10
Transportation and Erection of Pressure Vessels

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Procedure 10-1: Transportation of Pressure Vessels

The transportation of a pressure vessel by ship, barge, road, or rail will subject the vessel to one-time-only stresses that can bend or permanently deform the vessel if it is not adequately supported or tied down in the right locations. The shipping forces must be accounted for to ensure that the vessel arrives at its destination without damage.

It is very frustrating for all the parties involved to have a load damaged in transit and to have to return it to the factory for repairs. The cost and schedule impacts can be devastating if a vessel is damaged in transit. Certain minimal precautions can avoid the costly mistakes that often lead to problems. Even when all precautions are made, however, there is still the potential for damage due to unforeseen circumstances involved in the shipping and handling process.

Care should be taken to ensure that the size and location of the shipping saddles, tie-downs, or lashing are adequate to hold the vessel but not deform the vessel. Long, thin-walled vessels, such as trayed columns, are especially vulnerable to these shipping forces. The important thing to remember is that someone must take the responsibility. The barge and rail people have their own concerns with regard to loading and lashing. These may or may not coincide with the concerns of the vessel designer.

The shipping forces for ships, barges, trucks, and rail are contained in this procedure. Each method of transportation has its own unique load schemes and resulting forces. Barge shipping forces will differ from rail due to the rocking motion of the seas. Rail shipments, however, go around corners at high speed. In addition, rail forces must allow for the “humping” of rail cars when they are joined with the rest of the train. Ocean shipments have to resist storms and waves without breaking free of their lashings.

Whereas horizontal vessels on saddles are designed for some degree of loading in that position, vertical vessels are not. The forces and moments that are used for the design of a vertical vessel assume the vessel is in its operating position. Vertical vessels should generally be designed to be put on two saddles, in a horizontal position, and transported by various means. That is the purpose of this procedure. Too often the details of transportation and erection are left in the hands of people who, though well versed in their particular field, are not pressure vessel specialists.

Often vessels are transported by multiple means. Thus there will be handling operations between each successive mode of transportation. Often a vessel must be moved by road to the harbor and then transferred to a barge or ship. Once it reaches its destination, it must be reloaded onto road or rail transport to the job site. There it will be off-loaded and either stored or immediately erected. A final transport may be necessary to move the vessel to the location where it will be finally erected. At each handling and transport phase there are different sets of forces exerted on the vessel that must be accounted for.

Shipping Saddles

The primary concern of the vessel designer is the location and construction of the shipping saddles to take these forces without overstressing or damaging the vessel. If saddles are to be relocated by the transporter, it is important that the new locations be reviewed. Generally only two shipping saddles should be used. However, this may not always be possible. Remember that the reason for using two saddles is that more than two saddles creates a statically indeterminate structure. You are never assured that any given saddle is going to take more than its apportioned load.

Here are some circumstances that would allow for more than two saddles to be used or for a special location of two saddles:

- Transporter objects due to load on tires.
- Transporter objects due to load on barge or ship.
- Very thin, long vessel.
- Heavy-walled vessels for spreading load on ship or transporters.

Shipping saddles can be constructed of wood or steel or combinations. The saddles should be attached to the vessel with straps or bolts so that the vessel can be moved without having to reattach the saddle. Horizontal vessels may be moved on their permanent saddles but should be checked for the loadings due to shipping forces and clearances for boots and nozzles. Shipping saddles should have a minimum contact angle of 120°, just like permanent saddles. Provisions for jacking can be incorporated into the design of the saddles to allow loading and handling operations without a crane(s).
Shipping saddles should be designed with the vessel and not left up to the transport company. In general, transportation and erection contractors do not have the capability to design shipping saddles or to check the corresponding vessel stresses for the various load cases.

Whenever possible, shipping saddles should be located adjacent to some major stiffening element. Some common stiffening elements include stiffening rings, heads (both internal and external), or cones. If necessary, temporary internal spiders can be used and removed after shipment is complete.

Key factors for shipping saddles to consider:

- Included angle.
- Saddle width.
- Type of construction.
- Lashing lugs.
- Jacking pockets.
- Method of attachment to the vessel.
- Overall shipping height allowable—check with shipper.

Recommended contact angle and saddle width:

<table>
<thead>
<tr>
<th>Vessel Diameter</th>
<th>Contact Angle</th>
<th>Minimum Saddle Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>D &lt; 13 ft-0 in.</td>
<td>120°</td>
<td>11 in.</td>
</tr>
<tr>
<td>13 ft-0 in. &lt; D &lt; 24 ft-0 in.</td>
<td>140°</td>
<td>17 in.</td>
</tr>
<tr>
<td>D &gt; 24 ft-0 in.</td>
<td>160°</td>
<td>23 in.</td>
</tr>
</tbody>
</table>

Vessel Stresses

The stresses in the vessel shell should be determined by standard Zick’s analysis. The location of shipping saddles should be determined such that the bending at the midspan and saddles is not excessive. Also, the stresses due to bending at the horn of the saddle is critical. If this stress is exceeded, the saddle angle and width of saddle should be increased. Also, move the saddle closer to the head or a major stiffening element.

Lashing

Vessels are lashed to the deck of ships and barges. In like manner they must be temporarily fixed to railcars, trailers, and transporters. Lashing should be restricted to the area of the saddle locations. Vessels are held in place with longitudinal and transverse lashings. Lashings should never be attached to small nozzles or ladder or platform clips. In some cases, lashing may be attached to lifting lugs and base rings. Lashings should not exceed 45° from the horizontal plane.

Other Key Factors to Consider

- Shipping clearances.
- Shipping orientation—pay close attention to lift lugs and nozzles.
- Shipping route.
- Lifting orientation.
- Type of transport.
- Watertight shipment for all water transportation.
- Escorts and permits.
- Abnormal loads—size and weight restrictions.
- Vessels shipped with a nitrogen purge.
- Shipping/handling plan.

Organizations That Have a Part in the Transportation and Handling of Pressure Vessels

- Vessel fabricator.
- Transport company.
- Engineering contractor.
- Railway authorities.
- Port authorities.
- Erection/construction company.
- Trailer/transporter manufacturer.
- Ship or barge captain.
- Crane company/operator.

Special Considerations for Rail Shipments

1. Any shipment may be subject to advance railroad approval.
2. Any shipment over 10 ft-6 in. wide must have railroad approval.
3. A shipping arrangement drawing is required for the following:
   a. All multiple carloads (pivot bolster required).
   b. All single carloads over 10 ft-6 in. wide.
   c. All single carloads over 15 ft-0 in. ATR (above top of rail).
   d. All single carloads that overhang the end(s) of the car and are over 8 ft-0 in. ATR.
4. Clearances must be checked for the following:
   a. Vessels greater than 9 feet in width.
   b. Vessels greater than 40 feet overall length.
   c. Vessels greater than 50 tons.
5. The railroad will need the following specific data as a minimum:
   a. Weight.
   b. Overall length.
   c. Method of loading.
   d. Loadpoint locations.
   e. Overhang lengths.
   f. Width.
   g. Height.
   h. Routing/route surveys.
   i. Center of gravity.
6. A swivel (pivot) bolster is required whenever the following conditions exist:
   a. Two or more cars are required.
   b. The capacity for a single car is exceeded.
   c. The overhang of a single car exceeds 15 feet.
7. Rated capacities of railcars are based on a uniformly distributed load over the entire length of the car. The capacity of a car for a concentrated load will only be a percentage of the rated capacity.
8. Rules for loads, loading, and capacities vary by carrier. Other variables include the types of cars the carrier runs, the availability, and the ultimate destination. Verify all information with the specific carrier before proceeding with the design of shipping saddles or locations.
9. For vessels that require pivot bolsters, the shipping saddles shall be adequately braced by diagonal tension/compression rods between the vessel and the saddle. The rods and clips attached to the vessel shell should be designed by the vessel fabricator to suit the specific requirements of the carrier.
10. If requested, rail bolsters can be returned to the manufacturer.
11. Loading arrangement and tie-downs will have to pass inspection by a representative of the railways and sometimes by an insurance underwriter prior to shipment.
12. Accelerometers can be installed on the vessel to monitor shipping forces during transit.
13. A rail expediter who accompanies the load should be considered for critical shipments.
14. The railroad will allow a fixed time for the cars to be offloaded, cleaned, and returned. Demurrage charges for late return can be substantial.

