked by hull belts as vessels rise and fall because of draft and/or tidal changes. With proper maintenance, most fenders can be maintenance-free for 10 years or more. Many properly designed fenders seldom require maintenance.

Mounting and Installation

Fender installations should be as simple and rugged as possible. The use of chains or other flexible restraints, turnbuckles, and moving parts should be kept to a minimum. The ability of a pier or berthing structure to distribute and resist all berthing and mooring reaction forces must be carefully checked. Fig. 5-20 shows a representative contemporary rubber, buckling-column type fender installation fitted with a

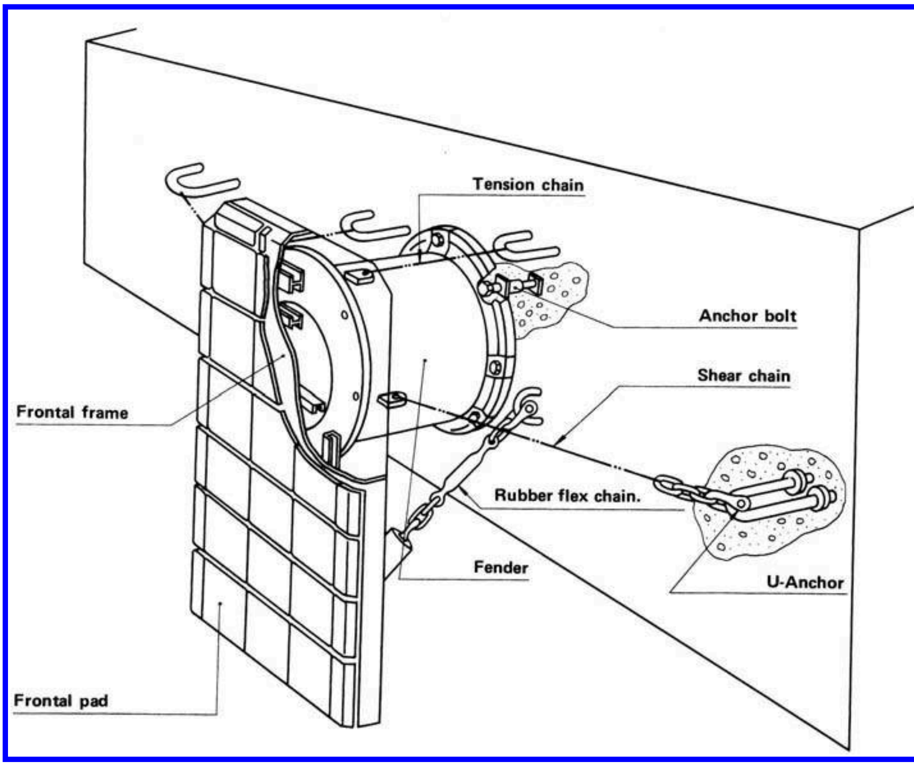

Fig. 5-20. Rubber fender installation

Source: Bridgestone Tire Co. (n.d.); reproduced with permission from Bridgestone

low-friction face panel and flexible restraints. Alternatively, the face panel may be mounted on piles where large tide ranges must be accommodated. The installation of high-energy-capacity units on piers often requires the use of raised parapets or lowered skirt beams along the pier face.

Chains are often an integral part of fender systems provided for preventing fender damage by relieving weight and checking excessive movements and for retention of floating fenders, for example. Chains can therefore be broadly categorized as follows:

- Weight or suspension chains,
- Tension chains,
- Shear chains, and
- Retention chains.

Guidance for designing chains and their arrangements can usually be found in a manufacturer's product literature. Allowance for corrosion and wear and means for ready replacement of damaged chains are important considerations.

Rubber fenders generally are capable of very large shear deflections without damage, and under the design loads there is likely to be no damage caused by the deflections. Rubber dock fenders that are self-supporting and have a frontal load-distribution panel often use suspension, or weight, restraints to help support panel weight, and sometimes also use shear and tension restraints for improved performance. The use of weight restraints is not so much to limit creep, which it does, but to improve fender useful life. When weight restraints are used, they are best attached to the panel at or slightly above the vertical center of the rubber elements' reaction. Since most flexible restraints are incapable of absorbing significant energy, they are not useful to restrain "hooking." Shear restraints are useful in applications in which vessels may use the fender for warping, and they may also be useful in oil tanker unloading berths. Vertical shear restraints are often useful in oil tanker unloading berths. Tension restraints often are required when low-freeboard vessels contact fender panels below the center of the fender elements' reaction.

