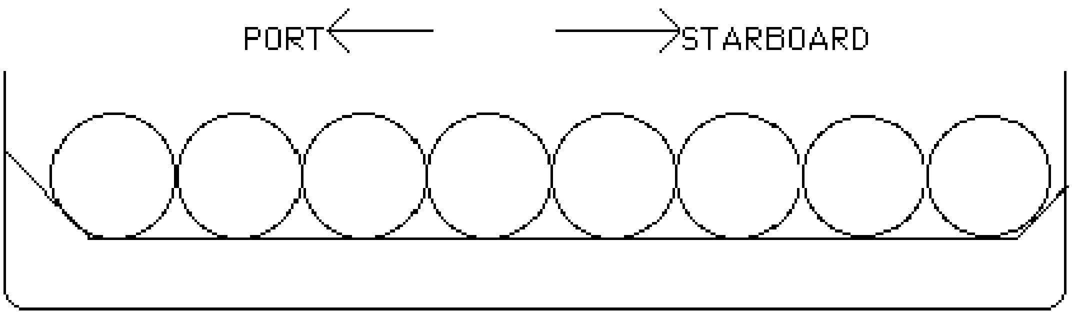
THOERITICAL CALCULATION FOR DUNNAGING WITH STEEL COILS

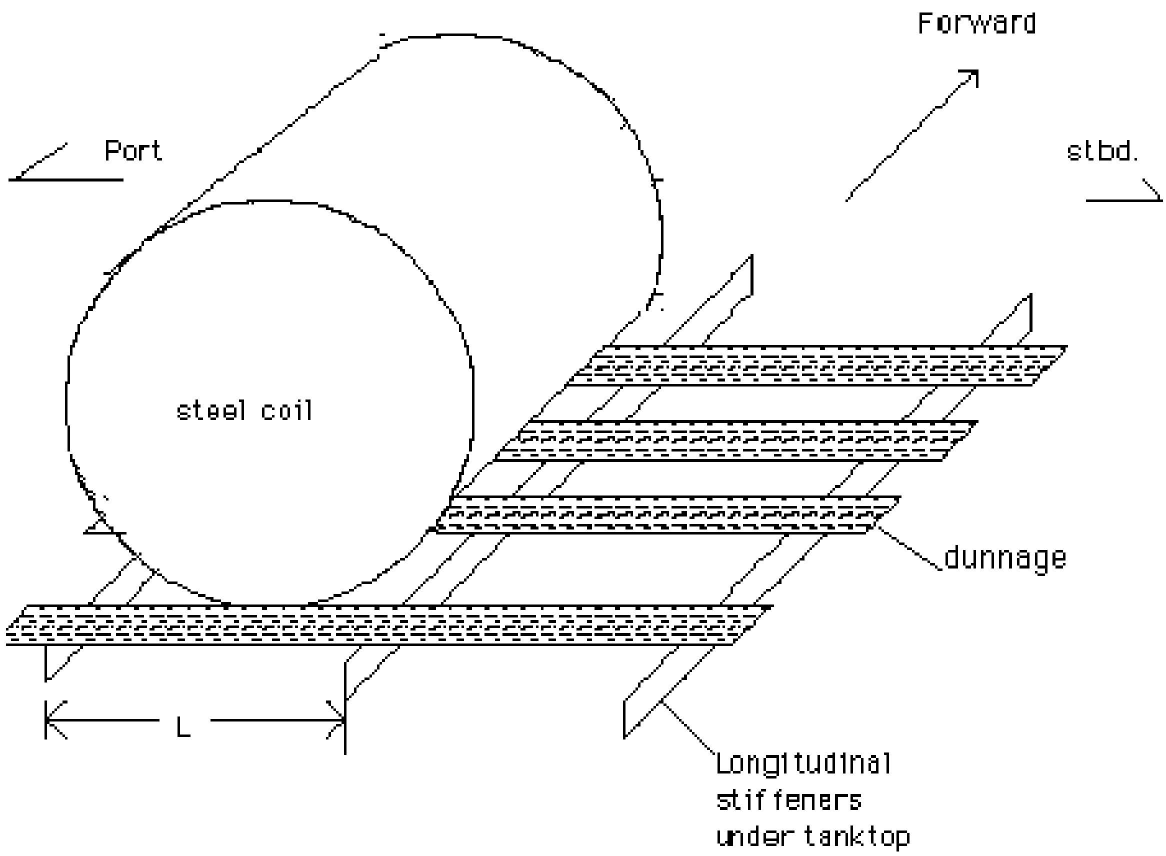
We enclose a description from a Japanese loading manual showing the kind of dunnage the Japanese recommend for a ship whose longitudinal frame spacing is 750 mm and whose floor space is 1600 mm. Please note that Japanese coils are typically 1 meter in diameter and width varies from about 1.5 to 2 meters. The Japanese do not show how they arrived at this proposed dunnage; however we made the analysis below which we believe can be applied to any ship. To make the calculation you must know the following:

1) THE DIAMETER OF THE COIL
2) THE WIDTH (SOMETIMES ALSO CALLED LENGTH) OF THE COIL.
3) THE LONGITUDINAL FRAME SPACING OF THE TANKTOP
4) THE FLOOR SPACE (SPACE BETWEEN TRANSVERSE WEBS).

At this point, some judgement must be used as there are two possible models for calculating the correct type of dunnage.

In most cases, steel coils are always loaded so that the coils are placed side by side from port to starboard by their diameters. This is done for safety reasons in order to prevent the coils from moving when the ship is rolling. In this way the coils are effectively locked together to prevent any shifting of cargo in heavy weather.



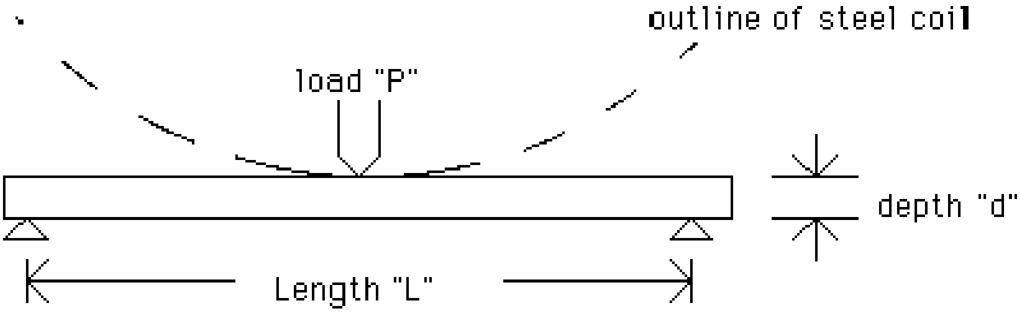


We need to use a simple model in order to calculate approximately the kind of wood we need.

The actual case in theory is a bending stress problem in which a weight rests on a plank of wood which then rests on a steel plate which is welded (fixed) to beams. Furthermore, the contact between the wooden plank and the tanktop is not perfect because there may be local damages on the tanktop as well as well as some sagging of the tank top plates. We can simplify this model though by imagining the following:

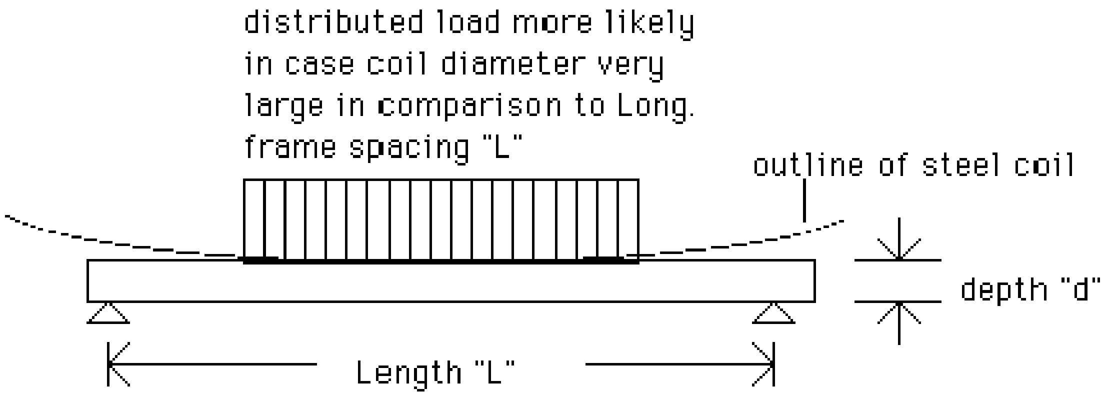
In the worst case we can imagine that the ship has no tank top and that the wood must carry all the weight of the steel coil. Obviously if the dunnage can completely support the weight of the steel coil, then there will be no possible damage to the steel tank top. We use this model with the dunnage (wooden beam) being long enough so that it is supported by the steel longitudinal frames underneath the tank top. At this point <u>depending on the diameter of the coil compared to the longitudinal frame spacing,</u> we either assume:

Case 1) that the coil is touching the dunnage at only one point (point load) as shown in the diagram below.



or

Case 2) The diameter of the coil is so big, that a large part of the coil touches the dunnage so that a uniformly distributed load is placed on the wood.