Outline of Methods of Vessel Shipping and Transportation

1. Road.
   a. Truck/tractor and trailer.
   b. Transporters—single or multiple, self-propelled or towed.
   c. Special—bulldozer.
   d. Frame adapters.
   e. Beams to span trailers or transporters.
   f. Rollers.
   g. Special.
2. Rail.
   a. Single car.
   b. Multiple cars.
   c. Special cars.
   d. Types of cars.
      * Flatcar.
      * Fishbelly flatcar.
      * Well car.
      * Heavy-duty car.
      * Gondola car.
3. Barge.
   a. River barge.
   b. Ocean-going barge.
   c. Lakes and canals.
4. Ships.
   a. Roll-on, roll-off type.
   b. Loading and off-loading capabilities.
   c. In-hull or on-deck.
   d. Floating cranes.
5. Other.
   a. Plane.
   b. Helicopter.
   c. Bulldozer.
Table 10-1
Overland shipping limits in the US

<table>
<thead>
<tr>
<th>State</th>
<th>Length, ft</th>
<th>Width, ft</th>
<th>Height, ft</th>
<th>Gross Weight, lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alabama</td>
<td>150</td>
<td>16</td>
<td>16</td>
<td>180,000</td>
</tr>
<tr>
<td>Arizona</td>
<td>120</td>
<td>14</td>
<td>16</td>
<td>250,000</td>
</tr>
<tr>
<td>Arkansas</td>
<td>100</td>
<td>14</td>
<td>14</td>
<td>120,000</td>
</tr>
<tr>
<td>California</td>
<td>120</td>
<td>14</td>
<td>16</td>
<td>220,000</td>
</tr>
<tr>
<td>Colorado</td>
<td>130</td>
<td>17</td>
<td>16</td>
<td>228,000</td>
</tr>
<tr>
<td>Connecticut</td>
<td>120</td>
<td>15</td>
<td>16</td>
<td>250,000</td>
</tr>
<tr>
<td>Delaware</td>
<td>120</td>
<td>15</td>
<td>15</td>
<td>250,000</td>
</tr>
<tr>
<td>Florida</td>
<td>150</td>
<td>16</td>
<td>16</td>
<td>250,000</td>
</tr>
<tr>
<td>Georgia</td>
<td>100</td>
<td>14</td>
<td>14</td>
<td>120,000</td>
</tr>
<tr>
<td>Idaho</td>
<td>110</td>
<td>16</td>
<td>15'6&quot;</td>
<td>200,000</td>
</tr>
<tr>
<td>Illinois</td>
<td>145</td>
<td>14'6&quot;</td>
<td>15</td>
<td>250,000</td>
</tr>
<tr>
<td>Indiana</td>
<td>110</td>
<td>16</td>
<td>15</td>
<td>250,000</td>
</tr>
<tr>
<td>Iowa</td>
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<td>18</td>
<td>16</td>
<td>250,000</td>
</tr>
<tr>
<td>Kansas</td>
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<td>250,000</td>
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<td>110</td>
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<td>15</td>
<td>250,000</td>
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<td>250,000</td>
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<td>Maine</td>
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<td>16</td>
<td>16</td>
<td>250,000</td>
</tr>
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<td>Maryland</td>
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<td>15'11</td>
<td>220,000</td>
</tr>
<tr>
<td>Massachusetts</td>
<td>115</td>
<td>14</td>
<td>14</td>
<td>240,000</td>
</tr>
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<td>Michigan</td>
<td>150</td>
<td>16</td>
<td>15</td>
<td>230,000</td>
</tr>
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<td>Minnesota</td>
<td>95</td>
<td>14'6&quot;</td>
<td>14</td>
<td>250,000</td>
</tr>
<tr>
<td>Mississippi</td>
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<td>14</td>
<td>14</td>
<td>120,000</td>
</tr>
<tr>
<td>Missouri</td>
<td>100</td>
<td>14</td>
<td>14</td>
<td>120,000</td>
</tr>
<tr>
<td>Montana</td>
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<td>120</td>
<td>14</td>
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<td>212,000</td>
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<tr>
<td>Nevada</td>
<td>105</td>
<td>17</td>
<td>16</td>
<td>240,000</td>
</tr>
<tr>
<td>New Hampshire</td>
<td>120</td>
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<td>16</td>
<td>250,000</td>
</tr>
<tr>
<td>New Jersey</td>
<td>120</td>
<td>18</td>
<td>16</td>
<td>220,000</td>
</tr>
<tr>
<td>New Mexico</td>
<td>120</td>
<td>14</td>
<td>16</td>
<td>250,000</td>
</tr>
<tr>
<td>New York</td>
<td>120</td>
<td>14</td>
<td>14</td>
<td>160,000</td>
</tr>
<tr>
<td>North Carolina</td>
<td>100</td>
<td>14</td>
<td>14</td>
<td>120,000</td>
</tr>
<tr>
<td>North Dakota</td>
<td>120</td>
<td>14'6&quot;</td>
<td>15'6&quot;</td>
<td>150,000</td>
</tr>
<tr>
<td>Ohio</td>
<td>100</td>
<td>14</td>
<td>14'10&quot;</td>
<td>120,000</td>
</tr>
<tr>
<td>Oklahoma</td>
<td>100</td>
<td>16</td>
<td>16</td>
<td>212,000</td>
</tr>
<tr>
<td>Oregon</td>
<td>105</td>
<td>14</td>
<td>16</td>
<td>220,000</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>120</td>
<td>16</td>
<td>15'6&quot;</td>
<td>201,000</td>
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<tr>
<td>Rhode Island</td>
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<td>120,000</td>
</tr>
<tr>
<td>South Carolina</td>
<td>125</td>
<td>16</td>
<td>14</td>
<td>250,000</td>
</tr>
<tr>
<td>South Dakota</td>
<td>120</td>
<td>14'6&quot;</td>
<td>15'6&quot;</td>
<td>150,000</td>
</tr>
<tr>
<td>Tennessee</td>
<td>120</td>
<td>16</td>
<td>15</td>
<td>250,000</td>
</tr>
<tr>
<td>Texas</td>
<td>125</td>
<td>20</td>
<td>18'11&quot;</td>
<td>252,000</td>
</tr>
<tr>
<td>Utah</td>
<td>125</td>
<td>15</td>
<td>16'6&quot;</td>
<td>250,000</td>
</tr>
<tr>
<td>Vermont</td>
<td>100</td>
<td>15</td>
<td>14</td>
<td>150,000</td>
</tr>
<tr>
<td>Virginia</td>
<td>150</td>
<td>14</td>
<td>15</td>
<td>150,000</td>
</tr>
<tr>
<td>Washington</td>
<td>150</td>
<td>14</td>
<td>16</td>
<td>200,000</td>
</tr>
<tr>
<td>West Virginia</td>
<td>150</td>
<td>16</td>
<td>15</td>
<td>212,000</td>
</tr>
<tr>
<td>Wisconsin</td>
<td>150</td>
<td>16</td>
<td>16</td>
<td>250,000</td>
</tr>
<tr>
<td>Wyoming</td>
<td>110</td>
<td>18</td>
<td>17</td>
<td>252,000</td>
</tr>
</tbody>
</table>

Note: This information in this Table is for general, reference information only and should not be relied upon for any given application. These values change regularly and local, state and national regulations should be checked for any given haul application.
Notes:

1. Allowable vessel weight ranges and limits are subject to reductions under certain conditions and as noted herein.
2. Dimension $A = $ ATR, above top of rail.
Rail—Multiple Car Loading Details

If more than 2', a follower car is req'd.

Double or Single Car—Borderline Cases

Idler car

Bolster load with overhang over fourth car is acceptable. A brakewheel must be used in at least 1 of every 3 cars.

Avoid combination of dissimilar cars.

Truck Centers for Bolster Loads

Rail—Clearances

1' min

4" min

13'-4"

1' ± min

4" min

Clearance of Projections
Note: Minimum clearance to any moving part. This includes nozzles, shipping covers, or clips.

Offset Loads
Ballast may be required to offset heavy loads. "Depressed center cars" are favored for these applications.
1. Flatcars with both fish belly center and fishbelly side sills and all flatcars built after January 1, 1965.

