High quality concrete piles are very durable and are essentially permanent where they are entirely embedded in soil. Special types of cement are available to resist the attack of ground water sulfates where they are found to occur. The portion of the pile above the mudline is subject to deterioration by abrasion, freeze-thaw, and cover spalling. These topics and the proper methods of protection are addressed by Hubbell and Kulhawy (1979a).

Specifications for conventional and prestressed precast piles are available from the Portland Cement Association.

Composite Piles

Piles that consist of one type of material for the lower portion and another type of material for the upper part are considered composite piles. The most common type that has been used is an untreated timber pile supporting a cast-in-place concrete upper (AAPA, 1964). The untreated timber is terminated below the permanent water table where the oxygen content is minimal and decay processes are therefore very slow. The compressive strength of the timber pole limits the load that can be supported by a wood/concrete composite pile such that it must be considered a low capacity foundation.

Where high load capacities are required, composites of steel and concrete may be used. A concrete filled steel pipe lower section with a concrete top can be driven to high resistance to develop high load carrying capacity in friction. Steel H-piles are used as the lower section to obtain better penetration when end bearing is expected.

Another variation that is not a true composite pile is when a timber or steel pile is encased in concrete to protect the top portion from
deterioration and damage. In this case, the concrete shell is intended to be sacrificial rather than a load carrying element.

The most critical part of composite pile design is the joint between the upper and lower sections. This joint must be both watertight and capable of withstanding tensile and bending stresses. It should also be fast and economical to produce in the field so that pile driving progress is not interrupted. Peck, Hanson, and Thornburn (1974) state however that "the cost and difficulty of forming a suitable joint have led to the virtual abandonment of this type of construction in the United States and Canada."

6.3 SELECTION OF PILE TYPE

As the previous sections indicate, the various types of piles are best suited for different applications. Several factors should be considered when selecting pile material including availability, durability, strength, and estimated costs. Appearance is also a conceivable criterion for material selection but will not be addressed here because of its subjective nature.

While timber, steel, and concrete products are all readily available throughout most of the United States, they must be transported to the construction site. Availability is a factor then, not because the materials are scarce, but instead because of shipment and handling problems. Timber piles are light, strong in bending, and usually in lengths of less than 60 ft. (18 m). They can be easily shipped by land carriers with little concern for damage and at relatively low cost (AAPA, 1964). Steel is much heavier per foot of pile and is much more expensive to ship. Heavy equipment is required to handle
steel piles, but their excellent strength characteristics prevent damage. While short lengths may be shipped by land carrier, with splicing performed on the construction site, it is preferable to use full length piles. Special heavy equipment is also required to ship and handle precast concrete piles. Their weight and length makes them costly to ship unless they can be transported by barge. Multiple pickup points or strong-backs are usually used when handling concrete piles in an effort to reduce the bending stresses incurred that may cause tensile cracking. Once in place, these cracks could act as a pathway for water to reach the reinforcing steel. Prestressing minimizes this problem, but durability may still be adversely affected.

Durability must be measured in terms of the intended design life of the structure. Although the deck superstructure of a fixed dock, pier, or wharf is relatively easy to repair, its pile foundation is both difficult and expensive to replace. Material deterioration depends on site specific conditions such as the level of the permanent water table, the presence of insects and borers, groundwater chemistry, and scour related abrasion. Piles should be selected carefully with respect to the environment they will be placed in and the service life expected. Some manner of preservative treatment is usually required for piles to achieve a reasonable design life. Hubbell and Kulhawy (1979a) discuss material deterioration and protective methods for timber, steel, and concrete in the marine environment.

Foundation pile capacity is more often limited by the surrounding soil conditions than by the pile axial compressive strength. Material strength is important, however, during handling and driving operations
to avoid structural damage to the pile. Sizeable bending stresses are induced by the pile weight in beam-like loading as it is moved from transportation to storage to the pile driving rig. Both timber and steel have excellent tensile strengths (per unit weight). Concrete, however, has small tensile strength and must be reinforced with steel bars or mesh. This reinforcement is often a major cost item but may be reduced by extra care in handling or by prestressing.

The final and often controlling factor in the selection of pile type is cost. To be consistent, costs for each material must be compared over the anticipated structure design life. Included must be installation and maintenance costs with installation covering such areas as pile purchase, preservative treatment, transport, handling, splicing, driving, and cut-off to the finished elevation. While timber piles may have the lowest cost after installation, other materials could be favored because of environmental conditions that cause excessive maintenance costs.

6.4 DESIGN AND INSTALLATION OF PILE FOUNDATIONS

The capacity of a pile foundation depends on many factors such as the properties of the soil mass, the dimensions and material properties of the pile, the method of installation, and the loading conditions imposed. These topics are covered in detail by Cheung and Kulhawy (1981) and will not be presented here.

6.5 DECKING AND FRAMING DESIGN CONSIDERATIONS

Subsequent to the construction of the pile foundations for a fixed dock, pier, or wharf, the deck superstructure must be erected. The piles are first trimmed to the proper elevation, followed by the installation
of the bracing and pile caps to finish each pile bent. Next, the stringers or beams correlating each bent are installed and the deck is placed to complete the structure. The following discussion addresses the design considerations of each of the components mentioned above.

A well designed fixed dock, pier, or wharf must satisfy several seemingly non-essential criteria. Poor appearance, smell, or "feel" may discourage potential users of an otherwise adequate facility. The latter of these is probably the most difficult to quantify. In fact, Chamberlain (1979) has said that "one of the worst faults in marina structure, whether fixed or floating, is a lack of rigidity, or at least a sense of rigidity." This "sense of rigidity" may be achieved in one of two ways. Gross overdesign of all the structural members and connections will result in a solid, stable structure at unnecessary expense. This approach may be justifiable for very small facilities where the savings in design fees compensate for the added material costs, or where the design loads cannot be properly quantified. A more reasonable approach, certainly for larger projects, is to consult a competent structural engineer familiar with marina design. After an analysis of structural geometry and design loads, each structural member and connection may be designed for the loads it must carry, achieving structural integrity at lower overall cost.

