FENDER SYSTEM DESIGN

1. INTRODUCTION

A fender is the interface between a ship and the shore facilities. Generally, its main objective is to protect the ship's hull from damage. In some cases it's the shore facilities that require protection against the impact of the ship.

There are many types of fender systems available ranging in complexity from a simple bolt-on timber whaler to a very sophisticated arrangement of frames, chains and buckling components.

A proper berth design will include a comprehensive analysis of two or three fendering alternatives, as the choice of fendering system could have a significant impact on the berth design. Consideration of such items as damage risk, load distribution to the structural members, pier facing design and cost will influence the total berth design.

The designer must first put together all available information on the design vessel and on the site conditions. Next he/she must judge the primary objective of the fender system which will include considerations for:

1) absorbing a certain amount of the energy generated on berthing the ship,
2) the role of the fender after the ship has been moored and it is subject to more or less static loads,
3) the role of the fender when the ship is moored and is subject to significant dynamic loads resulting from wave action, surges, high winds, etc.

With this, the designer will have developed the Design Criteria for the fender system and it is a matter of analyzing the available alternatives and selecting that system which best meets the Design Criteria.

Our manual is set-up in such a way to take the designer through a step-by-step procedure to arrive at the optimal fender selection for his/her project.

1.1 DESIGN WORKSHEET

To further assist the Engineer we've prepared a "Design Worksheet" which can be filled out and used during the fender system design process. This four page worksheet is located at the back of this section. Standard metric conversions are also included in Section 3.0 for convenience.

1.2 BERTHING ENERGY REQUIREMENTS

In general, the determination of the absorbed energy of a berthing ship can be made by the following methods:

a) Kinetic Energy Method
b) Statistical Method
c) Scale Model Tests
d) Mathematical Modeling

The most commonly used approach and the one covered here is the KINETIC ENERGY METHOD. It is the traditional method and is subject to the judgement of the designer, however, it is time tested and seems to account for the major variables influencing vessel berthing.

The Kinetic Energy of the berthing ship is calculated using the formula:

$$E_{Ship} = 1/2\ MV^2$$

Where E_{Ship} = Energy on Berthing
M = Mass or Water displacement of the ship
V = Approach Velocity of the ship at the moment of impact with the fender

This energy must be factored up or down, depending on rotation of the vessel on impact, the amount of water moving with the vessel thereby adding to its mass, the deformation of the ship's hull and the berth type.

Therefore, Energy to be absorbed by the fender system is:

$$E_{Fender} = E_{Ship} \times f$$

Where $$f = C_e \times C_m \times C_s \times C_c$$

C_e = Eccentricity Factor
C_m = Virtual Mass Factor
C_s = Softness Factor
C_c = Berth Configuration Coefficient

These variables are covered in detail on the following pages. Also, convenient charts are provided in Section 2.3 which indicate the amount of berthing energy generated by various ship sizes under standard conditions.

2. CALCULATING BERTHING ENERGY

2.1 KINETIC ENERGY EQUATION

The equation detailing the variables:

$$E_{Fender} = 1/2\,MV^2 \times C_e \times C_m \times C_s \times C_c$$

2.2 VARIABLES

a) Mass - M

One or more of the following weights should be readily available from the facility user:

Displacement Tonnage - DT
This is the weight of the water displaced by the immersed part of the ship.

Dead Weight Tonnage - DWT
This is the weight that the ship can carry when loaded to a specified load draft. (Includes cargo fuel, stores, crew, passengers.) It is the most common measurement.

Gross Tonnage - GT
This is based on the cubic capacity of the ship below the tonnage deck with allowance for cargo compartments above.

When calculating the mass - M, use the loaded displacement tonnage DT.

Typically DT is 30% - 40% greater than DWT.

