CHAPTER 6

FIXED DOCKS, PIERS AND WHARVES

For the purposes of this report, docks, piers and wharves that are pile supported will be considered fixed structures. Fixed docks and piers are generally less expensive to construct than equivalent floating berths. In spite of their economic advantage, however, there has been a trend away from the fixed structure toward the use of floating slips for all small craft marinas (Dunham, 1969). Fixed berths are usually limited to locations where water surface fluctuations do not exceed 4 ft (1.2 m) and the basin depth is less than about 20 ft (6.0 m). Where greater water surface changes occur, boats are difficult to board at extreme low water, and traveling irons must be provided for safe mooring at all levels. Deep water installations (in excess of 20 ft or 6.0 m) are not economically feasible since piles represent a major portion of the cost of a fixed pier structure, and their cost is directly proportional to the length required.

Fixed pier construction is particularly favorable for covered berthing since long piles can be used to support both the deck and roof. While covered slips provide excellent protection from the elements, they have several disadvantages (Dodds, 1971). The cost of constructing and maintaining the roof must be borne by increased slip rental fees. Since wood is the material commonly used for such structures, fire hazards are dramatically increased while the enclosure makes it difficult to fight the fires. Changing the slip sizes of an open slip system is difficult, but the problem is compounded by a covering which interferes with the equipment needed to pull and drive piles. The economics and
feasibility of the covered berth depend on the analysis of the individual marina site, the intended user, and any future plans for expansion. For small craft up to 30 ft (9 m) in length, dry stack storage as shown in Figure 6.1 should be considered an attractive alternative (New York Sea Grant, 1978). Where covered berths are to be built, standard pole-shed construction is recommended as presented by Patterson (1969). Covered berthing will not be addressed further in this report except to note that failure to design properly for wind uplift forces has been the major cause of damage in these structures (Dodds, 1971).

Fixed docks in general are subject to damage by ice in northern areas. Lateral forces because of expansion/contraction of the ice sheet, as well as vertical forces resulting from water level changes, literally tear a structure apart (Wortley, 1981). Bearing piles are abraded at the waterline and "jacked" out of the bottom. Bracing members are knocked off by ice floe impact, while utility lines are bent or broken by protruding ice rubble. Design of harbor structures for such conditions may be one of two types: with or without ice suppression. Design with ice suppression relies on the operation of a bubbler or propeller system to reduce the ice sheet thickness and the resulting forces. Compressed air bubbles (Figures 6.2 and 6.3) circulate warm water from the harbor bottom by entraining water into the rising bubble plume. Propeller systems operate in the same manner but are more suitable to warmer water of 33 to 36°F (0.5° to 2.0°C). Harbor structures designed without ice suppression must resist the full forces of the ice mass which may approach its crushing strength of about 400 psi (2.8 MN/m²). Design of dock, pier, and wharf structures for northern small craft harbors is addressed
Figure 6.1 Dry-Stack Storage
Figure 6.2 Compressed Air-Ice Suppression System
(Wortley, 1979, p. 5)

Figure 6.3 Air Bubbler Layout (Dunhem and Finn,
1974, p. 216)

Several manufacturers have developed modular fixed dock and pier systems which offer the marina designer several advantages over a system specifically designed for one location. Design costs are absorbed by the manufacturer and spread out over several installations, thus reducing the total cost per unit. From experience gained by the building of similar structures, many construction problems can be eliminated and necessary design modifications made. Prefabricated systems also lend themselves to rapid installation and ease of expansion. On the other hand, Dunham (1969) notes that most steel and aluminum prefabricated docks have had problems with corrosion in salt water, while Dunham and Finn (1974) state that they are more suitable for individual docks than for large installations as required in marinas. Since these limitations must be considered minor for such a rapidly evolving industry, the marina designer should consider modular dock and pier systems a viable solution to marina berthing design.