Rubbing Forces

Because the velocity of impact seldom acts exactly normal to the fender face, there usually is some horizontal component of velocity acting parallel to the face of the structure. If shear friction is a concern, either because of the distortion it induces in the fender or because of the wear it causes in fender contact surfaces, fender contact surfaces should be of ultrahigh-molecular-weight polyethylene (UHMW).

The actual dry coefficient of friction of UHMW against steel is less than 0.2. However, it is not very hard, and very high mooring or storm forces can cause imprinting of hull irregularities into the surface of the material, raising the effective coefficient of friction. For most applications, the use of 0.3 as a design coefficient of friction is a conservative value. For unusual, high-pressure applications, contact a fender manufacturer. There is a wide range of reported values of the coefficient of friction against a steel hull, ranging from 0.3 to 1.0 for timber (0.4 to 0.6 is more typical), 0.15 to 0.75 for steel (0.25 is more typical), 0.5 to 1.0 or more for rubber, and 0.08 to 0.2 for UHMW. The actual value also depends upon whether the surfaces are wet or dry, covered with ice or oil, rough or smooth, and the condition of the vessel's hull.

Maximum rubbing forces, both vertical and horizontal, usually are associated with mooring forces rather than berthing forces, although it is usual for designers to apply an assumed value of μ times the design berthing reaction force. Vertical forces, however, are more likely to occur while the vessel is moored than during berthing. DOD (2005) suggests designing for a longitudinal force of 0.5 times the maximum berthing load and for a vertical force of 0.3 times the maximum berthing load. A value of 0.3 for both vertical and horizontal shear loads seems reasonable for most design applications. The primary application that clearly exceeds these values from time to time is oil tanker unloading berths, and this exceedance occurs entirely because, at many terminals, ships' crews can be negligent in tending lines. As the tankers are unloaded, they may rise more than 20 ft. If lines are not carefully tended, this results in the vessels being pulled tightly against the fenders. Strong upward vertical shear restraints are not always successful in preventing damage under these conditions. It is recommended that the vertical and longitudinal rubbing forces associated with the fender reaction forces under the maximum design mooring conditions also be checked and compared with the berthing conditions.

Allowable Hull Pressures and Fender Face Dimensions

Vessel parameters affecting fender layout and design include hull strength and allowable bearing pressures and hull geometry, especially hull curvature and length of parallel midbody. For smaller vessels, the local hull strength is not usually a problem because of the closer frame spacing, greater curvature, and inherently greater stiffness, compared to larger vessels. For larger vessels with large areas of vertical and parallel sides, the shell plating and stiffeners, which are designed for local hydrostatic pressures, are vulnerable to local point loads. The allowable hull pressure for a given vessel then depends not only upon the fender face contact area, but also, importantly, on its placement in relation to the ship's shell plating and internal framing (see Section 2.3).

Svendsen and Jensen (1970) provide a general solution in graphical form for tankers and bulk carriers based on the plastic moment capacity in bending of longitudinal and transverse stiffeners and frames for mild ship-hull steel. The ratio between the fender panel width and the vessel transverse frame spacing should not be less than 0.5 to 0.65, and the ratio between the fender panel height and the side longitudinal spacing not less than about 2. Ideally, the allowable pressure should be obtained from the vessel's owner/operator and its naval architect. In lieu of specific vessel information, PIANC (2002) provides some general guidance summarized in part as follows:

- LNG/LPG and contemporary bulk carriers: <4,200 lb/ft^2
- Tankers: < 60,000 DWT: <6,200 lb/ft^2
- Tankers: Very large crude carriers (VLCCs): 3,000 to 4,200 lb/ft^2
- General cargo >20,000 DWT: < 8,400 lb/ft^2
- Containerships: First and second generation (<1,000 TEU): <8,400 lb/ft^2
- Containerships: Panamax (<3,000 TEU): <6,200 lb/ft^2
- Containerships: Super post-Panamax (>8,000 TEU): <4,200 lb/ft^2