Where: $M = \dfrac{DT}{g}$

DT = Displacement Tonnage (tonnes)

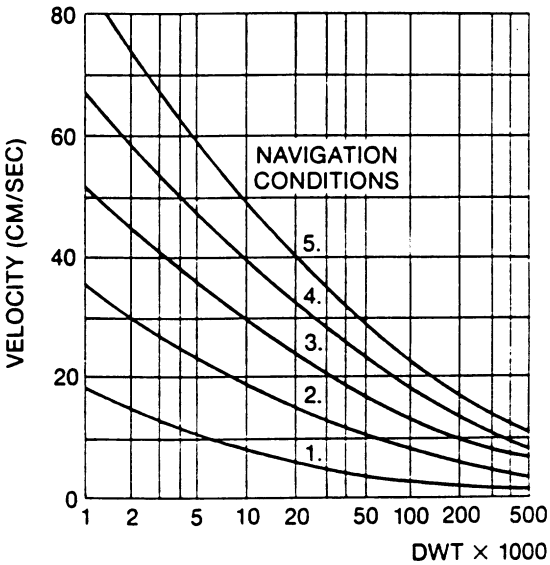
g = Acceleration Due to Gravity = 9.81 M/Sec^2

b) Velocity - V

As can be seen from the Kinetic Energy Equation, the energy to be absorbed is a function of the square of the approach velocity. For this reason, **DETERMINING THE VELOCITY IS ONE OF THE MOST IMPORTANT DECISIONS IN THE DESIGN.**

The choice of design velocity (velocity component normal to the dock) is a judgement based on ship size, site exposure and berthing procedure. Environmental aspects such as wind and current forces may be an influence. Section 2.5 b) describes how these forces can be calculated. Consultation with Port Management, ship operators and any other available information should be used when making the judgement.

The following chart is offered as a guide to assist in selecting a design velocity:

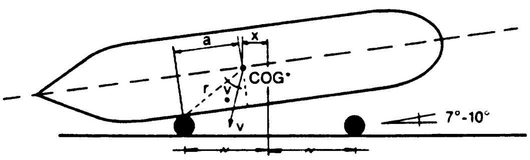


Navigation Conditions

1. Easy Docking; Sheltered
2. Difficult Docking; Sheltered
3. Easy Docking; Exposed
4. Good Docking; Exposed
5. Difficult Docking; Exposed

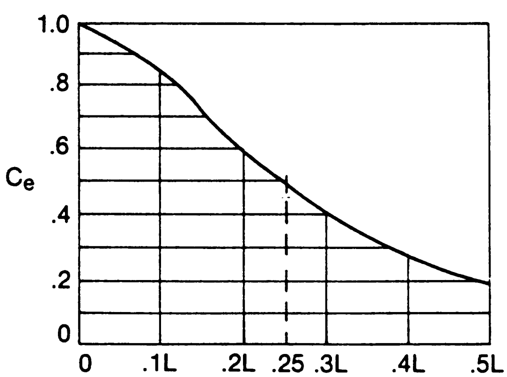
c) Eccentricity - C_e

Usually the ship is not parallel to the pier face during berthing. As a result, not all of the Kinetic Energy will be transmitted to the fenders. At impact, the ship will start to rotate around the contact point thus dissipating part of its energy.



Schematic diagram of berthing ship

The following graph illustrates the relationship between the eccentricity coefficient and the distance "a" (as shown above).



Alternatively, it is represented by the formula

$$C_e = \frac{K^2}{a^2 + K^2}$$

Where:

- **K** = radius of longitudinal gyration of the ship
- **a** = distance between the ship's centre of gravity and the point of contact on the ship's side projected onto the longitudinal axis (in terms of L - the ship's length)

The value of K is related to the block coefficient of the ship and its length. It can be approximated by the following expression:

$$K = (0.19\, C_b + 0.11) \times L$$

and the block coefficient C_b

$$C_b = \frac{DT}{D \times B \times L \times Wo}$$

Where:

- **DT** = Displacement of the ship (tonnes)
- **D** = Draft (m)
- **B** = Width (m)
- **L** = Length (m)
- **Wo** = Water Density (tonnes/M^3)

Typical Seawater Wo = 1.025 tonnes/M^3 (64 lb/ft^3)

Typical Freshwater Wo = 1.00 tonnes/M^3 (62.3 lb/ft^3)

- for larger Bulk Ships and Tankers
  $K = 0.2L - 0.25L$
- for Passenger Ships and Ferries
  $K = 0.17L - 0.2L$
- for 1/4 point Berthing $a = 0.25L$

The formula is based on the generally accepted assumptions that at the moment of maximum fender deflection:

1. Rotation only occurs at the contact point
2. Ship's hull does not slide along the fender
3. Forces such as wind, currents tugs are negligible compared to the fender reaction.