We cannot, ahead of time, advise you which is the better model to use because frankly it depends on the diameter of the coil and on the longitudinal frame spacing. For example, Japanese coils are typically about 1 meter diameter and 1.6 meters wide. In this case the circumference of the coil is 3.14 meters (_ (pi) x dia) . If we assume that the coil is touching over about a 30 degree angle at its bottom with the wood dunnage (assume some local compression/distortion of the wood dunnage so that the contact cannotbe at a single point), then the touching length would be (30? /360) x 3.14 meters which equals 260 mm. If the longitudinal frame spacing is 750 mm, this case is more similar to point load as only 260 mm of the 750 mm length of the wood has contact with the coil. However, if the steel coil is 2.70 meters in diameter, then the same 30 degree area would produce a touching length of 700 mm. In the case of this larger diameter coil, almost the entire length of the wood plank between longitudinals bears direct contact with the coil, and the uniformly distributed load case is more likely to produce a correct result. In case there is any doubt, the point load case (case 1) always provides the more conservative answer (least risk).

Formulas

For point load - Case 1

The basic formula for maximum allowable load, P, on a beam is defined from bending theory as:

$$P = \frac{\sigma\, b\, d^2}{k * L} \qquad \text{or} \qquad P = \frac{Fb\, b\, d^2}{1.5*L}$$

b - is the width of the wood plank.
d - is the thickness (depth) of the wood plank.
L - is the length of the wood, but in this case we assume it to be the length between longitudinal frames in case coils are loaded as shown in the drawings above.
k - is a constant which for simple beams loaded at the middle = 1.5. (from beam theory).
σ can be converted to F_b which is known as the maximum allowable bending stress at the midspan (L/2) of the wood involved. Typically, commerical lumber is graded in North America and the grade stamp "f" on the lumber is the same as $F_{b.}$ We are not sure how lumber is graded in Europe but it would be safer to assume that a similar system is employed to show the strength of the wood. F_b is the maximum stress at which the lumber will perform as per Young's law where the the stress is proportional to strain (no permanent deformation). In case you do not care about permanent deformation to the wood after loading, then you could conceivably apply a load which stresses the wood up to the value "MR" which is also known as the modulus of rupture. This is the stress at which the wood is about to break (rupture).

For unifomly distributed load - Case 2,

$$P = \frac{\mathbf{2} \times Fb\, b\, d^2}{1.5*L}$$

This follows from Bending theory since for a uniformly distributed load, the bending moment at the center of the beam is one half of that for point load. So maximum allowable force can be doubled in case of uniform load.

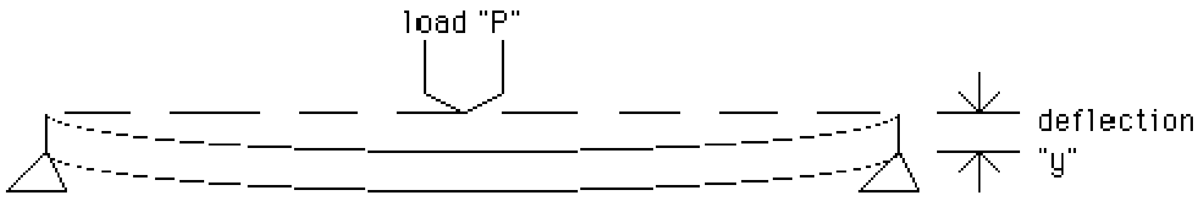
Typically from test samples, (see enclosed table) there are a variety of values of both F_b and MR for hardwoods and softwoods. As you can imagine, there are various types and quality of dunnage available depending on how much money the shipper wants to spend for wood.

In case of softwoods, we are using values of about 6500 psi (pounds per sq in.) for F_b and a modulus of elasticity,E, of 1,250,000. These are approximate values for Pine.

In case of hardwoods, we are using values of about 8000 psi for F_b and a modulus of elasticity of 1,500,000 psi.

Naturally hardwoods will have a higher allowable stress as they are stronger than softwoods (in general). However they are also generally more expensive.

In order for the wood to be effective as dunnage, it must not reach the rupture limit. If the wood breaks or cracks, it is obviously useless in protecting the tanktop against point loads. Additionally the wood must not deflect(bend) too much because then you will not get even distribution of weight on the steel floor below. It will not touch the steel tanktop properly. Generally in North America we look for deflections of less than L/360. In other words if frame spacing is 750 mm, we would prefer to see the deflection "y" to be maximum about 2 mm. However as there is indeed a steel floor underneath the wood we can accept somewhat larger deflections as the steel floor will limit the amount the wood can deflect anyway. However as you will see from the examples below, if the wood stays within the elastic range, it will not deflect (bend) very little (unless L is very large).