The following discussion addresses the design considerations of the components of a fixed dock, pier, or wharf. These topics include structural geometry, pile types by material of construction, design of pile foundations, and decking and framing details. Mooring provisions and fenders as they relate to fixed docks and piers are also addressed briefly.

6.1 STRUCTURAL GEOMETRY

The structural geometry of fixed docks, piers and wharves is relatively simple, as illustrated in Figures 6.4 and 6.5. Piles are arranged
Figure 6.4 Fixed Pier Construction (Dunham, 1969, p. 97)

Figure 6.5 High-level Fixed Wharf Construction (AAPA, 1964, p. 38)
in rows or "bents" spaced 10 to 14 ft. (3 to 4 m) apart. A pile cap connecting all the piles in a bent runs from one side of the pier to the other and supports the stringers and deck. Lateral cross-bracing is used to resist lateral loads and provides stability and a sense of rigidity. Where lateral loads are large, inclined or batter piles are used instead. The fixed wharf closely resembles a solid fill relieving platform as described in the previous chapter. The fundamental difference lies in the fact that the fill of a relieving platform extends over the deck to provide additional weight for stability. Fixed wharves typically have high level decks in which the deck superstructure system is supported directly on piles arranged in transverse rows. A lighter deck is therefore acceptable and fewer piles are required since the vertical loads are greatly reduced. Open type fixed wharves are less expensive and easier to construct than are relieving platform wharves.

Fixed docks and piers are smaller (See Chapter 2) and therefore less substantial than fixed wharves. Their structural geometry is the same, however, with pile bents, caps, and stringers supporting a continuous deck. Since fixed docks and piers are built for the purpose of berthing boats, they are generally constructed with a deck elevation 1 ft. (0.3 m) above extreme high water. Sloping gangways connect the low level decks of the berthing system with the perimeter wharf or bulkhead wall.

6.2 PILE FOUNDATIONS

The basic material types for piles used in waterfront construction are timber, steel, and concrete (Figure 6.6). Composite piles formed by combinations of these materials are also used for special conditions. There are two general classes of piles including bearing piles and sheet
Figure 6.6  Typical Pile Types Used in Waterfront Construction  
(Tobiasson, 1979, p. 2)
piles. Bearing piles are used to support structural loads (both lateral and vertical) while sheet piles form continuous walls to resist horizontal soil and water pressures. Bearing piles may be further classified as "end-bearing" or "frictional" piles. End-bearing piles rely on point bearing on a firm stratum to support the pile load. Frictional piles transfer the applied load into the surrounding soil along the pile embedded length (Figure 6.7). The following section focuses on the bearing pile types by material of construction, the selection of the proper pile type for a given location, the design of pile foundations, and the installation of piles. Pile foundations are also addressed by Cheung and Kulhawy (1981).

Timber Piles

Timber piles are probably the most commonly used pile type on the waterfront because of their availability, constructability, and low cost. According to Tobiasson (1979), timber piles often cost less per foot when in place than other pile types. For many applications, however, their use is limited by their load carrying capacity, length availability, and susceptibility to deterioration. In addition to soil conditions at the point of installation, the capacity of a timber pile is determined by its axial strength which is a function of the material defects inherent in a wood member. Wood defects and strength properties are discussed in Chapter 4. Timber piles are best used as friction piles in soft soils because of their relatively small cross-sectional area and tapered shape. Where they are intended to be used in end-bearing, hard driving through highly resistant soils may cause crushing and damage that is mistaken for additional penetration. The result of over-driving is a structural
Figure 6.7 Bearing and Batter Piles (Tobiasson, 1979, p. 4)
failure of the pile before it is even loaded. For the above reasons, wood piles must be considered low capacity foundations when compared with steel or concrete piles. This is of little consequence in marina design where the pile spacing is determined by superstructure framing details and only a portion of the piles load carrying capacity is used.