The approach angle is usually taken as 7° with a maximum of 10°. If the ship is berthing properly under control at the moment of contact with the fender then the direction of travel will be at right angles to the berthing face.

Examples:

In the case of a two dolphin mooring where the dolphins are 1/3 L distance apart, the minimum C_e is reached when the center of gravity of the large ship falls halfway between the two dolphins on contact with the fenders.

This is when $a = 1/6\,L$

therefore

$$C_e = \frac{(.25L)^2}{(1/6L)^2 + (.25L)^2} = 0.692$$

The maximum in this case, would occur when the ship's center of gravity falls in line with the point of contact with the fender or $a = 0$ Then $C_e = 1$.

In the case of a continuous fender system and a large oil tanker $a = 0.3L$

therefore

$$C_e = \frac{(0.25L)^2}{(0.3L)^2 + (0.25L)^2} = 0.41$$

Generally C_e ranges between 0.4 and 0.8

d) Virtual Mass Coefficient - C_m

When the ship is in motion and contacts the fender, the mass of the ship has to be decelerated as well as a certain mass of water surrounding and moving with the ship. This additional mass is accounted for in the virtual mass coefficient - C_m which is a function of: the block coefficient of the vessel, its draft and its width.

where:

$$C_m = 1 + \frac{\pi}{4\,C_b} \times \frac{D}{B}$$

C_b = block coefficient (see section 2.2c)
D = Draft
B = Width

an alternate formula recommended by Vasco Costa is:

$$C_m = 1 + \frac{2D}{B}$$

Since there is no conclusive experimental data, we would recommend calculating C_m both ways and using the higher value.

e) Softness Coefficient - C_s

This factor accounts for the relation between the rigidity of the ship and that of the fender. It expresses that proportion of impact energy absorbed by the fender. For a soft fender $C_s = 1.0$ as deflection of the ship's hull will be negligible and therefore all the energy will be absorbed by the fender. In the instance of hard fenders, it is assumed that the ship's hull will absorb 2 to 7 percent of the impact energy so C_s is taken as 0.98 to 0.93.

f) Berth Configuration Coefficient - C_c

This factor attempts to quantify the difference between an open pile supported pier and a solid sheetpile or concrete crib structure.

In the first case, the water being pushed by the berthing ship is easily able to be displaced around the pier. In the second case, the moving water is squeezed in between the structure wall and the ship causing a cushion effect. A reduction factor has to account for this effect.

For solid structures with parallel approach $C_c = 0.8$. As the approach angle increases from zero and as the under keel clearance increases then C_c increases to 1.0 which is the value for an open type support structure such as a pile supported pier.

2.3 VESSEL DIMENSIONS AND TYPICAL ENERGY REQUIREMENTS

The following tables show typical weights and dimensions for the various vessel classes. These are general and should be used only as a cross reference.

A berthing energy has been calculated based on standard conditions where:

1. Velocity: 0.15 m/sec in all cases
2. Eccentricity Coefficient: 0.5 (for 1/4 point berthing)
3. Virtual Mass Coefficient: as shown
4. Softness Coefficient: 1.0
5. Berth Configuration Coefficient: 1.0
6. Large under keel clearance / open berth