<table>
<thead>
<tr>
<th>Length</th>
<th>Capacity Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 18 ft</td>
<td>75%</td>
</tr>
<tr>
<td>18 ft or over</td>
<td>100%</td>
</tr>
</tbody>
</table>

2. Flatcars not equipped with both fishbelly center and fishbelly side sills built prior to January 1, 1965.

<table>
<thead>
<tr>
<th>Length</th>
<th>Capacity Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 ft or less</td>
<td>66.6%</td>
</tr>
<tr>
<td>Over 10 ft to 21 ft</td>
<td>75%</td>
</tr>
<tr>
<td>Over 21 ft to truck centers</td>
<td>90%</td>
</tr>
<tr>
<td>Truck centers and over</td>
<td>100%</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Length</th>
<th>Capacity Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 18 ft</td>
<td>75%</td>
</tr>
<tr>
<td>18 ft or less than 24 ft</td>
<td>87%</td>
</tr>
<tr>
<td>24 ft or over</td>
<td>100%</td>
</tr>
</tbody>
</table>

*B3' restricted @ center of car to 50,000 lb except for heavy-duty cars

Bolster Locations
Rail—Details of Pivoted Bolster Loads

Longitudinal tie-downs are required at each saddle to suit the individual carrier. Tie-downs may consist of two brace rods, steel cables, and turnbuckles or a brace frame against the vessel base plate to take the longitudinal loads. The vessel fabricator should provide adequate clips or like attachment to the vessel for securing this bracing to the vessel shell. It is imperative that any welding to the vessel be done in the shop!

BOLSTER SETTING & CLEARANCES

1. Set X, Y, and Z so that clearance at points A, B, and C are adequate.
2. Watch relationship between bolsters and car trucks and car ends.
3. Add a minimum of 1 in. to all lateral dimensions to allow for shipping covers and small projections.
4. Dimension "D" shall be a maximum of 15 ft-5 in. of occupied space based on a 10° curve.
Details of Bolsters

PIVOT BOLSTER
Pivots only

SLIDING PIVOTED BOLSTER
Allows for longitudinal and angular movement

Notes:
1. Pivoting bolsters must be used for all rail shipments.
2. Pivoting bolsters must be utilized for all vessels spanning two or more railcars.
3. Design pin for shear based on full load of $F_x$.
4. Do not anchor the saddle plate to the bolster plate or the railway bed. The saddle plate must be free to rotate on the bolster plate. Only the bolster plate is anchored to the railway bed. The most common means of anchoring the bolster plate to the railway bed is welding. Design anchorage for a load of $\frac{1}{4}F_x$.
5. Apply grease generously between saddle base plate and bolster plate.
6. In general all clips or welds on the railcar will have to be removed, ground, and cleaned to the satisfaction of the railway's prior to return.
### Table 10-2
Barge shipping forces

<table>
<thead>
<tr>
<th>Case</th>
<th>Condition</th>
<th>$F_x$</th>
<th>$F_y$</th>
<th>$F_z$</th>
<th>Diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gravity</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>2a</td>
<td>Roll</td>
<td>±0.45w</td>
<td>—</td>
<td>—0.4w</td>
<td>—</td>
</tr>
<tr>
<td>2b</td>
<td>Roll</td>
<td>±0.45w</td>
<td>+0.4w</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>3a</td>
<td>Pitch</td>
<td>—</td>
<td>—1.5w</td>
<td>1.0w</td>
<td>—</td>
</tr>
<tr>
<td>3b</td>
<td>Pitch</td>
<td>—</td>
<td>+1.5w</td>
<td>1.0w</td>
<td>—</td>
</tr>
<tr>
<td>4</td>
<td>Heave</td>
<td>—</td>
<td>—</td>
<td>1.2w</td>
<td>—</td>
</tr>
<tr>
<td>5</td>
<td>Collision</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>±1.5w</td>
</tr>
<tr>
<td>6a</td>
<td>Roll + Gravity</td>
<td>+0.95w</td>
<td>+0.05w</td>
<td>—1.266w</td>
<td>—</td>
</tr>
<tr>
<td>6b</td>
<td>Roll + Gravity</td>
<td>—0.95w</td>
<td>—0.05w</td>
<td>—0.466w</td>
<td>—</td>
</tr>
<tr>
<td>7a</td>
<td>Pitch + Gravity</td>
<td>—</td>
<td>—2.5w</td>
<td>±0.5w</td>
<td>—</td>
</tr>
<tr>
<td>7b</td>
<td>—</td>
<td>—</td>
<td>+0.5w</td>
<td>±0.5w</td>
<td>—</td>
</tr>
</tbody>
</table>
Pitch

Cases 3a and 3b

Forces in Vessel Due to Pitch

General:
\[ F = ma = \left( \frac{W}{g} \right) \left( \frac{2\pi}{T} \right)^2 \left( \frac{R\theta\pi}{180} \right) \]

\[ F = 0.0214 \frac{WR\theta}{T^2} \]

\[ \phi_1 = \tan^{-1} \left( \frac{a}{R_1} \right) \]

\[ F_p = \frac{0.0214WR_1\theta_1}{T_1^2} \]

Case 3a: \[ F_y = -F_p \sin \phi_1 \]
\[ F_z = F_p \cos \phi_1 \]

Case 3b: \[ F_y = F_p \sin \phi_1 \]
\[ F_z = -F_p \cos \phi_1 \]

Roll

Case 2a: \( \theta_2 = 30^\circ \) max

Forces in Vessel Due to Roll

\[ \phi_2 = \tan^{-1} \left( \frac{c}{d} \right) \]

\[ R_2 = \frac{e}{\sin \phi_2} \]

\[ F_R = \frac{0.0214WR_2\theta_2}{T_2^2} \]

Case 2a: \[ F_y = -F_R \sin \phi_2 \]
\[ F_x = F_R \cos \phi_2 \]

Case 2b: \[ F_y = F_R \sin \phi_2 \]
\[ F_x = -F_R \cos \phi_2 \]
The job of the designer is to translate the loads resulting from the movement of the ship into loads applied to the pressure vessel that is stored either at or below decks. The ship itself will rotate about its own center of buoyancy (CB) depending on the direction of the sea and the ship’s orientation to that direction of sea. The vessel strapped to its deck is in turn affected by its location in relation to the CB of the ship. For example, if the CG of the vessel is located near the CB of the ship, the forces are minimized. The farther apart the two are in relation to each other, the more pronounced the effect on the vessel.

The ship’s movement translates into loads on the three principal axes of the vessel. Saddles and lashings must be strong enough to resist these external forces without exceeding some allowable stress point in the vessel. The point of application of the load is at the CG of the vessel. These loads affect the vessel in the same manner as seismic forces do. In fact, the best way to think of these loads is as vertical and horizontal seismic forces. Vertical seismic forces either add or subtract to the weight of the vessel. Horizontal seismic forces are either transverse or longitudinal.

The X, Y, and Z axes translate into and are equivalent to the following loadings in the vessel:

- **X axis:** horizontal transverse.
- **Y axis:** corresponds to vertical loads by either adding or subtracting from the weight of the vessel.
- **Z axis:** longitudinal axis of the vessel. All Z axis loads are longitudinal loadings.

### Load Combinations for Sea Forces

1. dead load + sway + heave + wind
2. dead load + surge + heave + wind
Forces on Truck and Rail Shipments

Rail

Truck/Trailer

Truck/Trailer

Rail
Axle Loads

The number of axles that must be placed under a load is determined by analyzing the weight restrictions and allowable bearing load from local, state or national regulations. The transportation contractor is responsible for determining the axle loads based on the equipment used and the weight and distribution of the loads. The authorities that permit the load will require an analysis of the axle loads to ensure that the roadbed is not overloaded. Axle loads include the weight of the vessel, transport saddles, beams, hauler (tractor), dollies, etc.

There are three different methods used to distribute the loads to the axles:

1. Flatbed: This method uses conventional tractor-trailer assembly with various numbers of axles and wheels under the trailer bed to distribute the weight to the road surface.
2. Bolstered: This method is used for abnormally long loads in which the sets of axles are attached directly to the load via the transport saddle. Both sets of axles will have steering capabilities.
3. Bolstered loads using equalizing transporting beams: This method is much the same as the bolstered, long vessel load. In this case the load is too heavy for a flatbed, yet too short for bolstered axles. The solution is to utilize beams between bolster to suspend the load.

Transporter Stability

There are two types of stability checks that should be performed on each load. The first has to do with the tipping point of the load relative to the roadway as the load shifts due to the camber of the road. The second has to do with the turning radius of bolstered loads. As the load goes around curves, the C.G. shifts from being in line with the dollies, to an eccentric condition. In tight curves the eccentricity of the load can overload the outer set of wheels to the point of rollover. The two cases are;

1. Rollover stability due to road camber
2. Turning stability due to turning radius

Case 1:

Due to the camber in roads, the load will be subject to various angles, $\theta$, that will change the location of the center of gravity of the load. On a flat surface, the center of gravity is in line with the centerline of the trailer. As the road camber increases, the C.G. is steadily moved toward the outer set of wheels. At some point the wheels are overloaded on one side and the entire assembly reaches a tipping point. Beyond this, the trailer turns over and the load is lost. This condition has resulted in numerous rollovers.