The above tabulation has been abbreviated from the PIANC table, and values have been converted from SI and rounded to U.S. customary units. Values from PIANC (2002) go as high as 14,600 lb/ft^2 for smaller general cargo vessels. Thus, the above values fall in the range of <30 $lb/in.^2$ (4,320 lb/ft^2) to approximately 100 $lb/in.^2$ (14,400 lb/ft^2) maximum. Note that many vessel types, such as Ro/Ro and ferries, are typically "belted" with steel strakes projecting typically from 8 to 16 in.

and of similar width girdling the vessel at the main deck level and sometimes at upper decks as well. Barges and some tankers, as well as tugs and workboats, often have belting of half-round shape that produces high local contact pressures. Although the belting protects the vessel, it produces high localized loads and wear on fender face materials that must be considered in fender system design. In addition, belting may become caught on the tops or bottoms of fender face panels with changing water levels and vessel drafts so that careful attention to vessel positions and face panel design is required.

Caution should be applied in dealing with lightly constructed vessels, such as certain contemporary naval warships; NFESC (1997) gives limiting hull-contact pressures for uniform contact over an entire shell plating panel area ranging from as low as 8 lb/in.^2 up to 87 lb/in.^2; the majority of U.S. Navy vessel types are more within the range of 15 to 20 lb/in.^2 (2,160 to 2,880 lb/ft^2) for a wide range of vessel types. The NFESC technical report (1997) also gives limiting pressures and total forces based upon the fender load distribution area in relation to the ship's framing. Where hull pressures may be critical, the naval architect or vessel owners should be consulted for specific requirements.

Fender Spacing and Layout

The vessel's geometry affects fender spacing in particular, as well as the location and number of fenders contacted. Fender spacing additionally depends upon the type of fender system and structural support, the range of vessel sizes to be accommodated, and the type and arrangement of berth and mooring loads. Typical berth arrangements are discussed in Chapters 3 and 6. A tanker often is moored against two discrete dolphins, spaced on the order of 25% to 50% of the vessel's LOA apart. The fender spacing should allow for the smallest design vessel to safely lie alongside at any location. Spacing ranging from 8% to 15% BSI (1994) of the vessel's LOA have been proposed. The distance between centers of fender units often is referred to as the *pitch*. Specific recommendations have been made for Ro/Ro and ferry-type vessels (PIANC 2002, BSI 2014). Fig. 5-21 illustrates typical fender spacing for various berth types.

As a guide to establishing distance between fenders on a continuous wharf, the formula below gives an indication of the approximate, safe maximum fender pitch, P, for the smallest ship's bow radius (r):

$$\mathrm{P} = 2\sqrt{r^2 - [r - h - C]^2} \tag{5-19}$$

where

r = radius of hull curvature at level and point of contact;

h = overall fender standoff at rated deflection, measured on the fender centerline; and

C = desired clearance between vessel at point of closest approach and dock fascia (should be at least 10% of undeflected fender standoff).