The standard lengths of timber piles are limited by the height of suitable wood species. Southern pine and Douglas fir are the principal species used for treated piling in saline environments. Red pine, Norway pine, Oak, Red cedar and other species are also acceptable if properly treated with preservatives. Southern pine is readily obtained in lengths to 60 ft. (18 m) while Douglas fir is available on the West Coast in lengths up to 100 ft. (30 m). With the low applied loads and shallow water depths typical of the recreational marina, timber piles are rarely found to be inadequate because of their available length.

Unlike load capacity or length availability, rapid deterioration in the marina environment is a serious problem. Timber piling comes under the attack of insects, marine borers, organic decay, and abrasion from boats and scour currents. Protection in the form of a pressure impregnated preservative is required in most cases. Material deterioration and preservative treatment is discussed by Hubbell and Kulhawy (1979a). Encasement in a concrete jacket or various patented methods of plastic wrap have also been used to protect timber piles in saltwater locations where marine organism attack is especially severe (Tobiasson, 1979).

Additional protection must be provided to the top of timber piles where they extend above dock level. First, the top of the pile where it is cut off must be sealed to keep moisture from penetrating the end
grain and starting decay (Chaney, 1961). Chaney suggests that the pile butt be swabbed with creosote, followed by a thick coat of tar and a concrete or cast iron cap (Figure 6.8). Molded plastic or fiberglass pile caps (Figure 6.9) are suggested by Dunham and Finn (1974). The conical shape of these caps sheds the rain and helps keep birds off the piles. Secondly, when creosoted piles are used for support members, the portion above the deck line will always be dark and oily as the creosote seeps out of the wood. To avoid users clothing from coming in contact with this creosote, Dunham and Finn (1974) recommend a wood batten system as illustrated in Figure 6.10. Another alternative is to splice on a salt treated pile butt that is stained to match the creosote as in Figure 6.11.

Several agencies have prepared specifications for wood poles to be used as pile foundations. Among these, the American National Standard (ANSI 05.1-1979), American Society for Testing and Materials (Standards D25 and D2899), and American Wood Preservers Institute (Technical Guidelines P1 through P5) are recommended references for information on wood species, dimensions, general quality, strength, decay resistance, preservative treatment, inspection, splicing, storage, and handling of timber piles.

Steel Piles

Steel piles in the form of H-sections or pipes are widely used for pile foundations. Steel piles are especially applicable to conditions that require hard driving, great lengths, or high single pile capacities. Since H-piles displace relatively small volumes of soil, they are more easily driven than other pile types and are commonly used to reach strong
Nails Driven into the Pile to Hold on the Concrete Cap

Creosoted Timber Bearing Pile

Figure 6.8 Concrete and Tar Cap

Molded Plastic or Fiberglass Conical Cap

Bearing Pile

Figure 6.9 Molded Synthetic Cap
Figure 6.10 Wood Batten Pile Protection
Figure 6.11 Timber Pile Splice Detail
(Van Blancom, 1970, p. 3)
bearing strata at great depths. Pipe piles capped on the end by flat plates or conical points are sometimes harder to drive than H-piles because of their larger end area. Unlike H-piles which are most efficient in end bearing, pipe piles are more suitable as friction piles. A significant advantage of pipe piles is that they can be visually inspected after driving to identify any damaged casings and allow repair or replacement. Pipe piles are usually filled with concrete to increase their compressive strength and control internal corrosion.

Length is not a critical factor in the use of steel piles since they are easily joined on the job site by welding. At the other extreme, steel piles that are too long can be quickly trimmed to the proper height by oxyacetylene cutting, even under water. Large steel piles are considered very high capacity foundations and are rarely used in marina construction. Smaller sections with correspondingly lower capacities are more suitable but are also more easily damaged by handling and boat impact. As in the case of timber piles, deterioration proves to be the major factor determining the lifetime performance of steel piles.