It is not within the scope of this report to present the structural design philosophy and procedures for each of the components to be addressed. Structural design criteria for fixed timber docks and piers are presented by Chaney (1961). Dunham and Finn (1974) note that the design criteria for steel and concrete fixed-level berthing systems
are similar to timber construction except for the connection details and the magnitude of the dead load.

Two additional aspects of structural engineering bear mentioning at this point. While it is the designers duty to account properly for the anticipated loading conditions, it is the responsibility of the marina owner or manager to see that the design loads are not exceeded. The failure of a structure that has been improperly used (overloaded) will be identical to one that is structurally inadequate to begin with.

Secondly, the ease with which maintenance can be performed is largely a function of the design (Tobiasson, 1979). With regard to maintenance, a design which minimizes the potential for rot, corrosion of fastenings, and deterioration of main members is advantageous. For timber structures, holes should be predrilled and all cuts should be made before pressure treatment. Where this is not possible, and the timber must be bored or cut during construction, all open surfaces should be coated with preservative. Holes, joints and splices below the water line should be avoided. Timber pile tops must be waterproofed immediately after cut-off. Chamberlain (1977) notes that treated wood may not meet treatment specifications, and recommends that a clause requiring an independent assay of the wood be included in a specification for wood construction. The most common problem in concrete construction according to Buslov (1979) is "corrosion deterioration". This phenomenon occurs as moisture reaches the reinforcement steel and it starts to rust. It is usually most intense on lower horizontal surfaces and may be because of poor quality concrete, inadequate cover over the reinforcement, or a combination of the two. Corrosion deterioration is much
less a problem in precast elements because quality control is usually better. Finally, Tobiasson (1979) states that prompt repair of damaged structural components aids in reducing maintenance costs since local damage often leads to accelerated deterioration elsewhere.

**Bracing**

The purpose of bracing pile supported structures is to resist lateral loads, and to stiffen the structure to reduce side and end sway. Excessive sway is equivalent to lack of rigidity which is the primary cause for a dock or pier to "feel" unsafe. Bracing consists of batter piles, x-bracing, or knee braces as illustrated in Figure 6.14. Batter piles are driven at an angle to provide a horizontal load resisting component either in tension or compression. X and knee braces effectively reduce the free length of the pile above the mudline that is available for bending, thus stiffening the system and reducing lateral deflections. X-braces usually consist of steel tie rods or wood members. The tie rods are typically 5/8 to 3/4 in. diameter (16 to 19 mm) and are fitted through drilled holes that have been flooded with preservative (AWPI, 1975b). Note that they are only effective in tension since they are slender members. Wood x-bracing is constructed by bolting treated wood planks, typically 2 x 6 in. (51 x 152 mm) or 2 x 8 in. (51 x 203 mm) lumber, to the front and back face of a pile bent. Knee braces are similar but do not extend the full width of the bent.

Batter piles are the most effective means of reducing horizontal movement under lateral load. They are also more expensive than x or knee bracing and are difficult to replace if damaged. Chaney (1961) recommends that the batter pile be framed into the bearing piles as
Figure 6.14 Types of Fixed Pier Bracing

A. Batter Pile Brace
B. X-Brace
C. Knee Brace
near the low water line as practical to minimize decay. In the event that decay of the upper portion of a bearing pile requires that it be spliced, a low batter pile connection will retain its full bracing strength.

Of the three bracing systems mentioned, knee braces are the least effective means of controlling horizontal deformation, but are substantially better than no bracing at all. Both X and knee braces are easily installed by hand labor and may be repaired or replaced easily while the structure is in service. To retain its integrity, the connections of these braces must allow no slack so bolts alone are not adequate. Most references suggest a single-curve spike grid but that will be addressed in a subsequent section on connections. Care must be taken in using X or knee braces in cold regions where ice drift will loosen connections and knock the braces loose from the bearing piles (AWPI, 1971).

**Pile Caps**

The pile cap serves to distribute the loads from the stringers above among the piles of one bent. Two general configurations have been used, including a single member resting directly on the pile butts, and separate members attached to the sides of the piles (Figure 6.15). The second type is known as a "split-cap" and is favored for its ease of construction and because the piles may then extend up through the deck to support handrails, hose bibbs, fire extinguishers, electrical outlets, lights, and mooring hardware.

While timber, steel, and concrete are all used for pile caps, timber is again the most common. Chaney (1961) suggests that timber piles
Figure 6.15: Pile Cap Types (After Quinm, 1972, p. 277)
should be "dapped" or relieved about 1 in. (25 mm) when using split caps so that part of the load is taken in bearing and smooth surfaces are available for attachment. Timber cap size has traditionally been based on local experience with typical sizes of 12 x 12 in. (300 x 300 mm) for a single member or two 6 x 12 in. (150 x 300 mm) for a split cap (Tobiasson, 1979). In many cases, however, these members are grossly overdesigned, and economy may be achieved with the use of smaller members specified by a structural engineer after analysis of the structural geometry and design loads. Member sizes for concrete and steel pile caps are determined similarly.

It is usually difficult to drive piles to precise positions. As such, it may not be practical to use precast concrete pile caps since the connections would have to be preformed. Cast-in-place concrete pile caps, however, easily accommodate small pile deviations and still form excellent connections. Some of these connections are illustrated in Figure 6.16 for various pile types. Buslov (1979) cautions that severe spalling of cast-in-place pile caps has been observed at expansion joints, recesses for nuts and bolts, and lower surfaces which are damaged by main bar reinforcing corrosion.

Stringers

The stringers of a fixed dock, pier, or wharf lie between each pile bent and support the decking (See Figure 6.4). These stringers are very important in determining structural geometry and overall cost. While it has been noted that the pile foundations are the most expensive component of a fixed dock, the number of pile bents required is determined by the length of the stringers above. Longer
Figure 6.16 Typical Pile to Superstructure Connections
(AWPI, 1968, pp. 9, 10)
spans mean fewer piles at reduced cost.

The practical maximum span length depends on material strength as well as the standard sizes available. Concrete stringers are precast (Buslov, 1979) and may be formed to any desired dimension. Dunham and Finn (1974) propose a prestressed, precast concrete deck system that combines deck and beam properties in a single element (Figure 6.17).

Stringers may be designed as simple beams under a continuous uniform deck load or concentrated point loads as discussed in Chapter 3.