a) GENERAL CARGO

Tonnage (D.W.T.)	Length (m)	Width (m)	Height (m)	Loaded Draft (m)	Displacement Tonnage (DT)	Virtual Mass Coefficient	Berthing Energy (Tonne-M)*
800	56	9.0	4.0	3.8	1,115	1.6	1.02
1,000	58	9.4	4.6	4.2	1,390	1.59	1.27
2,500	83	12.4	6.7	5.5	3,470	1.58	3.15
5,000	109	15.0	8.4	6.7	6,930	1.57	6.23
7,500	129	18.0	10.2	7.7	10,375	1.59	9.48
10,000	142	19.1	11.1	8.2	13,800	1.56	12.32
12,000	150	20.1	11.9	8.7	16,500	1.55	14.73
15,000	162	21.6	12.7	9.1	20,630	1.52	18.02
20,000	180	23.5	14.0	10.1	27,400	1.54	24.19
25,000	195	25.0	14.5	10.3	34,120	1.50	29.35
30,000	200	26.0	15.7	11.0	40,790	1.48	34.62
35,000	210	27.2	16.2	11.7	47,400	1.49	40.50
40,000	217	28.3	17.3	12.0	54,000	1.47	45.52
45,000	225	29.2	17.9	12.4	60,480	1.46	50.65

b) CONTAINER SHIPS

Tonnage (D.W.T.)	Length (m)	Width (m)	Height (m)	Loaded Draft (m)	Displacement Tonnage (DT)	Virtual Mass Coefficient	Berthing Energy (Tonne-M)*
10,000	175	25.6	15.8	9.8	14,030	1.96	15.77
20,000	200	27.3	16.8	10.4	27,940	1.62	25.95
25,000	213	30.1	16.3	10.5	34,860	1.54	30.78
30,000	290	32.0	19.8	10.3	41,740	1.60	38.29
35,000	265	32.8	20.5	11.6	48,600	1.59	44.31
40,000	279	32.5	22.8	11.0	55,430	1.49	47.36
50,000	290	32.4	24.2	11.3	69,000	1.43	56.58

* These values are for general guidelines only. They should be checked using actual site conditions.

c) ORE CARRIERS

Tonnage (D.W.T.)	Length (m)	Width (m)	Height (m)	Loaded Draft (m)	Displacement Tonnage (DT)	Virtual Mass Coefficient	Berthing Energy (Tonne-M)*
2,500	83	11.9	6.4	5.4	3,290	1.59	3.0
5,000	105	14.9	8.0	6.5	6,570	1.54	5.8
10,000	140	18.5	10.5	8.0	13,100	1.55	11.64
15,000	160	21.0	12.0	9.0	19,600	1.53	17.19
20,000	175	23.5	13.0	9.7	26,090	1.51	22.60
30,000	195	26.6	14.4	10.5	38,970	1.44	32.18
40,000	210	29.7	15.9	11.1	51,740	1.40	41.53
50,000	222	32.5	17.0	11.8	64,390	1.40	51.69
60,000	238	34.0	17.6	12.3	76,940	1.38	60.88
80,000	259	38.0	19.1	13.1	101,690	1.35	78.72
100,000	278	41.0	21.0	15.2	126,000	1.41	101.87
150,000	310	45.5	25.0	17.6	184,840	1.42	150.50

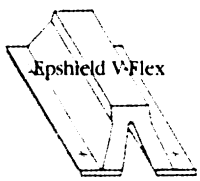
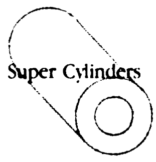
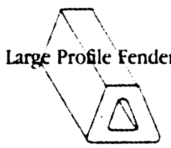
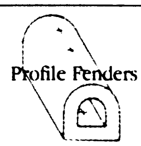
d) TANKERS