In case 1 - Point load:
The formula for deflection of the simply loaded wooden beam is

$$y = \frac{PL^3}{4Ebd^3} \quad \text{or} \quad \frac{.25 \times PL^3}{Ebd^3}$$

In case 2 - Uniform load
The formula for deflection of a uniformly loaded beam is:

$$y = \frac{60 \times PL^3}{384 \times Ebd^3} \quad \text{or} \quad \frac{.15625 \times PL^3}{Ebd^3}$$

where all values are as above for bending stress and "E" is the modulus of elasticity.

We know make a calculation as an example.

Assume
L = 750 mm (30 inches)
b = 200 mm (8 inches)
d = 50 mm (2 inches).
F_b= 6500 psi (for softwood).

Let us assume that we have a steel coil weighing 20 tons at that the width of the coil is 1.6 meters. The diameter is about 1 meter. Since the width of the coil is 1.6 meters, we decide to place 4 dunnage pieces undeneath. Since each piece is 200 mm wide, we can space them about 200 mm apart.

Each dunnage piece must support about 5 tons. (20 tons / 4 pieces).

We calculate maximum allowable load as follows (we use english units because allowable values we have in our table are in psi).

$$P \text{ allowable} = \frac{6500 \times 8 \times 2^2}{1.5 \times 30} = 4622 \text{ lbs per plank.} = 2.1 \text{ tons per plank.}$$

The dunnage appears too weak since we want to support 5 tons per plank of wood.

We decide to use hardwood. In this case::

$$P \text{ allowable} = \frac{8000 \times 8 \times 2^2}{1.5 \times 30} = 5688 \text{ lbs per plank.} = 2.6 \text{ tons per plank.}$$

Again with hardwood we have some improvement. However still not enough.

If we decide to use 75 mm thick wood (3 inches). Then we have a tremendous improvement. In this case with softwood.

$$P \text{ allowable} = \frac{6500 \times 8 \times 3^2}{1.5 \times 30} = 10400 \text{ lbs per plank} = 4.72 \text{ tons per plank.}$$

In case of hardwood, P allowable is increase to 5.8 tons per plank.

If we decide to to use MR (rupture stress) instead of F_b, the maximum elastic bending stress, then all above values can be increased by 50%.

We can also make a quick calculation of deflection using:

$$y = \frac{PL^3}{4Ebd^3}$$

In case of 75 mm hardwood, the maximum deflection will be

$$\frac{10400 \text{ lbs} \times (30)^3}{4 \times 1{,}500{,}000 \times 8 \times (3)^3} = .021 \text{ inches or } 0.5 \text{ mm.}$$

On a 750 mm spacing for the wood, 0,5 mm deflection is 1/1500 deflection. In other words we can fully expect the wood to evenly distribute the load to the tanktop underneath.

The Japanese in their enclosed example recomnmended to use 50 mm x 200 mm wood dunnage. Our calculation above suggests that 50mm wood is not quite strong enough, however we need to point out the following: In our above example, we were conservative by assuming a point load for the steel coil. In reality, even with small coils, the actual load on the wooden dunnage is somewhere between point load and fully distributed load. In case of uniform distributed load, the above values in all cases would be doubled. So even the softwood would allow 4.2 tons per plank (double of 2.1 tons) in case of uniform load. If we decide to throw away the dunnage after use of one loading, then we can also use the rupture stress of the wood instead of the Maximum bending stress. In which case the rupture stress allows again 50% more additional loading, or 6.3 tons. So if estimate that in actual loading situation the permissible loading value will be halfway between point load and full distributed load, or 3.9 tons, and we use the rupture stress (50% additional), the 50 mm softwood dunnage can allow to 5.85 tons of load before rupturing. Since the Japanese are talking about 10 ton to 20 ton coils, you can see that 20 ton coils are the worst case and 50 mm thick would probably be acceptable. The Japanese have chosen this size wood more from their practical experience rather than any theoretical calculation of the wood strength. However keeping in mind that 1) the actual situation has some uniform loading, 2) if one is not concerned if the dunnage is thrown away afterwards, and 3) realistically the steel tanktop underneath is providing some support to the wood, then the 2 inch thick dunnage becomes acceptable.