Decking

The decking of a fixed dock, pier, or wharf structure must satisfy several design criteria in addition to structural integrity. It must be durable, slip-proof, easily repairable, clean, and preferably attractive. The most common decking materials are timber, steel, concrete, and aluminum (Tobiasson, 1979). The metal decks are less cost effective than timber or concrete, and their use is usually limited to gangways and ramps.

Timber decks have traditionally been constructed of 2 in. by 6 in. (50 mm by 160 mm) wood planks spaced approximately ¼ in. (7 mm) apart (Dunham, 1969). Thinner members have been found to be too flexible and may break under concentrated loads. The planks should be laid with the proper grain orientation (Figure 6.18) to encourage water runoff as they warp with age. They are often installed diagonally (Figure 6.19) to stiffen the dock structure in the horizontal plane and to strengthen the finger pier-walkway connections. Chaney (1961) recommends that the wood be a wear-resistant species such as oak, maple, or black
Figure 6.17  Prestressed, Precast Concrete Deck System
(Dunham and Finn, 1974, p. 121)
Decking is Placed With Growth Rings Oriented Concave Up.

Figure 6.18 Proper Grain Orientation for Wood Plank Decking
Figure 6.19: Diagonal Deck Planking

- Conventional Decking
- Diagonal Decking
- Finger Pier
- Bearing Pile
- Main Walkway
- Knee Brace
gum. Redwood decking is very attractive but should be avoided because of its poisonous splinters (Dunham, 1969). Deck timbers must be treated to obtain a reasonable service life, but creosote should not be used (Koelbel, 1979). Creosote bleeds out of the wood and sticks to shoes, clothing, and boats, and discourages customers in the long run. Pressure impregnated salts are a much cleaner solution.

Exterior grade plywood has also been used as a decking material. According to Dunham (1969), 3/4 in. (20 mm) thick plywood provides greater structural strength in cross-bracing than 2 in. (50 mm) wood decking. To avoid delamination with age, plywood decks must be kept painted. Exterior house paint mixed with ½ lb. (0.23 kg) of coarse ground pumice per gallon (4.2 l) will give a satisfactory non-slip surface (Dunham, 1969). Plywood deck panels with a bonded synthetic non-slip surface are available from marine materials manufacturers at greater costs but correspondingly lower maintenance and longer life.

Sheet metal deck panels of steel or aluminum have found limited application on marine structures. These open grating type decks are suitable where deck areas are small or on gangways where low weight and good traction are required. Dunham (1969) indicates that while metal decks have performed acceptably in fresh water environments, their use is not recommended around salt water because of corrosion problems.

Concrete decks may be either precast or cast-in-place; in either case, they are more massive than timber or metal decks. Since heavier supporting systems and piles are then required, concrete decks are typically used on larger structures. A concrete dock may be designed as a one-way slab, a two-way slab, or as a "T-beam" which combines the
deck and girder in one element. While thin elements are not recommended (Chaney, 1961), properly designed concrete decks are durable, economical, and especially suitable to areas subject to marine borer attack. Tobiasson (1979) suggests that curing compounds be used to densify the top surface of the concrete to make it less permeable to water. Flexible expansion joints should also be provided to minimize cracking.

**Gangways**

The deck level of a berthing system is often lower than the marginal wharf on the harbor perimeter. When this is the case, some ramp or transition zone is necessary for ease of access to the berths. If the change in elevation between dock and wharf level is small, the difference can be accommodated by a sloping section of deck similar to the rest of the dock. Since this section should have a maximum slope of 1 vertical to 3 horizontal (State of California, 1980), its vertical rise is limited by its length which is a function of stringer size and design load. Gangways or "brows" are used when the vertical rise is too great for a sloping deck, or when a gentler slope is preferred (Figure 6.20). The handrail of most gangways doubles as a truss to help support the deck and increase the allowable span length.

**Connections and Hardware**

Joint design is probably the most involved and neglected element of timber structure construction, according to Chaney (1961). Presumably the same is true for steel and concrete design, although their material properties are much more predictable. Constructing a joint usually entails connecting various structural elements with some sort of fastener
Figure 6.20 Fixed Pier Gangway

- Gangway
- Bearing Piles
- Bulkhead Wall
- Backfill
- Mud Line
or hardware. The joint must transmit the full force of its members with approximately the same (but no less) stiffness. If the joint is either less stiff or weaker than the rest of the structure, large deflections may result that lead to fatigue failure. Joint stiffness is a function of connection geometry, material properties, and type of fastener used. Discontinuities in finger pier and walkway alignment (skewed walkways or pinwheel fingers as in Figure 6.21) are examples of poor structural geometry that lead to stress concentrations and a higher degree of sheared bolts and loosened joints (Curry, 1979). The following discussion presents the types of fasteners used for marina construction, followed by a brief review of joint design considerations.

Hardware, for the purposes of this report, refers to the fasteners necessary to hold a connection together. A greater number of fasteners are used for wood joints than for steel or concrete because of the complex nature of wood connectors. The bolted joint is the most common for timber dock, pier, and wharf construction. Other timber joint fasteners include washers, split rings, spike grids, screws, drift pins, nails, and shear plates (Figure 6.22). Washers are used to distribute the compressive stresses under bolts and avoid crushing the wood fibers. Split rings are installed in precut grooves of timber-on-timber joints to increase their axial shear strength (Timber Engineering Company, 1956). Split ring joints are highly resistant to loosening because of vibration, impact or cyclic loads, and are most suitable for completely prefabricated structures. Spike grids are used in similar wood-to-wood connections where prefabrication is impractical. Ordinary wood screws are seldom used in structural applications because they require significant labor to install, and while they have higher withdrawal
Figure 6.21 Finger Pier or Walkway Misalignment
Figure 6.22 Timber Joint Fasteners
(TECO, 1978, pp. 12, 15)
resistance than nails, such loading should be avoided if possible (Timber Engineering Company, 1956). Lag screws, however, are the connector most often used when a through bolt is impractical. Since they are inserted in predrilled holes and turned into place, they can be retightened if shrinkage of the wood or flexure causes them to loosen. Drift pins are also installed in predrilled holes but are driven into place rather than turned. They are often used to anchor heavy timbers to the tops of piles or beams. Nails and spikes are driven into wood members without predrilled holes, and must be loaded in shear since they have relatively low withdrawal resistance. While grooved or spiral nails resist loosening better than smooth nails, Chaney (1961) notes that nailed joints may work loose under repeated flexure. Nails are often used in conjunction with framing anchors or joist and beam hangers (Figure 6.23) to eliminate toe-nailing and improve the joints shear strength. Finally, shear plates (See Figure 6.22) are used in steel-to-wood connections or for timber joints that may need to be dismantled. Like split rings, they are installed in precut grooves but are flush with the timber face when in place (Timber Engineering Company, 1956). The design of wood connections using all of the above mentioned fasteners is presented in the "National Design Specification for Wood Construction" (National Forest Products Association, 1977, Supplement 1978).