Case 2:

For bolstered loads, the vessel must swivel on the deck of the trailer in order to accommodate curves in the road and corners. As the curve or corner is negotiated, the actual C.G. gets further away from the projected load point. This is true whether you have a single pivoting bolster or two, however the situation is more pronounced with the double pivoting case. There have been a number of rollovers as a result of the eccentricity, ie, shifting the load to the outer row of wheels until the load becomes unstable.
AXLE LOADS - TYPICAL EXAMPLE - 11 AXLE, DUAL LANE TRANSPORTER

AXLE LOADS

<table>
<thead>
<tr>
<th>AXLE NO.</th>
<th>1</th>
<th>2-3</th>
<th>4-5</th>
<th>6-7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>TOTALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>WIDTH (ft)</td>
<td>8</td>
<td>8</td>
<td>10</td>
<td>10</td>
<td>17</td>
<td>17</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TARE WEIGHT (lbs)</td>
<td>12200</td>
<td>15360</td>
<td>9640</td>
<td>12000</td>
<td>5450</td>
<td>5450</td>
<td>5450</td>
<td>5450</td>
<td>71000</td>
</tr>
<tr>
<td>MAX PAYLOAD (lbs)</td>
<td>1510</td>
<td>28610</td>
<td>46510</td>
<td>43680</td>
<td>39498</td>
<td>39498</td>
<td>39498</td>
<td>39498</td>
<td>278300</td>
</tr>
<tr>
<td>MAX LOAD (lbs)</td>
<td>13710</td>
<td>43970</td>
<td>56150</td>
<td>55680</td>
<td>44948</td>
<td>44948</td>
<td>44948</td>
<td>44948</td>
<td>349300</td>
</tr>
<tr>
<td>NO. OF TIRES</td>
<td>2</td>
<td>8</td>
<td>16</td>
<td>16</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>74</td>
<td></td>
</tr>
<tr>
<td>TIRE LOADING</td>
<td>6655</td>
<td>5496</td>
<td>3509</td>
<td>3480</td>
<td>5618</td>
<td>5618</td>
<td>5618</td>
<td>5618</td>
<td></td>
</tr>
<tr>
<td>ALLOW LOAD</td>
<td>14000</td>
<td>45000</td>
<td>58000</td>
<td>58000</td>
<td>45000</td>
<td>45000</td>
<td>45000</td>
<td>45000</td>
<td></td>
</tr>
</tbody>
</table>

EQUIPMENT WEIGHT

| TRACTOR | 22000 | ITEM | REACTOR |
| JEEP | 9200 | FOR | |
| BEAMS | 12000 | WEIGHT | 278,300 |
| DOLLY | 6000 | SIZE | 76’-6”LX15’-9”W X 14’-9”H |
| DBL DOLLY | 21800 | ORIGIN | |
| TOTAL | 71000 | DESTINATION | |
Examples of Road Transport

If a vessel is too heavy for one trailer and too short to span two trailers, then a pair of outrigger beams can be used to span the trailers and still distribute the load to the trailers. A wide variety of trailers, self-propelled transporters, and beam configurations have been utilized for these applications. Short, squat, heavy vessels are the most common.
Summary of Loads/Forces on Vessels During Transportation

Table 10-3  
Transportation load coefficients, K

<table>
<thead>
<tr>
<th>Forces</th>
<th>Road</th>
<th>Rail</th>
<th>Barge</th>
<th>Ocean</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_x )</td>
<td>0.5</td>
<td>1.0</td>
<td>0.95</td>
<td>1.0</td>
</tr>
<tr>
<td>( F_y )</td>
<td>1.5</td>
<td>2.0</td>
<td>1.3</td>
<td>1.5</td>
</tr>
<tr>
<td>( F_z )</td>
<td>1.0</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Loads \( F_x, F_y, F_z = KW_s \)

Verify coefficients with transport contractor/shipper.

Table 10-4  
Load per saddle due to transport forces

Due to . . . | Load per Saddle | Diagram |
---|---|---|
\( F_x \) | \[ Q_1 = \frac{W_s L_2}{L_1} + \frac{F_x B}{2A} \]  
\[ Q_2 = \frac{W_s L_3}{L_1} + \frac{F_x B}{2A} \] | |

\( F_y \) | \[ Q_1 = \frac{(W_s + F_y)L_2}{L_1} \]  
\[ Q_2 = \frac{(W_s + F_y)L_3}{L_1} \] | |

\( F_z \) | \[ Q_1 = \frac{W_s L_2}{L_1} + \frac{F_z B}{L_1} \]  
\[ Q_2 = \frac{W_s L_3}{L_1} + \frac{F_z B}{L_1} \] | |
Load Diagrams for Moments and Forces

Case 1

Note: \( W = \) weight of vessel plus any impact factors.

\[ \text{OAL} = L_1 + L_2 + L_3 \quad w = \frac{W}{\text{OAL}} \]

\[ Q_1 = \frac{w[(L_1 + L_2)^2 - L_3^2]}{2L_1} \]

\[ Q_2 = W - Q_1 \]

\[ M_1 = \frac{wL_2^2}{2} \]

\[ M_2 = Q_1 \left( \frac{Q_1}{2w} - L_2 \right) \]

\[ M_3 = \frac{wL_3^2}{2} \]

\[ M_x = \frac{w(L_2 - X)^2}{2} \]

\[ M_{x1} = \frac{w(L_2 + X_1)^2}{2} - Q_1 X_1 \]

\[ M_{x2} = \frac{w(L_3 - X_2)^2}{2} \]

Case 2

\[ w_1 = \frac{W_1}{L_2} \]

\[ w_2 = \frac{W_2}{L_3} \]

\[ Q_1 = \frac{W L_6}{L_1} \]

\[ Q_2 = W - Q_1 \]

\[ M_1 = \frac{w_1 L_4^2}{2} \]

\[ M_2 = \frac{M_1 + M_3}{2} - \frac{w_1 L_1^2}{2} \]

\[ M_3 = \frac{w_2 L_3^2}{2} \]
Case 3

\[ Q_1 = \frac{WL_1}{2(L_1 + L_2)} - \frac{W L_2^2}{2L_1(L_1 + L_2)} \]

\[ Q_2 = \frac{WL_1}{2(L_1 + L_2)} + \frac{W L_2}{L_1 + L_2} + \frac{W L_3^2}{2L_1(L_1 + L_2)} \]

\[ M_1 = \frac{Q_1^2(L_1 + L_2)}{2W} \]

\[ M_2 = Q_1 L_1 - \frac{W L_2^2}{2(L_1 + L_2)} \]

\[ M_x = Q_1 X - \frac{(W X^2)}{2(L_1 + L_2)} \]

Case 4

\[ w_1 = \frac{W_1}{L_2} \]

\[ w_2 = \frac{W_2}{L_3} \]

\[ Q_1 = \frac{w_1 L_2 (2L_1 - L_2) + w_2 L_3^2}{2L_1} \]

\[ Q_2 = \frac{w_2 L_3 (2L_1 - L_3) + w_1 L_2^2}{2L_1} \]

Moment at any point X from \( Q_1 \):

\[ M_x = Q_1 X - \frac{w_1 X^2}{2} \]

Moment at any point Y from \( Q_2 \):

\[ M_y = Q_2 (L_1 - Y) - \frac{w_2 (L_1 - Y)^2}{2} \]
**Transportation-Vertical Vessel on Two Saddles, Uniform Load Case, With Incorporation of Shipping Factors**

**Notation**

- $F_2$ = Additional load on $Q_2$, Lbs
- $F_Z$ = Longitudinal loading due to shipping forces, Lbs
- $F_Y$ = Vertical Loading due to shipping forces, Lbs
- $K_Z$ = Longitudinal impact factor
- $K_Y$ = Vertical impact factor
- $Q_1, Q_2$ = Saddle loads without impact factors, Lbs
- $Q_1', Q_2'$ = Saddle loads with impact factors, Lbs
- $W$ = Shipping weight of vessel without impact factors, Lbs
- $W_T$ = Shipping weight with impact factors, Lbs
- $w_1$ = Uniform load, without $F_Y$, Lbs/Ft
- $w_2$ = Uniform load including $F_Y$, Lbs/Ft