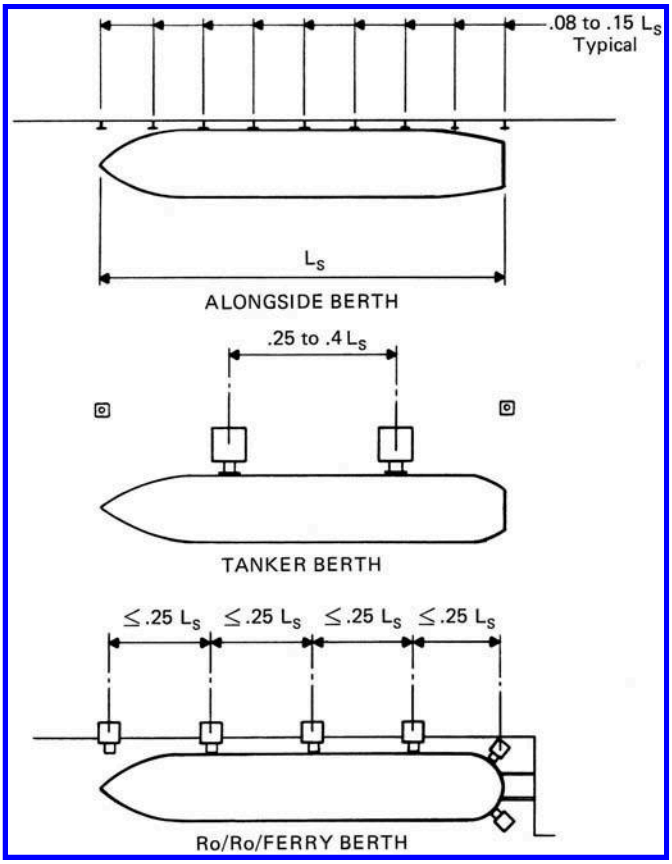

Fig. 5-21. Fender spacing for typical berth arrangements

Source: Compiled from data from BSI (1994)

The pitch produced by this formula is that which will not permit the vessel with the hull radius used for the calculation to approach any closer to the dock fascia, at a point halfway between adjacent fenders, than the clearance value inserted in the formula. All vessels with hull radii greater than the value used in the calculation have even greater clearances at full fender deflection. Technically, a vessel alongside only requires two points of contact while in berth, although three or more are recommended, which means that the absolute maximum spacing is controlled by the length of the vessel's parallel sides. However, when berthing alongside a pier, any fender pitch greater than that calculated above requires that care be taken to ensure that berthing vessels align themselves correctly with the fenders before attempting to berth against them. In general, the ratio of a vessel's parallel midbody length to its overall length is on the order of 35% to 55% of its LOA, usually larger for longer vessels. This ratio often determines the point of first

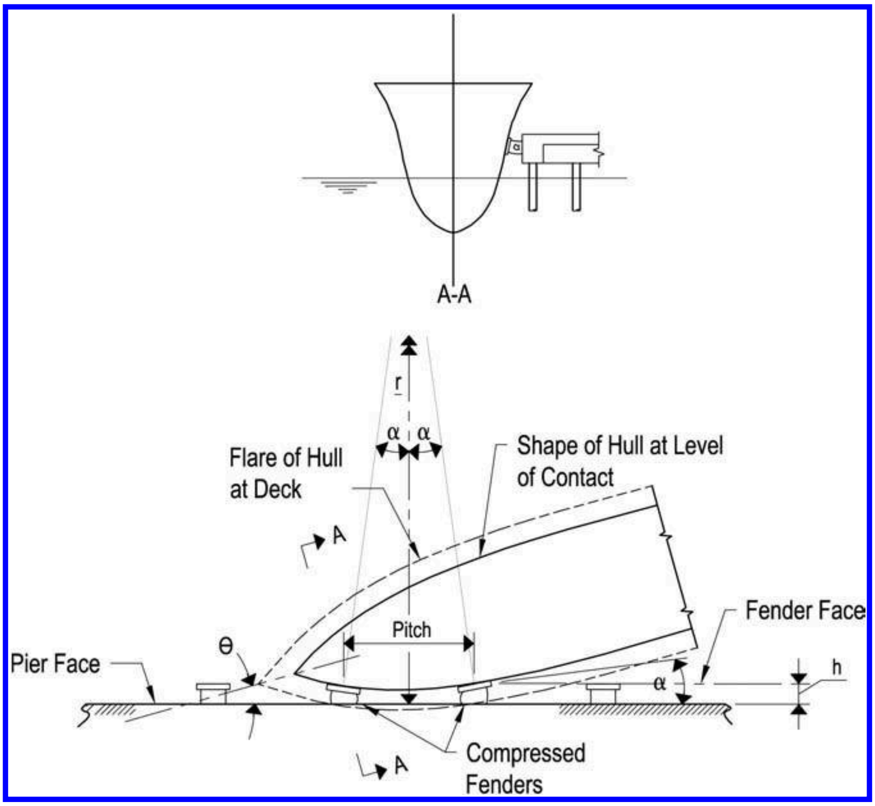

Fig. 5-22. Effect of hull shape on fender spacing

contact with the vessel's hull, which is usually at the end of the parallel midbody, and also the length of vessel available to contact fenders under moored conditions.