The principal methods of connection in steel construction are bolting and welding. High strength bolts have replaced rivets because of their ease of installation and higher initial tension that keeps the joint from loosening under dynamic loads. Bolts are also easily removed when dismantling or repair work is required. In situations where dismantling
Figure 6.23 Joist and Beam Hangars and Framing Anchors (TECO, 1978, pp. 3, 4)
is not critical, welded connections are prevalent. Welding allows reduced weight through elimination of secondary members such as gusset plates and connection angles (Chaney, 1961). The design of bolted or welded steel connections is presented in the "Manual of Steel Construction" (AISC, 1980).

Concrete joints or connections occur in several categories including those between precast members, between cast-in-place members, between precast and cast-in-place members, and between structural steel and both types of concrete. Joints may be made by welding steel reinforcement or structural steel inserts, by bolting, by pinning with dowels or key-type devices, by prestressing, and finally, with adhesives (ACI, 1977b). Encroachment of water into the joint is seen as the major cause of deterioration in concrete connections, so some method of sealing is required. Concrete joint design and sealing is addressed by the American Concrete Institute (1977a) and Noble (1964).

Joints or connections are often the areas of a structure most vulnerable to damage. This is especially true of dock, pier, and wharf structures in which a connection is afforded little protection. To be durable, a connection must resist both corrosion and fatigue failure by loosening. On the topic of corrosion, all light ferrous hardware should be hot-dipped galvanized (AWPI, 1975b). Contact of dissimilar metals must be avoided to minimize galvanic corrosion. Chaney (1961) recommends the use of wrought iron or malleable cast iron in place of steel. Finally, loosening of joints may be controlled by proper design initially, combined with good maintenance. Timber x-braces are a prime example. Instead of just a bolted joint that holds the brace
and pile in contact, a spike grid should be used inbetween. All bolts should be tightened during the early life of a structure to take up shrinkage and maintain full strength.

6.6 FIXED DOCK MOORAGE

Proper berthing of a small craft requires that the vessel be safely held in the slip without damage to itself or the structure. Mooring refers to the method of attachment of the boat to the dock. Fenders are provided to prevent damage resulting from hull to structure contact. While the primary task of the fendering system is to protect against impact on docking, it must be integrated into mooring design so that a vessel moored "alongside" is safe from abrasion.

Two types of mooring are currently used in recreational marinas: a stiff arm or strut system, and the traditional line mooring (Figure 6.24). Steel whips have been used to hold boats away from contact, as well as stern and bow clips. Dunham (1969) points out that while these systems work well initially, they become noisy with usage, and boarding may be difficult. Hull contact may also be avoided with line mooring systems if some provision is made to hold the craft away from the finger pier. The water level fluctuation that can be accommodated by fixed dock moorage systems depends on the length of the link between the dock and boat. Longer arms or tie lines allow greater height variations, but require more water area and larger berths.

Cleats are the most common method of attaching mooring lines between small craft and their berthing slips. Metal cleats of galvanized steel or noncorrosive alloy are available in several sizes from marina suppliers (Dunham and Finn, 1974). Some marina operators prefer wooden cleats
Figure 6.24  Small Craft Berthing Arrangements
(Dunham, 1969, p. 95)
(Figure 6.25), since they can be split to expose rusted bolts for repair. For small craft up to 40 ft (12 m), a 10 to 12 in. (250 to 300 mm) cleat is recommended. Since many cleat failures have been the result of pull-out under severe line stresses, Curry (1979) recommends that metal cleats be welded to a 1/4 x 3 x 6 x 12 in. (8 x 75 x 150 x 300 mm) angle that is then through bolted both vertically and horizontally to the dock. Lag bolts should not be used because they tend to loosen with stress and age.

While the ideal arrangement pattern will vary with each berthing system, Dunham and Finn (1974) suggest that one cleat fore and aft on either side of the vessel will be sufficient for boats up to 35 ft (11 m) long. The fore cleat should be mounted on the knee brace near the headwalk, while the aft cleat should be mounted near the end of the finger pier. Mooring systems for single and double-boat berths are illustrated in Figure 6.26. In the latter case, two cleats spaced 3 ft (0.9 m) apart on the edge of the headwalk replace the missing finger pier (Dunham and Finn, 1974). A tie-pile is also recommended as a substitute for the two outboard cleats of the finger, or a cooperative switch-tie system (Figure 6.27) may be used although this causes some inconvenience to the user.

Other methods of line attachment include rings, traveling irons and rails. Rings are used much like cleats but are less popular because they are somewhat noisy and because, unlike a cleat, the mooring line must be knotted. Traveling irons consist of hardware attached to the face of a dock that allows the point of fixity to move up and down with a moored boat as it rides the tide. Traveling irons are recommended by
A. Single Berth  

B. Double Berth

Figure 6.26 Line Mooring and Cleat Location for Single and Double Berths
Figure 6.27 Cooperative Switch-Tie System for a Double Berth
(Dunham and Finn, 1974, p. 111)
Chaney (1961) as a space-saving measure (Figure 6.28), and to eliminate
the need to change line lengths of moored craft as the water level
changes. Finally, Curry (1979) describes a "bull rail" system installed
along the main walkways of an Oregon commercial marina. These rails
consist of 6 by 6 in. (150 by 150 mm) or 8 by 8 in. (200 by 200 mm)
timbers set on 3 in. (75 mm) blocks on 4 to 6 ft (1.2 to 1.8 m) centers and
and bolted vertically with 5/8 in. (16 mm) bolts. A continuous rail
system is especially suited to the fuel dock where mooring is temporary
but large vessels must often be accommodated.