**Figure 10.3.** Data for uniform load case

**NOTE:** Assume that $F_Z$ & $F_Y$ do not occur at the same time

**Case 1: Adding Load for $F_Z$**

- Longitudinal load, $F_Z$
  
  $F_Z = K_Z W$

- Uniform load, $w_1$
  
  $w_1 = W/L_T$

- Additional load on saddle, $F_2$
  
  $F_2 = (F_Z B)/L_1$

- Saddle loads, $Q_1, Q_2, Q_1', Q_2'$
  
  $Q_1 = w_1 \left[ (L_1 + L_2)^2 - L_3^2 \right] / 2 L_1$
  
  $Q_1' = Q_1 - F_2$
  
  $Q_2 = W - Q_1$
  
  $Q_2' = Q_2 + F_2$

**Case 2: Adding Loads for $F_Y$**

- Longitudinal load, $F_Y$
  
  $F_Y = K_Y W$

- Vertical load, $F_Y$
  
  $W_T = W + F_Y$

- Uniform load, $w_2$
  
  $w_2 = W_T/L_T$

- Saddle loads, $Q_1' & Q_2'$
  
  $Q_1' = w_2 \left[ (L_1 + L_2)^2 - L_3^2 \right] / 2L_1$
  
  $Q_2' = W_T - Q_1'$

Select worst case and calculate moments;

$M_1 = w_1 L_2^2 / 2$

$M_2 = Q_1' (Q_1' / (2 w_n) - L_2)$

$M_3 = w_n L_3^2 / 2$

**Sample Problem**

Given;

- $B = 15.75$ ft
- $L_1 = 124$ ft
- $L_2 = 24$ ft
- $L_3 = 21$ ft
- $L_T = 169$ ft
Calculation

\[ F_Z = K_Z W = 0.6 \times 741 = 444.6 \text{ kips} \]
\[ F_Y = K_Y W = 0.5 \times 741 = 370.5 \text{ kips} \]
\[ W_T = W + F_Y = 741 + 370.5 = 1,111.5 \text{ kips} \]
\[ w_1 = \frac{W}{L_T} = \frac{741}{169} = 4.38 \text{ kips/ft} \]
\[ w_2 = \frac{W_T}{L_T} = \frac{1,111.5}{169} = 6.58 \text{ kips/ft} \]
\[ F_2 = \frac{(F_Z B)}{L_1} = \frac{[444.6 \times (15.75)]}{124} = 56.47 \text{ kips} \]

Case 1: Adding Load for \( F_Z \)

- Saddle loads, \( Q_1, Q_2, Q_1', Q_2' \)
  \[ Q_1 = w_1 \left[ (L_1 + L_2)^2 - L_3^2 \right] / 2 L_1 \]
  \[ = 4.38 \left[ (124 + 24)^2 - 21^2 \right] / 2(124) \]
  \[ = 379 \text{ kips} \]

\[ Q_1' = Q_1 - F_2 = 379 - 56.5 = 322.5 \text{ kips} \]
\[ Q_2 = W - Q_1 = 741 - 379 = 362 \text{ kips} \]
\[ Q_2' = Q_2 + F_2 = 362 + 56.5 = 418.5 \text{ kips} \]

Case 2: Adding Load for \( F_Y \)

- Saddle loads, \( Q_1' \) & \( Q_2' \)
  \[ Q_1' = w_2 \left[ (L_1 + L_2)^2 - L_3^2 \right] / 2 L_1 \]
  \[ = 6.58 \left[ (124 + 24)^2 - 21^2 \right] / 2(124) \]
  \[ = 569 \text{ kips} \]
\[ Q_1' = W_T - Q_1' = 1111.5 - 569 \]
\[ = 542.5 \text{ kips} \]

Worst case is Case 2:

Determine moments...

\[ M_1 = \frac{(w_2 L_3^2)}{2} = \frac{(6.58(24^2))}{2} \]
\[ = 1,895 \text{ ft – kips} \]
\[ M_2 = \frac{Q_1'(Q_1'/2 - L_2)}{2} \]
\[ = 569 \left( \frac{569/2 - 6.58}{2} \right) = 10,946 \text{ ft – kips} \]
\[ M_3 = \frac{(w_2 L_3^2)}{2} = \frac{(6.58(21^2))}{2} = 1,450 \text{ ft – kips} \]

Use these moments and loads to determine stresses in shell.
Shipping Saddles

**TIMBER CONSTRUCTION**

- Steel round bar: weld one end to flat bar, thread other end
- Tension bands, steel flat bar
- Not less than 3” clearance
- (2) Hvy. hex. nuts
- (1) Hvy. washer each end

**STEEL CONSTRUCTION**

- Steel round bar: weld one end to flat bar, thread other end
- Tension bands, steel flat bar
- Not less than 3” clearance
- (2) Hvy. hex. nuts
- (1) Hvy. washer each end
Shipping Saddle
Steel Construction with Jacking Pocket

Alternate Construction

Lifting Lugs (optional)
Lifting lugs should be plainly marked with capacity to indicate whether they are for lifting the saddles alone or the entire vessel.
Lashing

Reference

- 1-in. wire rope
  Allowable load = 14 kips
- 1¼-in. turnbuckle
  Allowable load = 15 kips
- 1½-in. turnbuckle
  Allowable load = 28 kips
- 1-in. Shackle
  SWL = 17 kips
- 1½-in. Shackle
  SWL = 34 kips

Steel or timber cribbing as required for load distribution to trailer bed or deck

Detail of Lashing to Deck
Tension Bands on Saddles

Notation

\[ A_r = \text{area required, in.}^2 \]
\[ A_s = \text{area of bolt, in.}^2 \]
\[ A_b = \text{area of band required, in.}^2 \]
\[ A_w = \text{allowable load on weld, lb/in.} \]
\[ B = \text{saddle height, in.} \]
\[ d = \text{bolt diameter, in.} \]
\[ f = \text{load on weld, kips/in.} \]
\[ F_1 = \text{allowable stress, tension, psi} \]
\[ F_x, F_y, F_z = \text{shipping, external forces, lb} \]
\[ K = \text{maximum band spacing, in.} \]
\[ N = \text{number of bands on one saddle} \]
\[ P_e = \text{equivalent external pressure, psi} \]
\[ R = \text{outside vessel radius, in.} \]
\[ T = \text{tension load in band, lb} \]
\[ T_{1,2,3} = \text{load cases in bolt and band, lb} \]
\[ T_b = \text{tension load in bolt, lb} \]
\[ W_s = \text{weight of one saddle, lb} \]
\[ \beta = \text{angle of tension bands, degrees} \]
\[ \sigma_a = \text{stress in bolt, psi} \]
\[ \sigma_b = \text{stress in band, psi} \]
Find tension in band, $T_1$, due to shipping forces on saddle, $F_x$ and $F_y$. 

$$T_1 = \cos \beta \left( \frac{F_x B}{4RN} + \frac{F_y - W_s}{4N} \right)$$

Area required for bolt:

$$A_r = \frac{T_1}{F_t}$$

Find bolt diameter, $d$.

$$d = \sqrt{\frac{4A_r}{\pi}}$$

Select nominal bolt diameter:

$$A_n =$$

Find maximum stress in bolt due to manual wrenching, $\sigma_a$.

$$\sigma_a = \frac{45,000}{\sqrt{d}}$$

Maximum tension load in bolts, $T_2$.

$$T_2 = \sigma_a A_n$$

Load due to saddle weight, $T_3$.

$$T_3 = \frac{W_s}{2N}$$

Note: Include impact factor in weight of saddle.

Find maximum load, $T$.

$$T = \text{greater of } T_1, T_2, \text{ or } T_3.$$

Load on weld, $f$.

$$f = \frac{T}{4\ell}$$

Determine size of weld from table based on load, $f$.

Use $w =$

Maximum band spacing, $K$.

$$K = \frac{4\sqrt{Rt}}{1.285}$$

Find area required for tension band, $A_r$.

$$A_r = \frac{T}{F_t}$$

Table 10-5

<table>
<thead>
<tr>
<th>Weld Size, w</th>
<th>E60XX*</th>
<th>E70XX*</th>
</tr>
</thead>
<tbody>
<tr>
<td>⅛ in.</td>
<td>2.39</td>
<td>2.78</td>
</tr>
<tr>
<td>¼ in.</td>
<td>3.18</td>
<td>3.71</td>
</tr>
<tr>
<td>⅜ in.</td>
<td>3.98</td>
<td>4.64</td>
</tr>
<tr>
<td>⅜ in.</td>
<td>4.77</td>
<td>5.57</td>
</tr>
<tr>
<td>¾ in.</td>
<td>5.56</td>
<td>6.50</td>
</tr>
</tbody>
</table>

*Kips/in. of weld.