You will note that in the case of 75 mm thick wood, there is absolutely no problem and no risk whatsoever. We need to emphasize that the type of dunnage used is most sensitive to thickness because allowable load is proporational to the square of the thickness. However the longitudinal frame spacing is also important as the allowable stress decreases proportionately to length (1/L).

Let us know look at steel coils of 2.70 meters diameter and 0.575 meters width weighing 25 tons each.

The spacing between longitudinal frames is assumed to be 750 mm.

In case we use wood dunnage of of d= 75 mm and b = 200 mm, we can only use two planks of wood under each coil. Because of the small width of 0.575 meters, a third plank cannot be inserted. So each plank must be able to carry 12.5 tons.

Because the diameter of the coil is so large, we would expect the load to be almost uniformly distributed between the longitudinal frames. In this case use:

$$P = \frac{2 \times F_b\, b\, d^2}{1.5 * L}$$

In case we use softwood, then

$$P \text{ allowable} = 2 \times \frac{6500 \times 8 \times 3^2}{1.5 \times 30} = 20800 \text{ lbs per plank} = 9.44 \text{ tons per plank.}$$

In case we use the modulus of rupture, this can be increase by 50% to 14.16 tons. So it seems that two planks under each coil of 75 x 200 x 1.6 meters should be OK.

We did not mention earlier why we prefer 1.6 meter long planking. Generally the standard size of planking available in the market is about 2 meters long (8 feet). In any case it is recommended to always have a plank that can extend across 3 longitudinal frames even though our above calculations are based on load on two frames. So for three frames, the total miminum distance is 1.5 meters (and we stated 1.6 m for safety).

If we look at the deflection (which is also very important). We use the formula for uniformly distributed load in the <u>elastic range of the wood</u> as follows:

$$y = \frac{60 \times PL^3}{384 \times Ebd^3} \quad \text{or} \quad \frac{.15625 \times PL^3}{Ebd^3}$$

In this case (we convert everything to inches)

$$= \frac{.15625 \times 20800 \times 30^3}{1{,}250{,}000 \times 8 \times 3^3} = .0108 \text{ inches or } 0.275 \text{ mm}$$

In reality, we would prefer to avoid going beyond the elastic limit of the wood, especially because these coils are so strange in size. So possibly another kind of dunnage is recommended.

Here in North America, a very common size is 100 mm x 100 mm. In this case, we can place underneath the steel coil 3 or 4 pieces of this size dunnage.

The allowable load for this size dunnage (softwood) is as follows:

$$P = \frac{2 \times Fb\ b\ d^2}{1.5 * L}$$

converting all dimensions to inches:

$$= \frac{2 \times 6500 \times 4 \times 4^2}{1.5 \times 30} = 18488 \text{ pounds or } 8.4 \text{ tons per plank.}$$

This means that if we use three planks under each coil, the total allowable weight is 25.2 tons which should be sufficient. However, because of the unusual size of this kind of coil, and because we used the uniformly distributed formula (actual distribution is slightly more concentrated), it would probably be more prudent to use 4 pieces of this wood - 100mm x 100mm x 1.6m (min). By making the wood thicker but less wide, we were able to maintain almost the same permissible load per plank, but allow more planks to be placed under the coil.

We need to emphasize that stevedores (shippers) typically try to use very cheap wood (softwood). Also, the thicker the wood is, the more expensive it is, so again they try to supply thin wood (less than 50 mm thick) or they try to say that two or three pieces of 25 mm thick wood placed on each other is as good as one piece of 50 mm or 75 mm wood. As you know, this is completely wrong and can be further shown by beam theory. The formulas shown above only work if the thickness of the wood is from one beam. Placing thin beams on top of each other, even if nailed together, does not provide nearly as much strength as one thick (deep) beam.

Furthermore, in the theory above, a judgement must be made about whether the load is distributed or point load. This is to some extent subjective. The diameter of the coil must be compared to the frame spacing. We used earlier the formula that contact surface length between steel coil and wood plank is calculated as

$$\frac{30 \text{ degrees} \times \text{Pi} \times \text{diameter}}{360 \text{ degrees}} = \text{approximate contact length.}$$

We would then say:
1) if approximate contact length is 0.3 x L or smaller then assume point load.(case 1).
2) if the approximate contact length is 0.7 x L or more then assume distributed load formula (case 2).
3) if approximate contact length is between 0.3 and 0.7 x L, then assume permissible load halfway between point and distributed load. (if allowable point load is P, and allowed distributed load is 2 x P, then use 1.5 x P).
However if there is ever any doubt, use the more conservative formula which is for point load(case 1).

We hope the above information is useful for calculating required dunnage with steel coils.