6.7 FIXED DOCK FENDERS

Fixed dock fendering systems are designed to absorb impact energy
through controlled deflection of the fender material and dock structure.
Fender design factors include vessel characteristics such as shape,
mass, and speed; the approach direction; and the rigidity of the dock.
While rubber, gravity, and floating fenders are all common to larger
structures, wood rubbing strips are the standard for small craft fixed
docks. Wood is an excellent material for such an application because
of its low initial cost, resiliency, and ease of placement (Texas A & M
University, 1971). Lasting performance should not be expected, however,
unless properly treated, stress graded lumber is used with non-corrosive
hardware. Furthermore, bolt hole diameter should be the same as the
attachment bolts used so that no slack can develop in the system.

Fixed pier fendering commonly runs vertically rather than horizontally
to accommodate water level changes. Wood rub strips are bolted to the
dock face at 8 to 10 ft (2.5 to 3.0 m) intervals so that they bear on
the rub nails or gunwale copings of small craft and hold them clear of
Figure 6.28 Traveling Iron
(Quinn, 1972, p. 596)
the rest of the dock superstructure. Typical sizes range from 3 x 4 in. (75 x 100 mm) to 8 x 8 in. (200 x 200 mm) depending on the size of the vessel berthed (Dunham and Finn, 1974). Length depends on the magnitude of water level variations but, in general, the fender must extend higher than the highest gunwale at extreme high water, and lower than the lowest rubbing strake at extreme low water. While all dock face hardware must be countersunk or recessed to avoid damage to the boats (Chaney, 1961), it should be noted that this reduces the working section of the wood member somewhat. Fender and attachment design must account for this reduced strength as well as any moments induced by cantilever bending loads as the fender is struck at its extreme ends.

Other fixed pier fender systems include vertical plastic tubes, fender piles, and dolphins. Vertical plastic tube fenders (Figure 6.29) work much the same as wood rubbing strips but are more flexible and exert a milder impact on hulls (Dunham and Finn, 1974). They may be supported as shown in the figure or suspended from a top bracket with a heavy weight hanging below the lowest possible point of hull contact. Fender piles also function like rubbing strips but have a lower point of fixity somewhere below the mud line. As Figure 6.30 illustrates, fender piles are slender, flexible piles that are driven at a slight batter and attached to the deck superstructure. Fender piles are more expensive than rubbing strips, and their higher load capacity is not necessary for small craft berths. Dolphins are isolated marine structures that protect ships and docks from damage and aid in mooring. Dolphins usually consist of clusters of piles that are placed at the corners of docks to protect these easily damaged areas. The piles may be driven
Figure 6.29 Vertical Tube Fender (Dunham and Finn, 1974, p. 181)
Figure 6.30 Vertical Fender Pile
to stand free, or be wrapped with several turns of steel cable (Figure 6.31) to work as a group.

6.8 SUMMARY

Fixed docks are supported by piles driven into the soil bottom of a marina basin. Fixed docks are best suited to locations where tidal variations are less than about 4 ft (1.2 m), total water depth is less than about 20 ft (6.0 m), and ice loads are not too severe. Fixed docks constructed in northern climates are usually provided with an air bubbling system to suppress the ice around the piles and minimize jacking and impact damage problems.

The most common pile type used in fixed dock construction is the pressure-treated timber pole. Other pile types include steel, concrete, and composite sections. The selection of pile type is based on availability, durability, strength, and estimated cost. Timber piles are generally the most readily available, the least expensive, and are durable if properly preserved. Steel piles are expensive to buy and transport, but can be spliced to any required length and can support very high capacity loads. Concrete piles include both cast-in-place piles and precast sections. Precast piles are more practical in the marina environment, but are very heavy and difficult to handle. Combination piles are not often used because of problems with the splice joint between the two materials.

The fixed dock superstructure consists of a pile cap connecting the piles of each "bent", stringers spanning between the bents, bracing to stiffen the framework, and a deck material laid over the top. A substantial portion of the cost of a fixed dock is spent on the pile
Figure 6.31  Typical Wood Pile Dolphins
(Quinn, 1972, p. 432)
foundations. The overall pile costs can be reduced by using fewer pile bents, spaced at greater intervals, but this requires longer stringers. The practical maximum span depends on the material strength of the stringers and the standard sizes available. The decking is often timber planking which is placed diagonally for a lateral bracing effect. Fixed docks are designed as rigid frameworks and require tight connections. If the connections loosen because of fatigue, wood member shrinkage, or deterioration, artificial hinges can develop that quickly destroy the structural integrity of the system.

Fenders for fixed docks usually consist of vertical wood rub strips. The rub strip should be smooth faced so that the gunwale or rub rails of a berthed boat can slide up and down smoothly. Other types of fixed dock fenders include vertical plastic tubes, fender piles, and dolphins.
CHAPTER 7
FLOATING DOCKS, PIERS AND WHARVES

Floating docks, piers, or wharves are those that rely on their buoyancy for support. They are the major alternative to fixed or pile-supported structures intended for the berthing of small craft. While the application of either the "fixed" or "floating" type to a particular location depends on many site specific factors, floating slips are generally favored for water level variations greater than about 4 ft (1.2 m) and for basin depths greater than about 20 ft (6.1 m). Large water level changes are common on flood control lakes, rivers, and tidal inlets on the coast. Under such conditions secure mooring of a small craft to a fixed dock is difficult and boarding may be hazardous. Since pile costs are responsible for a large portion of the overall cost of a fixed dock, factors that increase pile costs such as great depths, very soft bottoms, or very hard (ledge rock) bottoms all favor floating berths.

Cost comparisons between fixed and floating docks, piers, and wharves are very risky in today's economy. Dunham (1969) notes that while fixed docks appear to be less expensive, there is an increasing trend toward the use of floating berths for all small craft harbors. In a later report, Chamberlain (1977) also finds the floating systems preferable while stating that costs are competitive between the two types.