Tonnage (D.W.T.)	Length (m)	Width (m)	Height (m)	Loaded Draft (m)	Displacement Tonnage (DT)	Virtual Mass Coefficient	Berthing Energy (Tonne-M)*
1,000	58	9.4	4.5	4.2	1,360	1.60	1.25
2,500	82	12.0	6.1	5.5	3,400	1.59	3.10
5,000	102	15.0	7.7	6.5	6,790	1.51	5.88
8,000	126	15.7	9.0	7.4	10,600	1.52	9.24
10,000	140	19.0	9.8	7.9	13,540	1.52	11.80
15,000	163	20.0	11.2	8.6	20,250	1.48	17.19
20,000	175	23.5	12.3	9.6	26,930	1.48	22.85
30,000	195	27.0	14.1	10.7	40,190	1.45	33.41
40,000	213	29.6	15.2	11.8	53,300	1.45	44.31
50,000	224	32.0	16.6	12.3	66,270	1.41	53.58
60,000	236	34.0	17.7	12.7	79,100	1.39	63.04
70,000	248	35.8	18.6	13.5	91,790	1.40	73.69
85,000	260	38.1	18.7	14.0	110,550	1.37	86.84
100,000	285	40.1	21.1	14.8	129,000	1.39	102.82
150,000	300	46.1	24.3	17.0	188,200	1.37	147.84

* These values are for general guidelines only. They should be checked using actual site conditions.

2.4 OVERVIEW OF FENDER TYPES AVAILABLE BASED ON ENERGY RANGE REQUIRED

The following chart indicates the fender products available to cover particular energy ranges. It also points out the features and benefits of the various fender types.

ENERGY RANGE (Tonne-m)	FENDER TYPE	FEATURES	BENEFITS	RESTRICTIONS	REF. PAGE
50 & Larger	 Epshield V-Flex	A high efficiency fender which features rubber encapsulated steel mounting plates in its base. Rubber covered, slotted bolt holes are included. Available in a range of standard sizes and lengths.	High energy absorption capacity is obtained while minimizing the reaction load. No exposed metal and a secure mounting ensure low maintenance and a durable installation. Easily installed and the range of available lengths will fit most designs.	There are length restrictions.	
20 to 50	Epshield V-Flex	SEE ABOVE			
	 Super Cylinders	Good performance characteristics are achieved. Fender can roll for even wear. It is available in a wide selection of sizes.	Allows a wide range of ship sizes to use the pier. It is durable and easily accessible for maintenance or replacement.	Require large stand off distances. Exposed mounting hardware.	
	 Large Profile Fenders	Easily adaptable to specific mounting requirements.	These low initial cost fenders are well suited for parallel berthing in well protected conditions.	Mounting hardware is exposed.	
10 to 20	Epshield V-Flex	SEE ABOVE			
	Large Profile Fenders	SEE ABOVE			
	 Buckling Columns	Rubber encapsulated steel support plates. Good performance characteristics are achieved.	Excellent durability with no exposed metals. Mounted behind a protective fender pile system.	Cannot be used for direct contact.	
0 to 10	 Profile Fenders	A large selection of shapes and sizes.	Economical protection against wharf face damage.	Mounting hardware is exposed.	

2.5 OTHER FACTORS TO CONSIDER

Now that the fender design has been narrowed down to a couple of options, the designer must look at a number of other considerations and decide whether or not they are important in his design.

The following are a few common considerations:

a) Fender Performance Characteristics

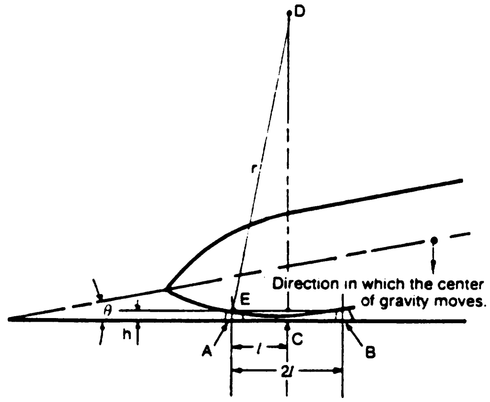
Not only must the fender design absorb the required berthing energy, but the designer must also consider the reaction loads that this system will impart to the structure. The reaction loads and their location may have a significant impact on the structure design. Generally the reaction loads are not a problem with gravity structures, however, with pile supported piers, the reaction loads may become critical to the design and may influence such things as batter pile locations and the rebar design.

b) Fender Spacing

Fender spacing along the pier face is an important design consideration. Here the designer is trying to maximize protective pier coverage while minimizing the fendering costs. Three methods are standardly used.

i) Fender spacing of not more than 1/10 the length of the design vessel.

ii) From the design vessel's geometry.



with the above configuration, the following formula can be developed:

$$2l = 2\sqrt{r^2 - (r - h)^2}$$

where:

r = the bent radius of the ship's hull at the contact line.

h = the compressed height of the fenders at their rated deflection.