Check shell stresses due to force $T$, $P_e$

$$P_e = \frac{4T}{\pi RK} < \text{ASME factor “B”}$$
Alternate Procedure

Tension Band Notation

- Number of bands on one saddle, \( N \)
- Total load on one saddle, Lbs, \( Q \)
- Outside vessel radius, in, \( R \)
- Tension load in band, Lbs, \( T \)
- Angle of tension bands, degrees, \( \beta \)
- Transverse shipping coefficient, \( K_1 \)
- Vertical shipping coefficient, \( K_2 \)
- Horizontal distance to centroid of saddle reaction, in, \( X \)
- Vertical distance to centroid of saddle, in, \( Y \)

Calculation

- Vertical distance to centroid of saddle, \( Y \)
  \[ Y = R \sin \theta / \theta \]
- Find angle, \( \alpha \)
  \[ \alpha = \cos^{-1} \left( \frac{Y}{R} \right) \]
- Horizontal distance to centroid of saddle, \( X \)
  \[ X = R \sin \alpha \]
- Tension load in band, \( T \)
  \[ T = \frac{Q \left[ (K_1 \frac{Y}{X}) + K_2 \right]}{2N \cos \beta} \]

Notes

1. Vertical reaction can be a result of longitudinal load. Use largest value
2. Use \( K_2 = 0 \) for transverse case
3. Use \( K_1 = 0 \) for longitudinal case
4. Use worst case of \( T_1 \) or \( T_2 \) and design the balance of components per previous method

Example

- \( K_1 = .25 \)
- \( K_2 = .5 \)
- \( Q = 500 \) kips
- \( R = 92.5 \) in
- \( \theta = 75^\circ = 1.308 \) rad
- \( \beta = 7.5^\circ \)
- \( N = 2 \)
- \( Y = R \sin \theta / \theta \)
  \[ Y = 92.5 \sin 75 / 1.308 = 68.3 \text{ in} \]
- \( \alpha = \cos^{-1} \left( \frac{Y}{R} \right) \)
  \[ \alpha = \cos^{-1} \left( \frac{68.3}{92.5} \right) = 42.4^\circ \]
- \( X = R \sin \alpha \)
  \[ X = 92.5 \sin 42.4 = 62.4 \text{ in} \]

Transverse (\( K_2 = 0 \))

- \( T_1 = \frac{[Q \left[ (K_1 \frac{Y}{X}) + K_2 \right]]}{2N \cos \beta} \)
  \[ T_1 = \frac{[500 \left[ (0.25 \cdot 68.3/62.4) + 0 \right]]}{2 \cdot 2 \cos 7.5} = 34.35 \text{ kips} \]

Longitudinal (\( K_1 = 0 \))

- \( T_2 = \frac{[Q \left[ (K_1 \frac{Y}{X}) + K_2 \right]]}{2N \cos \beta} \)
  \[ T_2 = \frac{[500 \left[ 0 + 0.5 \right]]}{2 \cdot 2 \cos 7.5} = 63.04 \text{ kips} \]
Check Vessel Shell Stresses

<table>
<thead>
<tr>
<th>Stress Type</th>
<th>General</th>
<th>At Saddle 1</th>
<th>At Saddle 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal bending at saddles</td>
<td>$S_1 = \frac{M}{K_1 r^2 t}$</td>
<td>$S_1 = \frac{M}{K_1 r^2 t}$</td>
<td></td>
</tr>
<tr>
<td>Longitudinal bending at midspan</td>
<td>$S_3 = \frac{M}{Z}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tangential shear</td>
<td>$S_7 = \frac{K_3 Q_t}{r t}$</td>
<td></td>
<td>$S_7 = \frac{K_3 Q_2}{r t}$</td>
</tr>
<tr>
<td>Circumferential stress at horn of saddle</td>
<td>$S_9 = \frac{Q_t}{4 r d} - \frac{3 K_6 Q_t}{2 t^2}$</td>
<td>$S_9 = \frac{Q_2}{4 r d} - \frac{3 K_6 Q_2}{2 t^2}$</td>
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<tr>
<td>$L &gt; 8 R$</td>
<td>$S_{10} = \frac{Q_2}{4 r d} - \frac{12 K_6 Q_t R}{L_t t^2}$</td>
<td>$S_{10} = \frac{Q_2}{4 r d} - \frac{3 K_6 Q_2 R}{L_t t^2}$</td>
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</tr>
<tr>
<td>$L &lt; 8 R$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circumferential compression</td>
<td>$S_{12} = \frac{K_3 Q_t}{t d}$</td>
<td>$S_{12} = \frac{K_3 Q_2}{t d}$</td>
<td></td>
</tr>
</tbody>
</table>

**Notation**

- $Z = \pi R^4 t$
- $r =$ radius of vessel, in.
- $R =$ radius of vessel, ft.
- $b =$ width of saddle, in.
- $d = b + 1.56 \sqrt{r t}$

**Notes:**

1. Check shell stresses at each change of thickness and diameter.
2. See procedure for the design of saddles for horizontal vessels for a detailed description of shell stresses and for values of coefficients $K_1$ through $K_7$.
3. Values of $M$ and $Q$ should be determined from the previous pages at the applicable location.
4. Allowable stresses:
   - Tension: $0.9F_y$
   - Compression: $1.2 \times \text{Factor } "B" \text{ from ASME Code}$
Procedure 10-2: Erection of Pressure Vessels

The designer of pressure vessels and similar equipment will ultimately become involved in the movement, transportation, and erection of that equipment. The degree of that involvement will vary due to the separation of duties and responsibilities of the parties concerned. It is prudent, however, for the designer to plan for the eventuality of these events and to integrate these activities into the original design. If this planning is done properly, there is seldom a problem when the equipment gets to its final destination. Conversely, there have been numerous problems encountered when proper planning has not been done.

There is also an economic benefit in including the lifting attachments in the base vessel bid and design. These lifting attachments are relatively inexpensive in comparison to the overall cost of the vessel and minuscule compared to the cost of the erection of the equipment. The erection alone for a major vessel can run into millions of dollars. If these attachments are added after the purchase order is awarded, they can become expensive extras.

There are also the consequences to life, property, and schedules if this activity is not carried out to a successful conclusion. Compared to the fabricated cost of the lifting attachments, the consequences to life, property, and schedule are too important to leave the design of these components and their effect on the vessel to those not fully versed in the design and analysis of pressure vessels.

In addition, it is important that the designer of the lifting attachments be in contact with the construction organization that will be executing the lift. This ensures that all lifting attachments meet the requirements imposed by the lifting equipment. There are so many different methods and techniques for the erection of vessels and the related costs of each that a coordinated effort between the designer and erector is mandatory. To avoid surprises, neither the designer nor the erector can afford to work in a vacuum. To this end, it is not advisable for the vessel fabricator to be responsible for the design if the fabricator is not the chief coordinator of the transport and erection of the vessel.

Vessels and related equipment can be erected in a variety of ways. Vessels are erected by means of single cranes, multiple cranes, gin poles, jacking towers, and other means. The designer of the lifting attachments should not attempt to dictate the erection method by the types of attachments that are designed for the vessel. The selection of one type of attachment versus another could very well do just that.

Not every vessel needs to be designed for erection or have lifting attachments. Obviously the larger the vessel, the more complex the vessel, the more expensive the vessel, the more care and concern that should be taken into account when designing the attachments and coordinating the lift. The following listing will provide some guidelines for the provision of special lifting attachments and a lifting analysis to be done. In general, provide lifting attachments for the following cases:

- Vessels over 50,000 lb (25 tons).
- Vessels with L/D ratios greater than 5.
- Vertical vessels greater than 8 ft in diameter or 50 ft in length.
- Vessels located in a structure or supported by a structure.
- High-alloy or heat-treated vessels (since it would not be advisable for the field to be doing welding on these vessels after they arrive on site, and wire rope slings could contaminate the vessel material).
- Flare stacks.
- Vessels with special transportation requirements.

At the initial pick point, when the vessel is still horizontal, the load is shared between the lifting lugs and the tail beam or lug, based on their respective distances to the vessel center of gravity. As the lift proceeds, a greater percentage of the load is shifted to the top lugs or trunnions until the vessel is vertical and all of the load is then on the top lugs. At this point the tail beam or shackle can be removed.

During each degree of rotation, the load on the lugs, trunnions, tailing device, base ring, and vessel shell are continually varying. The loads on the welds attaching these devices will also change. The designer should evaluate these loadings at the various lift angles to determine the worst coincident case.