In an effort to protect moored small craft better, floating and covered berths have been designed (Dunham, 1969). Two types are prevalent, differing in the method of supporting the roof. When the maximum water
level fluctuation is less than about 6 ft (1.8 m), the anchor piles of the float system may be extended up to support the top. In this type, pole shed construction is used that is identical to fixed-pier covered berths (See Chapter 6). The second type of floating-covered berth is suitable for water level variations in excess of 6 ft (1.8 m). Each floating pier is incorporated in a covered structural unit as illustrated in Figure 7.1. The superstructure consists of a continuous, truss-framed roof supported by columns from each side of the main walk and the outboard ends of the fingers. According to Dunham (1969), the superstructure is markedly different than a similar roof on land since it must provide structural rigidity for the entire float system that limits differential flexing to a small fraction of that which occurs in an open berth arrangement. Substantial bracing is required to achieve acceptable rigidity which leads to very large dead loads. The large above-water profile area causes high, wind-induced lateral loads that must be resisted by the anchorage system. Excepting very calm and protected waters, it is questionable whether floating covered berths are practical in light of their considerable cost for minimal benefits.

As with fixed-covered berths, dry stack storage is suggested as an alternative (New York Sea Grant, 1978).

Floating dock, pier and wharf systems are well-suited to modular construction, and several manufacturers are marketing complete berthing systems. In general, their approach has been to develop float units that can be fastened together in various arrangements appropriate for different sites. The float unit usually consists of a number of pontoons attached to a framework that supports the deck. A mixture of plastic,
Figure 7.1  Floating Covered Berths  
(Dunham, 1969, p. 112)
timber, steel, aluminum, and concrete materials is common for a well-designed system.

This chapter begins with a discussion of structural geometry of floating docks, piers, and wharves. Next, foam flotation is addressed, followed by the various types of pontoons differentiated by shell material. The selection of float type and design considerations for floating docks concludes this second section. Anchoring systems comprise the third section, including control piles, pile yokes, pipe struts, and cable anchors. The final section consists of the design considerations concerned with decking and framing for floating docks, piers, and wharves.

7.1 STRUCTURAL GEOMETRY

The structural geometry of floating docks, piers, and wharves is in a sense similar to the fixed structures described in Chapter 6. Vertical support is provided by flotation elements or pontoons which replace the pile bents and are arranged under a deck superstructure which acts to distribute the deck loads. The pontoons are most often rectangular (parallelepipeds or cylinders and may be placed transversely or longitudinally under the superstructure (PIANC, 1976). If placed transversely, the pontoon should be as long as the dock is wide to ensure maximum transverse stability. Stability is also a major concern when the longitudinal arrangement is used. Chaney (1961) notes that stability is maximized by concentrating the flotation elements under the edges of the dock, even for asymmetrical loading.

The deck superstructure of a floating dock or pier usually consists of a set of stringers that supports a deck that rides 15 to 20 in (380 to 510 mm) above the water with no live load (Figure 7.2). Other structural
Figure 7.2 Floating Dock Indicating Suggested Freeboard
(Ayers and Stokes, 1976, p. 37)
types include a metal truss system supporting the deck, a glued-laminated
marina plank, or a concrete deck that is monolithic with the floats
below (Figure 7.3). Along the perimeter of most of these systems lies
a heavy timber rub rail or waler.

Short float sections or modules are generally assembled on shore,
lunched, and then connected end to end to form the berthing system.
The main walkways of the piers extend outward from fixed or floating
marginal wharves. Small craft are berthed at finger floats attached
at right angles to the pier. Nonorthogonal connections in finger float
and walkway alignment should be avoided since they are subject to stress
concentrations that cause damage and increased maintenance (Curry, 1979).
Knee braces are commonly provided at the finger float/main walk
junction. The knee brace area is a good location for anchor piles, locker boxes,
and utility risers. Access to the float system is gained by means of
hinged gangways that slide along the deck as it rises and falls with
changes in water level. Anchorages in the form of guide pile or cable
systems are used to restrain floating berths against lateral loads.

7.2 DESIGN CONSIDERATIONS FOR FLOTATION ELEMENTS

According to Dunham (1969), the earliest known flotation is the
ordinary timber log. While logs are very economical on a first cost
basis, they have two main disadvantages. First, they tend to become
saturated with time and will sink after a few years. Secondly, they
are susceptible to marine borers and, if treated against biological
attack, they retain little of their original buoyancy. Except in unusual
circumstances, wood is not recommended as a flotation material. A suitable
replacement should be inexpensive, light, and impermeable to water.
A. Metal Truss System

B. Glued-Laminated Marina Plank

C. Monolithic Concrete

Figure 7.3 Floating Dock Structural Types (After Winzler and Kelly, 1979, V-5, V-32, VI-4)
To be durable in the marine environment, it should also be resistant to petroleum products, easily fastened to the deck structure, flame retardant, and resistant to ice damage in cold climates (Koelbel, 1979). Satisfactory float types include lightweight solids, hollow shells, or combinations of these. Several types of closed-cell foams qualify as acceptable lightweight solids. While there are many types of hollow shells that could be used as flotation devices, most are now being replaced with foam-filled shells (Dunham and Finn, 1974). Problems with leakage, internal condensation of moisture, impact damage and vandalism are largely responsible for the change. Combinations of shells and foam cores are therefore the primary float type to be addressed.

**Foam Flotation**

The most "successful" of the foam flotation materials include extruded polystyrene, expanded-pellet polystyrene, and foamed polyurethane (Dunham and Finn, 1974). While foam blocks have been used successfully as flotation elements without any surface coating, they suffer from a lack of durability. One of the worst problems is somewhat indirect. Large quantities of marine growth rapidly accumulate on unprotected foam floats. The plant matter attracts small organisms which in turn attract birds and sea animals to feed. It has been reported that large pieces of foam have been torn out as these animals seek marine life burrowed into the underside of the foam surface (Dunham and Finn, 1974). In addition, some foams are susceptible to damage from petroleum or ice contact, and may be flammable. For these reasons, some form of external protection is now applied to all foam floats, especially in saltwater. Protection may be in the form of a brushed-on coating or a more substantial
shell of plastic, fiberglass, metal, or concrete.