Some typical bow bent radius values are shown below. Exact values from the design vessel should be used.

Approach Angle	Contact Line	General Cargo 10,000 DWT	General Cargo 30,000 DWT	Ore Carrier 35,000 DWT	Tanker 50,000 DWT
1°	Load Line	209	230	240	240
	Upper Deck	155	200	360	240
5°	Load Line	54	70	85	110
	Upper Deck	53	70	100	85
10°	Load Line	44	60	70	75
	Upper Deck	40	65	55	60

Units: Meters

iii) From the site conditions.

The fender spacing can be determined using the wind and current forces and equating them to the fender reaction forces. Use the following formula:

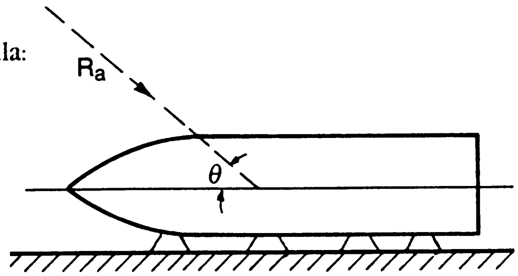
$$N = \frac{R_a + R_c}{R}$$

Where:

N = Number of fenders required
R_a = Load due to wind (see below)
R_c = Load due to current (see below)
R = Fender Reaction at rated deflection

Wind Loads

The wind loads can be calculated using the following formula:



$$R_a = 1/2 \times d_a \times (V_w)^2 \times C_w \times (A \cos^2\theta + B \sin^2\theta)$$

Where:

R_a = Force due to wind (kg)
d_a = Force of air (= 0.12 kg. sec²/m⁴)
V_w = Wind Velocity (m/sec)
C_w = Wind pressure coefficient
A = Area of the front projection of the vessel above sea level (m^2)
B = Area of the side projection of the vessel above sea level (m^2)
θ = Angle of the wind direction relative to the centerline of the vessel.

The wind pressure coefficient is relative to the angle of wind direction as shown in the table below:

Wind Direction θ°	0°	20	40	60	80	100	120	140	160	180
C_w	1.08	1.025	1.18	1.09	0.98	0.94	1.0	1.15	1.28	0.99

Current Loads

The loading on the vessel due to current pressure is calculated as follows:

$$R_c = 1/2 \times d_w \times C \times (V_c)^2 \times L \times D$$

Where:

R_c = Reaction load due to current (kg)
d_w = Water Force (= 104.5 kg. sec^2/m^4)
C = Current Pressure Coefficient
V_c = Velocity of the current (m/sec)
L = Vessel Length (m)
D = Vessel Draft (m)

The Current Pressure Coefficient is relative to the angle of current direction and to the water depth to draft ratio.

	C		
Current Direction θ°	H/D = 1.1	H/D = 1.5	H/D = 7.0
0	0	0	0
20	1.2	0.5	0.3
40	3.1	1.3	0.6
60	4.1	2.1	0.8
80	4.6	2.3	0.9
100	4.6	2.2	0.8
120	4.0	1.8	0.7
140	2.8	1.3	0.5
160	1.0	0.5	0.3
180	0	0	0

H = Water Depth; D = Draft

c) Normal Operations

i) Stand Off Distance

The allowable standoff distance will be governed by the loading/unloading activities and the normal operating procedures of the ship and pier while berthed. Operating constraints such as crane reach, roll, yaw and freeboard are major considerations in the design. The fenders must provide adequate protection yet accommodate the design.