The effect of the hull's curvature near the bow or stern on fender spacing is illustrated in Fig. 5-22. Vertical curvature of the hull, hull flare, and overhangs and/or projections, such as bulbous bows, also must be considered in fender system layout. As discussed previously, greater standoffs can often lead to more economical fender designs. However, in the case of containership and dry bulk berths, the maximum undeflected standoff must not exceed the maximum permitted by the berth's cranes or loading/unloading equipment. The minimum standoff at 120% of rated energy, or a fully compressed fender, should not permit contact between the berthing vessel superstructure and wharfside equipment, or between the bottom of the hull and battered piles or the dredged slope at the bottom of the berth. The standoff distance usually ranges from 3 to 6 ft for most seagoing terminal facilities. At offshore installations, this distance may be closer to 10 ft or more. Note that for the two-fender contact shown in Fig. 5-22, the berthing energy is shared by two fenders, but given the fact that buckling-type fenders reach their maximum reaction force at

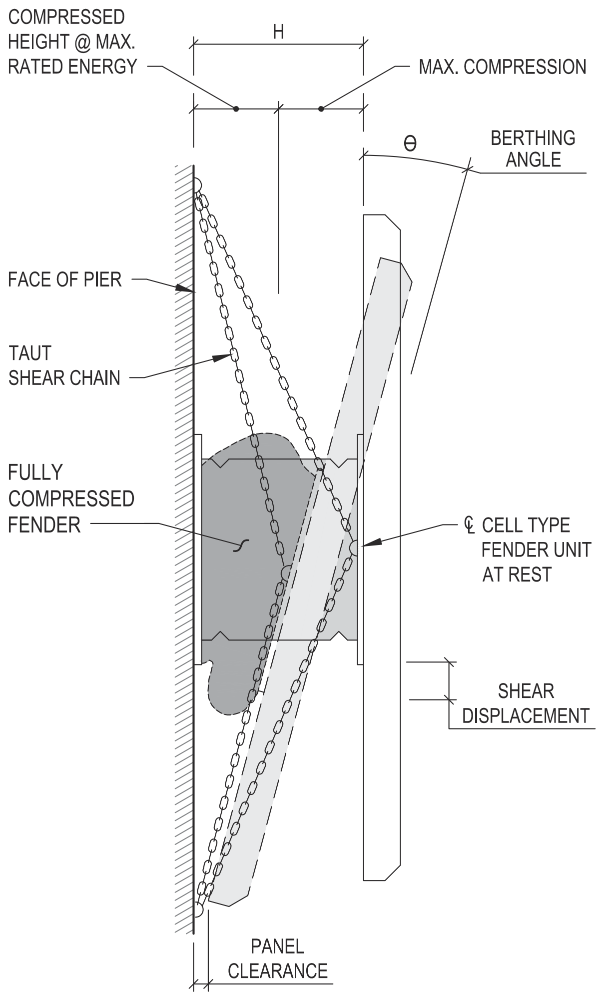

Fig. 5-23. Deflected geometry of fender face panel under combined shear and compression

about 30% deflection, they may exert greater total force on the pier or wharf than a single fully buckled fender for the same berthing energy. For multiple fender contacts, the energy is shared among the fenders, but they are not necessarily shared equally. Such would be the case for a three-fender contact, where the central fender would have a greater deflection than the adjacent fenders. The designer must therefore consider the load deflection characteristics as well as the vessel geometry to determine the total force and load distribution along the pier structure. For angular impacts, the fully compressed fender also deflects horizontally until checked by the shear chains, and the face panel assumes a new rotated position, as illustrated in Fig. 5-23, which also needs to be checked in the design process.

5.7 Fender Materials and Specifications

Hardware

Fender system hardware includes shackles, chain hardware, bolts, and connection hardware, as well as anchor bolts and pad eyes. All materials for fender installations should be specified to meet minimum strength and durability requirements, as described in Section 3.5. All metal hardware items should in general be galvanized, per the requirements of either ASTM A153 or B695 or should be of AISI 316 stainless steel. Some fender manufacturers also offer protective coatings, which may require recoating on a more frequent basis than would a touch-up of galvanizing. Anchor bolts are normally called out under ASTM F-1554-GR 105.