There are two basic approaches to manufacturing foam-filled pontoons. The first method is to use a block of foam as the internal form and construct the shell around it. The alternative is to finish the shell first and foam the core material in afterward. Extruded polystyrene (commonly called styrofoam) in the form of planks is most suitable for the internal form construction because of its low cost and uniform quality, and because it is completely impervious to water (Dunham and Finn, 1974). While the expanded-pallet polystyrene may be less expensive than styrofoam, it is subject to quality control problems. Overexpansion of the beads or non-uniform heating will produce a low quality friable foam that is permeable to water. Since polystyrene is a common flotation material, the following specification recommended by the California Department of Navigation and Ocean Development (State of California, 1971) is reproduced for potential buyers:

"(1) Materials: Cellular polystyrene may be formed by the expansion of high density beads or granules in a mold or directly from the base resin by extrusion. The material shall be firm in composition and essentially unicellular. No reprocessed materials shall be used.

(2) Dimensions: Unless otherwise specified, the manufacturers' standard size will be acceptable if incorporated into the design with a minimum of field cutting. The tolerance in each dimension shall be plus 1 inch or minus 0.5 inch.

(3) Color: As normally supplied by the manufacturers for the particular type of polystyrene. Variation in color indicative of damage or deterioration will not be accepted.

(4) Surface Finish: Surface shall be stressed, polished, free from pits, blisters, cracks, dents, waviness, heat marks, or deep scratches.

(5) Odor: The material shall be free from any objectionable odor."
(6) Exterior Coating: In all locations where the waterfront is subject to infestation by marine borers which damage polystyrene, the flotation material shall be protected with an adequate material capable of resisting any anticipated attack by marine organisms.

(7) Physical Properties: Specimens from polystyrene planks shall conform to the requirements stated below:

(a) Density: 1.5 pounds per cubic foot (minimum).
(b) Compressive Strength: 20 pounds per cubic inch minimum at 5 percent deflection.
(c) Tensile Strength: 40 pounds per square inch minimum at break.
(d) Shear Strength: 25 pounds per square inch minimum at break.

(8) Moisture Absorption: The maximum water absorption shall be 0.12 pounds per square foot of skinless or windless surface when tested by immersion method in accordance with U.S. Department of Defense, Military Specifications MIL-P-40619 (3 April 1962) 4.5.7.

(9) Hydrocarbon Resistance: Polystyrene planks to be used in the vicinity of gas docks or other areas subject to petroleum products floating on water shall be hydrocarbon resistant. The materials shall show no apparent softening or swelling when tested by the immersion method specified in the U.S. Department of Defense, Military Specifications MIL-P-40619 (3 April 1962) 4.5.10.

(10) Shape: Surfaces of the finished planks shall lie in normal planes so that the plank, when installed in final position in the floating dock, shall lie in a true horizontal plane with the water. Edges formed by molding or cut sections may be either rounded or square.

Polyurethane is often preferred over polystyrene when the foam is to be placed inside a finished shell. Of the two types of polyurethane available, only the monomeric variety is non-absorbent and should always be specified (Dunham and Finn, 1974). While polyurethane foams are naturally resistant to hydrocarbons, they are prone to oxidation and should be provided with a protective covering.

One final note regarding foam flotation has to do with polymer compatibility. Some coatings or adhesives will work well with one foam
but react with another. According to Dunham and Finn (1974), polyester resins are compatible with polyurethane but not with polystyrene. Most manufacturers have representatives available for technical advice should such a question arise with the use of their product.

**Coated Lightweight Pontoons**

Lightweight shell pontoons are those in which the coating is a form of protection only and does not add significant strength to the foam core. Common protective coverings include brush or spray coats of polyvinyl-acetate emulsion or dense polyurethane (Dunham and Finn, 1974), epoxy paint (Dunham, 1969), and fiberglass reinforced polyester (PTANC, 1976). These coatings all bond to the foam core and provide a tough flexible skin that attracts less marine life and is easily wiped off. Compatibility between the coating and core should be checked to ensure the two materials do not react. For example, if the protection of a fiberglass and resin shell is desired over a polystyrene foam core, an intermediate coating of epoxy that is compatible with the resin must first be applied (Dunham and Finn, 1974).

Concrete has also been used as a coating for light, foam core floats. Although it adds considerable weight which must be compensated for with more flotation material, concrete provides an armored surface that may prolong the life of the system (Dunham, 1969). Concrete coated floats are stable because of their increased mass, and are quite durable as long as they are protected from impact damage. Noble (1964) cites the use of a polystyrene pontoon coated with 3/8 in. (10 mm) of concrete troweled in place. PTANC (1976) recommends a coat of fiber reinforced
concrete about 3/4 in. (20 mm) thick. Shotcrete has also been used with some success as a coating material. These pontoons are similar in appearance to the concrete shell type but float much higher.

**Synthetic Molded Shells**

The most common molded synthetic shells are made of fiberglass-reinforced polyester resin or high density polyethylene. Material technology in the field of synthetics is rapidly evolving, however, and other shell materials that are equally acceptable may be available. An attempt should be made by potential users of these materials to investigate their service record with respect to durability.

Fiberglass and polyethylene shells tend to be more durable than the lightweight shells mentioned above because of their better quality and increased strength. Brushed or sprayed-on coatings are typically non-uniform in thickness and contain local defects such as air bubbles or contaminants. This leads to cracking, pinhole leaks, and general slow deterioration (Dunham, 1969). The fiberglass and polyethylene shells on the other hand, are pressure molded between matched dies to ensure uniform wall thicknesses. Controlled manufacturing and curing conditions eliminate the defects experienced with lightweight shells.

As pontoon materials, fiberglass and polyethylene have many other advantages that are attractive to the marina designer and owner. Floats made of these materials are non-corrosive, non-conductive, resist marine life build-up, are not affected by petroleum spills, and have excellent impact strengths. In addition, one piece seamless construction is possible with provision for easy attachment to the deck framing.
Steel or Aluminum Shells

Metal shelled floats of steel or aluminum are another alternative for floating dock pontoons. Two shapes are common including a rectangular unit of folded thin gauge metal sheet with stiffener baffles, or a tubular one with end caps that resembles a corrugated drainage pipe. Used steel oil drums have been used as flotation units but should be considered only for short term or temporary projects because of their poor durability (Dunham, 1969). While fabricated steel and aluminum floats are also subject to rapid corrosion, they are commonly protected by manufacturer-applied preservative coatings both inside and out. In spite of this coating, most metals are not recommended for use on the sea coast because of their high corrosion rate in the saltwater environment (Dunham, 1969). Corrosion resistant alloys are available at some extra cost that may overcome this objection. Metal floats are nearly all foam-filled to provide extra protection against leakage, internal condensation, and internal corrosion (Dunham and Finn, 1974). Metal pontoons are particularly serviceable where ice formation and heavy floating debris is encountered.