ii) Vertical vs. Horizontal Mounting

There is an ongoing concern as to when the fenders should be mounted horizontally and when vertical. In general, vertically mounted fenders provide the best coverage for piers which experience tidal fluctuations. Where the operating procedures require that the vessel slide along the pier face, horizontal bolt-on fenders provide good protection. A combination of horizontal and vertical arrangements are often used.

iii) Tidal Variation

The change in water level due to tides will have a significant impact on the operation of the pier and consequently the pier design and the fender design as well. Protection in all cases must be achieved for both the largest and smallest ships.

iv) Range of Ship Sizes

While the energy absorption capacity of the fender system is chosen for the design vessel, the fender system should be suitable for the full range of ships expected to use the facility. Fender stiffness on the smaller vessels may have an influence on the arrangement of the fenders. Also, if barges are to use the facility, special attention must be given to their fender requirements.

v) Frequency of Berthing

A high frequency of berthings normally justifies greater capital expenditures for the fender system.

d) Accidental Impact

The fender system is less expensive than the dock structure and it should be recognized that damage to the fenders is less critical than to the vessel or the structure. The design should incorporate a reasonable level of energy absorbing capacity. If the fender system fails, it would be an advantage if the structure were designed so that it could inexpensively be repaired. The mode of failure of a fender and its effect on the dock structure should be considered.

e) Ongoing Maintenance Costs

Maintenance costs can be an important factor and should be considered when analyzing the overall costs of the various fender options. Maintenance costs will vary with fender type.

f) Ease of Installation

A well designed fender system will be as easy to install as possible. This will minimize initial capital costs and reduce down the road maintenance costs.

3.0 CONVERSION TABLES

Distance

From	To	Factor	Reciprocal
inch	mm	25.4	0.03937
ft.	m	0.3048	3.2808
Yd.	m	0.9144	1.09361

Velocity

From	To	Factor	Reciprocal
cm/sec	ft./min.	1.969	0.508
cm/sec	ft./sec.	0.0328	30.48
Knot	ft./sec.	1.689	0.592
miles/hr	ft./min.	88.0	0.0114
miles/hr	Km./hr.	1.609	0.6215
m/sec	ft./sec.	3.281	0.3048

Force

From	To	Factor	Reciprocal
Kg	lbs.	2.205	0.454
Kips	lbs.	1000.0	0.001
Kips	tonnes	0.454	2.205
Tons (long)	lbs.	2240.0	0.000446
Newtons	lbs.	0.225	4.45
Kg	Newtons	9.807	0.102

Energy

From	To	Factor	Reciprocal
ft.-Kips	Tonne-Meters	0.1383	7.235
ft-lbs.	Newton-Meters	1.356	0.738
Tonne-Meters	KN-Meters	9.807	0.102

Pressure

From	To	Factor	Reciprocal
lbs./ft.^{2}	Kg/m^2	4.882	0.2048
lbs./ft.^{2}	psi	0.006944	144.0
psi	Kg/m^2	702.9	0.00142
tonne/m^2	Kips/ft.^{2}	0.2048	4.882
tonne/m^2	KN/m^2	9.807	0.1020
Kips/ft.^{2}	KN/m^2	47.86	0.02090

4. FENDER OPTIONS

Using the total berthing energy calculated in part 3 as a guideline, review available fender products and narrow down the number of possible options to two or three. Refer to "Fender Overview Guide" sub-section 2.4 in the Engineering section.

	OPTION 1	OPTION 2
Fender Type (make, model)		
Energy Absorption/unit (from literature)		
Quantity Required = E/Energy absorbed per unit		
Reaction Load (from literature)		
Cost Estimate:		
1. Rubber Fenders (Supply & Install)		
2. Hardware (Supply & Install)		
3. Maintenance Costs		
4. Other Costs (Modifications for mounting, fender piles, frames, etc.)		

5. ANALYSE THE OPTIONS

Do a detailed review of the two or three options making sure to consider any special circumstances or requirements. Refer to sub-section 2.5 for additional factors to consider.

6. FINAL DESIGN

Specification should include:

1. Performance requirement for the fender in terms of energy and reaction
2. Material specification for the rubber
3. Part dimensions
4. Fastening details