Rubber

Fender rubber compounds may be of natural rubber (NR) or of synthetic rubber elastomers, such as styrene butadiene rubber (SBR), butyl rubber, neoprene, ethylene propylene diene monomer (EPDM), and polyurethane. Rubber properties can be varied widely to obtain the desired stiffness and resistance to aging and atmospheric ozone. The final rubber compound is a blend of raw rubber, a reinforcing filler called carbon black, and other chemicals that improve its physical properties. As previously discussed, an important property of elastomeric materials is their hysteresis. Rubbers with a greater hysteresis exhibit less recoil or tendency to bounce the vessel off. Rubber exhibits a unique rheological response under stress in that its reaction force and energy absorption both increase with the rate of load application or strain rate. Rubber's elastic properties also vary significantly with temperature, generally becoming stiffer at lower temperatures. Therefore, a velocity factor (VF) and temperature factor (TF) correction needs to be applied to the rated performance data (RPD) as determined by testing and described in the following section. These factors are sensitive to the polymer composition of the rubber compound, which can be widely varied to produce a range of fender properties (Kumar 2014). The compound modulus (rubber stiffness) is a determining factor in fender performance and is greatly affected by carbon black dispersion. Rubber properties can be determined by thermogravimetric analysis testing (Trelleborg n.d.).

Specifications for rubber fenders should include the required energy, reaction, and sufficient definition of the rubber compound to be ensured of satisfactory life expectancy under most normal conditions (more than 15 years). The rubber compound should be specified as in compliance with the following line callout per ASTM D2000 (2001):

$$3BAx20\ A14,C12,F17$$

where x may be either 4, 5, 6, or 7, as necessary to provide the specified performance. If vessels are berthing at temperatures below approximately 14°F (−10°C), the F17 callout should be changed to F19.

Most of the tests stipulated by the above line callout have no specific, required results, and some also cover various alternative test variations and lengths. Furthermore, in rubber testing, heat is used to increase the severity of a test. Specifying a test without also specifying a test temperature and a duration, in many cases, makes the specification worthless. The recommended line callout specifies durometer hardness, elongations, ultimate strengths, ozone concentration, test temperatures, and durations and sets the minimum acceptable values for each tested parameter. Other properties are often specified, but the value of doing so is somewhat questionable because it is not clear that any other properties have a well-established relationship to fender life. ASTM D2000 (2001) defines the parameters that directly affect longevity; it is a shorthand method to list all the necessary information in a succinct but complete manner. The much more impressive looking listing of all the separate tests, if all the necessary information were presented in the correct manner, would take more than a page. ASTM D2000 references 19 separate ASTM test standards, including multiple variations of many of them, and provides a code for stipulating 24 different test temperatures and the recommended minimum test results. Furthermore, it only recommends tests and results in certain compatible combinations, depending on rubber type and intended use. Certified compliance with the above ASTM D2000 line callout is all that is required to get satisfactory life out of a rubber fender in almost all applications. PIANC (2002) also specifies rubber physical properties for resistance to heat aging and ozone in particular, and it in turn references appropriate ASTM, ISO, and JIS test methods.

Performance Requirements and Testing

Performance testing is conducted to determine rated performance data (RPD) (i.e, rated energy capacity at given deflection and associated reaction force). Performance testing is carried out under ASTM F2192 (2002a) or PIANC (2002) requirements, which requires type approval and verification testing. Test results include the effects of rate of load application, velocity factor (VF), effect of temperature (TF), effect of angular compression (0° to 20°) and durability with a minimum of 3,000 cycles to rated deflection without failure. Pass/fail criteria allow a ±10% RPD performance tolerance for most molded shapes but up to ±20% for extruded shapes, and other tolerances may apply for other fender types. These tolerances apply only to the RPD and should be considered in final fender selection or pier design because a given fender unit could have 10% less energy at a 10% higher reaction force.

Fender Panels and Facing Materials

Fender face panels are normally of a mild carbon or low-alloy structural steel that has a minimum thickness of around 1/2 in. where it is exposed on both sides and around 3/8 in. where it is enclosed or fully protected on one side. Panels must be sized for the allowable hull pressure and must be able to support the fender reaction force with an appropriate factor of safety. Panel face edges should be beveled to reduce that chance