Concrete Shells

Concrete has proven to be an excellent material for marina pontoons (Noble, 1964). Several manufacturers market floats with lightweight concrete shells around foam cores. The concrete usually used has a density of 100 to 110 pcf (15.7 to 17.3 kN/m³) significantly less than the 145 pcf (22.8 kN/m³) density of normal concrete (Curry, 1979). The primary advantage of lightweight concrete is that less buoyancy is required to support its dead weight. Pontoons of normal concrete
also require larger handling equipment and the resulting handling stresses are more critical because of increased size and weight (Noble, 1964).

Concrete floating dock systems are often cited for their stability and durability (Noble, 1964; Dunham, 1969). The heavier the pontoon, the greater its stability, providing the center of gravity remains low. Concrete pontoons tend to be more massive than other float systems and do not respond as quickly to load impulses or small waves. The mass of a concrete float system may work against it, however, in areas subject to long period waves or harbor surge (Curry, 1979). Considerable damage has been noted at locations where surge ran 10 to 18 in. (250 to 450 mm) at periods of 1 to 5 minutes. While concrete is very durable in the marina environment, it has three main weaknesses. First, reinforcement corrosion has led to deterioration of the walls of concrete shells. Since these must be thin-wall structures, it is difficult for the manufacturer to keep the reinforcing mesh in place at the center of the concrete section. For this reason, many designers do not use any reinforcement but instead design the float so that at no point will the tensile strength of the concrete be exceeded (Dunham, 1969).

Second, concrete borers of the pholad family may damage concrete pontoons. Resistance to pholads depends on the quality and dispersion of the aggregate. Noble (1964) notes that ordinary rock and expanded shale aggregate have resisted attack while perlite aggregate, shotcrete without coarse aggregate, and plaster concrete coatings can be bored in 3 to 4 years. Finally, concrete pontoons are very susceptible to poor quality control and poor installation practices (Curry, 1979). Care must be taken during construction to use the proper quantity and quality of
foam core material, to locate the core correctly in the form, and to vibrate and finish the concrete shell properly. These steps will ensure that the floats are balanced and uniform, with walls, bottoms, and decks of the proper thickness and concrete quality. The best designed floats of the finest quality will still not function properly if poor installation procedures are used. Rough handling during transportation and launching will induce bending and impact stresses that lead to broken corners, cracks, and holes (Dunham, 1969). Rapid temperature changes and improperly tightened connections may also cause cracking.

7.3 SELECTION OF FLOAT ELEMENT TYPES

Of the decisions that must be made by the designer of a floating dock, pier, or wharf, the choice of flotation material may be the most controversial (Dunham, 1969). In some cases, the proper judgment is obvious. Logs, unprotected foam billets, and waste oil drums are acceptable only as temporary or short term float materials. On the other hand, the selection of a particular type of foam-filled shell may be based largely on the preference of the marina operator or patrons. Availability, durability, stability, and life cycle costs are factors to be considered in selecting a float type for a given marina installation. As in the case of fixed docks, piers, or wharves, appearance may also be an important criterion but will not be addressed here.

Pile foundations such as those used for fixed docks, piers, and wharves are also used to support other structures located on soft ground. For this reason, the various types of piles addressed in Chapter 6 are generally available regardless of location. Floats, on the other
hand, are not as readily available because of their narrower scope of application. The marina designer must first determine which float types may be obtained, followed by probable shipment and handling problems. In general, flotation elements are light and bulky, so all may be transported by land carriers. Lightweight and synthetic shell pontoons are easily handled manually while metal and concrete shell pontoons are heavy enough to require light machinery.

Durability is not a problem with any of the established float materials as long as they are used within their limitations. Lightweight shells are most suitable to calm, protected harbors where they will not be subjected to a lot of abrasion or impact. Metal shells, regardless of the coating applied, should not be used in saltwater because of their potential for corrosion. Care must be taken during the construction and launching of concrete shells to avoid tensile cracks that will lead to deterioration later on. The materials industry, especially in the field of synthetics, is rapidly evolving and has produced many new materials with potential application to float construction. The designer should be cautious in the use of these products, however, as they lack reliable data on fatigue, weathering, and wearing qualities (Dunham, 1969).

When used to describe a floating dock, pier, or wharf system, the term "stability" refers to how steady the structure feels underfoot. For a given deck superstructure, heavier floats will feel more stable to the user. Massive float systems do not respond as quickly to wave chop or dynamic live loads. Lightweight floats, however, tend to feel bouncy in the same conditions. The opposite is true in locations sub-
ject to long period (1 to 5 minute) surge, according to Curry (1979),
where concrete float systems have experienced considerable damage.

Life cycle costs should also be considered when selecting flotation
elements for a floating dock, pier, or wharf. Life cycle costs include
both the initial installation cost and maintenance costs over a standard
design life. Generally, lighter, less substantial floats will be less
expensive to purchase, but will require more maintenance. Heavier,
more durable floats may be preferable from an operators standpoint
since they minimize downtime during which maintenance is performed.

7.4 DESIGN CONSIDERATIONS FOR FLOAT COMPONENTS

The design of a floating structure is very complex, particularly
the connections between the float modules. Unlike a fixed structure,
the vertical support is not uniform and varies continuously with changes
in water level and deck loading. The deck and framing system must
be flexible enough to conform to the water surface while at the same
time having sufficient rigidity to distribute loads without the local
overstressing that leads to the development of an artificial hinge.
This tradeoff is a difficult one and, according to Chamberlain (1978),
the design of such systems is not safely left to amateurs. Two alterna-
tives are available to the designer of a floating dock. First, a
number of manufacturers are marketing float systems, some of which
have many years of performance records that show them to be successful.
Second, an expert with experience in the design of similar facilities
may be consulted. While it is difficult to equate the two approaches
in terms of cost, the prefabricated docks may be less expensive because
of volume production and lower design costs. Unfortunately, they