Deterioration of steel usually takes the form of oxidation corrosion, more commonly called rust. In the tidal range, bare steel exposed to saltwater may corrode up to 0.020 in. (0.5 mm) per year (AAPA, 1964). In such an environment, steel piles must be considered temporary unless some effective form of protection can be devised. Epoxy coatings, concrete encasement, and sacrificial cathodes are some of the techniques that are successful depending on site specific conditions. For example, cathodic protection is not reliable in the tidal zone (Peck, Hanson,
and Thornburn, 1974), and coatings may be worn away by sand blast abrasion near the harbor bottom (AAPA, 1964). Hubbell and Kulhawy (1979a) discuss the corrosion process of steel in the marine environment with various coatings or cathodic protection.

Specifications for steel piles are much less detailed than those for wood because, as a man-made material, steel is much more uniform and predictable. Material properties and standard dimensions for steel H-piles and pipe piles are specified by the American Society for Testing and Materials (1980) in standards A690-77 and A252-77a respectively. Manufacturers of steel piles (Bethlehem Steel Corporation or the U.S. Steel Corporation, for example) also publish product literature and are available for technical consultation.

Concrete Piles

Concrete piles may be divided into two main categories, cast-in-place and precast. Cast-in-place piles may be further classified as cased or uncased. The concrete of a cased pile is poured inside a form that remains in the ground. The form is usually a steel shell or thin pipe that has negligible strength with respect to the structural capacity of the pile. In some ground conditions, the shell may be driven alone, but often it must be supported by an internal driving mandrel to prevent collapse. The mandrel is withdrawn and reused on subsequent piles but it still represents a source of expense and construction difficulties. Uncased cast-in-place piles are less expensive since elimination of the casing lowers the material costs. A mandrel is again driven and withdrawn before or during the placement of the concrete. These piles should be considered only where it is certain that the hole will not be partially
or completely closed by soil stresses after the removal of the shell, since imperfections or discontinuities will result that severely weaken the pile (AAPA, 1964). Waterfront construction with uncased piles presents a problem above the mudline where the concrete is not retained by the surrounding soil. Figure 6.12 illustrates the various types of cast-in-place piles used in North America.

Precast concrete piles have found more extensive use in marine installations (AAPA, 1964). Square, round, or octagonal shapes are common with tapered or constant cross-sections. Conventionally reinforced precast piles generally have pointed driving ends and hollow cores for low weight. Examples of precast conventional piles are illustrated in Figure 6.13. Prestressed, precast concrete piles have also come into general use (AAPA, 1964). Prestressing reduces the incidence of tensile cracking during handling and driving since the piles are stronger in bending when subject to lateral loads and buckling. Theoretically, prestressed piles should therefore be more durable, but Buslov (1979) noted in a study of the durability of wharves that after 15 years in service, "no major differences in performance were found between regular and prestressed piles."

The load capacity of concrete piles is highly variable depending on cross-sectional area, concrete quality, thickness of the steel shell, and the amount of reinforcing steel. Very large concrete piles are of medium to high capacity, being somewhat less than large steel piles but considerably greater than the average timber pile. As in the case of steel piles, only smaller sections have found extensive use in marina construction since high single pile capacity is rarely required.
Figure 6.12 Examples of Cast-in-Place Concrete Piles
(Pack, Hanson and Thornburn, 1974, p. 205)
Figure 6.13 Examples of Precast Concrete Piles
(Peck, Hanson and Thornburn, 1974, p. 206)
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 water
tight 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 con-
sidered 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 8.14 Types of Fixed Pier Bracing
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
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 1/4 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)
Figure 6.18 Proper Grain Orientation for Wood Plank Decking

Decking is placed with growth rings oriented concave up.

Wood Deck Planks

Stringer
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 (Koepl, 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 1/2 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
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
joist and beam hangers

framing anchors

framing anchors

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
Figure 6.26 Line-Mooring and Cleat Location for Single and Double Berths

A. Single Berth

B. Double Berth
Figure 6.27 Cooperative Switch-Tie System for a Double Berth (Dunham and Finn, 1974, p. 111)

TIE SYSTEM
WITH BOTH BOATS DOCKED

TIE SYSTEM
WITH ONE BOAT DOCKED
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 bubbler 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.