The worst case is dependent on the type of vessel and the type of attachments. For example, there are three types of trunnions described in this procedure. There is the bare trunnion (Type 3), where the wire rope slides around the trunnion itself. While the vessel is in the horizontal position (initial pick point), the load produces a circumferential moment on the shell. Once the vessel is in the upright position, the same load produces
a longitudinal moment in the shell. At all the intermediate angles of lift there is a combination of circumferential and longitudinal moments. The designer should check the two worst cases at 0° and 90° and several combinations in between.

The same trunnion could have a lifting lug welded to the end of the trunnion (Type 1). This lug also produces circumferential and longitudinal moments in the shell. However, in addition this type of lug will produce a torsional moment on the shell that is maximum at 0° and zero at 90° of angular rotation. The rotating lug (Type 2) eliminates any torsional moment.

There is one single lift angle that will produce the maximum stress in the vessel shell but no lift angle that is the worst for all vessels. The worst case is dependent on the type of lift attachments, distances, weights, and position relative to the center of gravity.

The minimum lift location is the lowest pick point that does not overstress the overhanging portion of the vessel. The maximum lift location is the highest pick point that does not overstress the vessel between the tail and pick points. These points become significant when locating the lift points to balance the stress at the top lug, the overhang, and the midspan stress.

The use of side lugs can sometimes provide an advantage by reducing the buckling stress at midspan and the required lift height. Side lugs allow for shorter boom lengths on a two-crane lift or gin poles. A shorter boom length, in turn, allows a higher lift capacity for the cranes. The lower the lug location on the shell, the shorter the lift and the higher the allowable crane capacity. This can translate into dollars as crane capacity is affected. The challenge from the vessel side is the longitudinal bending due to the overhang and increased local shell stresses. All of these factors must be balanced to determine the lowest overall cost of an erected vessel.

**Requirement for Erection and Setting of Vertical Vessels**

The following is a brief synopsis of general recommendations regarding the setting, leveling and shimming of vertical vessels. The following should be considered as guidelines only. There are no codes or standards that are applied. In general, company specifications contain contract requirements for the contractors scope of supply or duties. The following lists help to clarify general construction practices with regard to the setting of vertical vessels and towers.

### Contractor Duties

1. Prepare tops of foundations (bush hammer if required)
2. Perform surveying as required to establish centerlines, sole plate or shim elevations at bottom of base of equipment
3. Shimming
4. Erect equipment
5. Level/plumbing
6. Final alignment
7. Grouting
8. Bolting

### Tolerances

Out of vertical tolerance for vertical vessels, unless specified otherwise, shall be 0.1% of the vessel height, or about \( \frac{1}{4} \) inch for every 20 feet to a maximum of \( \frac{3}{4} \) inches.

**Soleplates (also called bearing pads, leveling plates or embedments)**

Soleplates are stainless steel plates, 0.5 inches to 0.75 inches thick, set in grout, on top of the foundation at the exact height of the underside of the base plate. As a rule, two soleplates should be installed per anchor bolt, one on each side of the bolt. Depending on the tower diameter, and the distance between the anchor bolts, another soleplate may be installed between adjacent anchor bolts. The dimensions of the soleplates will vary according to the width of the vessel base ring and vessel weight. Soleplates are supported in place by a mixture of Portland cement and sand in proportions 1:3. The vessel should not be erected until the soleplates have been in place for 28 days to allow for concrete curing. Shims and soleplates will remain in place after the grouting operation.

**Shims**

Shims are used to provide precise leveling of the vessel. Shim packs may be grouted into the foundation in lieu of sole plates but this practice is unusual. Typically, shims are used on top of the sole plates for the leveling operation. Special shims may be required for unique applications such as a large vessel supported on a braced frame structure with minimal contact/bearing at each support point.
point. The following are some guidelines for the use of shims.

1. Shims. If left in place, shall be stainless steel
2. Shims must have rounded corners
3. Shims will be fixed in place
4. Shims shall be deburred
5. Shims shall be full bearing
6. Shims may be horseshoe type
7. Shims thinner than 0.001 inches are not allowed
8. Shims with holes are not allowed
9. Shims should be the full width of the base plate

**Leveling/Straightness/Plumbness**

After the vessel has been placed on its foundation it must be checked to be certain it is vertical and plumb. Leveling is normally checked by use of two theodolites, 90 degrees apart. The theodolites shall be spaced an adequate distance from the vessel to allow visual field of the entire height of the vessel. Adjustments can be made to the vessel alignment by means of wedges, either powered or not, and then shimmed. The wedges should not be left in place after shimming.

The vessel may be heated by the sun to a higher temperature on one side than the other. This can create a slight “banana” effect which should be taken into account when checking levelness. The equation for calculating the deflection from this effect is as follows:

\[
\varsigma = \frac{\pi D^2 \cdot t \cdot H \cdot \alpha \Delta T}{8I}
\]

where;
- \(\varsigma\) = Deflection, in
- \(D\) = Diameter, ft
- \(T\) = Thickness, in
- \(H\) = Height, ft
- \(\alpha\) = Coefficient of thermal expansion, in/in/°F
- \(\Delta T\) = Temperature difference from one side of the column to the other, °F
- \(I\) = Moment of inertia of vessel cross section, ft⁴

**Bolting**

After the vessel is aligned and shimmed, the nuts on the anchor bolts must be tightened. The vessel should not be left standing without the crane attached unless all anchor bolts have been tightened.

The anchor bolts should not be tightened to their maximum load until the drypacking under the base plate is complete. At this stage, the base plate is suspended between the soleplates until the drypack is installed. Since the soleplates straddle the anchor bolts, there is a chance of deforming the baseplate prior to the installation of the drypack, if the anchor bolts are over tightened.

After drypacking, the anchor bolts should be tightened to the correct torque to produce the maximum allowable bolt stress. The anchor bolts should not be tightened beyond the point of maximum allowable bolt stress.

Note that the initial anchor bolt tension does not increase the maximum bolt tension caused by wind or earthquake. This initial tension will only clamp the base ring to the concrete. Both are in equal compression until the external load is applied. The external load reduces the compression in the concrete before additional load is applied to the bolts. After the external load overcomes all the compression in the concrete, the stress in the bolt will increase to the value it would have been, had there been no initial tension.

**Grouting**

Grout under base plates shall provide full uniform load transfer between the bottom of the base plate and the top of the foundation. Load transfer to the foundation must be through the grout, not through the shims or soleplate.

Prior to setting of the vessel, the top of the foundation should be bush hammered and cleaned. This ensures that the grout will adhere to the surface of the foundation. Bush hammering may be done strictly under the base plate or across the entire top of the foundation.

Once the vessel is leveled, shimmed and bolted it is ready to be grouted. Grouting shall consist of filling the void area between the top of foundation and the underside of base plate with cementitious grout. The grout shall be installed in accordance with the manufacturers recommendations and any applicable contract specifications.

Depending on the type of grout to be used, grout dams may be used.
Figure 10-5. Typical example of erection study.
Steps in Design

Given the overall weight and geometry of the vessel and the location of the center of gravity based on the erected weight, apply the following steps to either complete the design or analyze the design.

Step 1: Select the type of lifting attachments as an initial starting point:

Lift end (also referred to as the “pick end”):
   a. Head lug: Usually the simplest and most economical, and produces the least stress.
   b. Cone lug: Similar to a head lug but located at a conical transition section of the vessel.
   c. Side lug: Complex and expensive.
   d. Top flange lug: The choice for high-pressure vessels where the top center flange and head are very rigid. This method is uneconomical for average applications.
   e. Side flange lug: Rarely used because it requires a very heavy nozzle and shell reinforcement.
   f. Trunnions: Simple and economical. Used on a wide variety of vessels.
   g. Other.

Tail end:
   a. Tail beam.
   b. Tail lug.
   c. Choker (cinch); see later commentary.

Tailing a column during erection with a wire rope choker on the skirt above the base ring is a fairly common procedure. Most experienced erectors are qualified to perform this procedure safely. There are several advantages to using a tailing choker:

- Saves material, design, detailing, and fabrication.
- Simplifies concerns with lug and shipping orientations.
- May reduce overall height during transportation.

There are situations and conditions that could make the use of a tailing choker impractical, costly, and possibly unsafe. Provide tailing lugs or a tailing beam if:

- The column is more than about 10 feet in diameter. The larger the diameter, the more difficult it is for the wire rope to cinch down and form a good choke on the column.
- The tail load is so great that it requires the use of slings greater than about 1½ inches in diameter. The larger the diameter of the rope, the less flexible it is and the more likely that it could slip up unexpectedly during erection.

Step 2: Determine the forces T and P for all angles of erection.

Step 3: Design/check the lifting attachments for the tailing force, T, and pick force, P.

Step 4: Design/check the base ring assembly for stresses due to tailing force, T.

Step 5: Determine the base ring stiffening configuration, if required, and design struts.

Step 6: Check shell stresses due to bending during lift. This would include midspan as well as any overhang.

Step 7: Analyze local loads in vessel shell and skirt due to loads from attachments.

Allowable Stresses

Per AISC:

Tension

\[ F_t = 0.6F_y \] on gross area

\[ = 0.5F_u \] on effective net area

\[ = 0.45F_y \] for pin-connected members

Compression

(for short members only)

\[ F_c = \text{Use buckling value.} \]

\[ = \text{for vessel shell: } 1.33 \times \text{ASME Factor “B”} \]

Shear

\[ F_s = \text{Net area of pin hole: } 0.45F_y \]

\[ = \text{other than pin-connected members: } 0.4F_y \]

\[ = \text{fillet welds in shear: } \]

E60XX: 9600 lb/in. or 13,600 psi

E70XX: 11,200 lb/in. or 15,800 psi

Bending

\[ F_b = 0.6F_y \text{ to } 0.75F_y, \text{ depending on the shape of the member} \]

Bearing

\[ F_p = 0.9F_y \]

Combined

Shear and tension:

\[ \frac{\sigma_a}{F_a} + \frac{\tau}{F_s} \leq 1 \]
Tension, compression and bending:

\[ \frac{\sigma_a}{F_a} + \frac{\sigma_b}{F_b} \leq 1 \quad \text{or} \quad \frac{\sigma_T}{F_T} + \frac{\sigma_b}{F_b} \leq 1 \]

**Note:** Custom-designed lifting devices that support lifted loads are generally governed by ASME B30.20 “Below the hook lifting devices.” Under this specification, design stresses are limited to Fy/3. The use of AISC allowables with a load factor of 1.8 or greater will generally meet this requirement.

**Notation**

- A = area, in.²
- Aa = area, available, in.²
- Ab = area, bolt, in.²
- An = net cross-sectional area of lug, in.²
- Ap = area, pin hole, in.²
- Ar = area, required, in.²
- As = area, strut, in.² or shear area of bolts
- C = lug dimension, see sketch
- D0 = diameter, vessel OD, in.
- D1 = diameter, lift hole, in.
- D2 = diameter, pin, in.
- D3 = diameter, pad eye, in.
- Dsk = diameter, skirt, in.
- Dm = mean vessel diameter, in.
- E = modulus of elasticity, psi
- fL = tail end longitudinal force, lb
- fT = tail end radial force, lb
- fsc = shear load, lb or lb/in.
- Fa = allowable stress, combined loading, psi
- Fb = allowable stress, bending, psi
- Fc = allowable stress, compression, psi
- Fp = allowable stress, bearing pressure, psi
- Fs = allowable stress, shear, psi
- Ft = allowable stress, tension, psi
- Fy = minimum specified yield stress, psi
- I = moment of inertia, in.⁴
- Jw = polar moment of inertia of weld, in.⁴
- K = end connection coefficient
- KL = overall load factor combining impact and safety factors, 1.5–2.0
- Ki = impact factor, 0.25–0.5
- Kt = internal moment coefficient in circular ring due to radial load
- Ks = safety factor
- KT = internal tension/compression coefficient in circular ring due to radial load
- Ls = length of skirt/base stiffener/strut, in.
- M = moment, in.-lb
- Mb = bending moment, in.-lb
- MC = circumferential moment, in.-lb
- ML = longitudinal moment, in.-lb
- MT = torsional moment, in.-lb
- nb = number of bolts used in tail beam or flange lug
- N = width of flange of tail beam with a web stiffener
- (N = 1.0 without web stiffener)
- nL = number of head or side lugs
- P = pick end load, lb
- Pe = equivalent load, lb
- PL = longitudinal load per lug, lb
- Pr = radial load, lb
- PT = transverse load per lug, lb
- Rb = radius of base ring to neutral axis, in.
- r = radius of gyration of strut, in.
- Rc = radius of bolt circle of flange, in.
- Sa = minimum specified tensile stress of bolts, psi
- tb = thickness of base plate, in.
- tg = thickness of gusset, in.
- tl = thickness of lug, in.
- tp = thickness of pad eye, in.
- ts = thickness of shell, in.
- T = tail end load, lb
- Tb = bolt pretension load, lbs
- Tt = tangential force, lb
- w1 = fillet weld size, shell to re-pad
- w2 = fillet weld size, re-pad to shell
- w3 = fillet weld size, pad eye to lug
- w4 = fillet weld size, base plate to skirt
- w5 = uniform load on vessel, lb/in.
- WE = design erection weight, lb
- WEL = erection weight, lb
- Z = section modulus, in.³
- α = angular position for moment coefficients in base ring, clockwise from 0°
- β = angle between parallel beams, degrees
- σ = stress, combined, psi
- σb = stress, bending, psi
- σp = stress, bearing, psi
- σc = stress, compression, psi
- σcr = critical buckling stress, psi
- σT = stress, tension, psi
- τ = shear stress, psi
- τT = torsional shear stress, psi
- θ = lift angle, degrees
- θb = minimum bearing contact angle, degrees
- θH = sling angle to lift line, horizontal, degrees
- θv = sling angle to lift line, vertical, degrees
Procedure 10-3: Lifting Attachments and Terminology

Types of Lifting Attachments

LIFT END OPTIONS
1. Shell flange lug
2. Top head lug
3. Top flange lug
4. Trunnion
5. Side lug
6. Cone lug

TAIL LIFT OPTIONS
7. Tail beam
8. Tail lug
9. Choker (sling)
10. Base ring stiffener
Miscellaneous Lifting Attachments

1. **Top Flange Lug with Spreader**
   - Link
   - Pin
   - Lug
   - Top nozzle

2. **Sheave Assembly Direct Mount—200 Ton**
   - 5"-2½ NC
   - 7½" φ
   - Re-pad
   - Shell OD
   - Washer
   - Sheave
   - Retaining clips

3. **Trunnion with Fixed Lug Type 1**
   - Ret-rod if req’d

4. **Trunnion with Rotating Lug Type 2**
   - Rotating lifting assembly—remove after erection

5. **Stiffener Pipe Through Studding Outlets—Blind After Erection**
   - Studding outlet

6. **Trunnion Without Lug Type 3**
   - Remove lifting assembly after erection

7. **Temporary Top Head Flange Lug Over Top Nozzle**
   - Top head
Tailing Devices for Vessels with Chambers Projecting through Skirt

Utilize Projection with Base Extension

Parallel Tailing Beams Without Skirt Stiffeners

Frame-Type Tailing Device

Bolted on Ring Beam Extension

Base with Parallel Tailing Beams

Base with Internal Base Stiffeners and Dual Tailing Lugs
HORIZONTAL VESSELS

\[ P = W_E \]
\[ P_L = \frac{0.5W_E}{\sin \theta} \]

For Small Vessels

Typical sling arrangement, no lugs

Alternate sling arrangement

Trunnions on saddles

VESELS, BINS, AND HOPPERS ON LEGS

Do not lift by legs

Tail lug or choke bottom of vessel

Do not lift by nozzle

Tailing lug or choker

Partial ring stiffener

Cone compression ring

SMALL VESSELS

LARGE VESSELS

Use standard lifting lug or trunnion
SIDE LUG WITH SWIVEL LUG

Ensure clearance with nozzles and clips

Add re-pad under trunnion if additional reinforcement is necessary
SIDE LUG COMBINATION WITH STIFFENERS

- Lifting Lug
- Vacuum stiffener
- Optional internal pipe—remove after erection

TYPICAL SIDE LUG

- Bend lines-typical
- Weld
- Stiffener plates
**Tailing Trunnion**

Utilizes reinforced openings in skirt with through pipe. Pipe is removed after erection and the openings used as skirt manways.

---

**Shell Flange Lug**

---

**Lifting Device Utilizing Top Body Flanges**
### Rigging Terminology

1. Boom  
2. Mast  
3. Gin pole  
4. Crane mats  
5. Dead men  
6. Outriggers  
7. Load block  
8. Whip line  
9. Cranes  
10. Derricks  
11. Hoist  
12. Hooks  
13. Jacks  
14. Slings  
15. Pins  
16. Spreader beams  
17. Equalizer beams  
18. Links  
19. Shackles  
20. Wire rope  
21. Counterweight  
22. Trailing counterweight  
23. Struts  
24. Lashings  
25. Guy streamers  
26. Bail  
27. Tensioning blocks  
28. Hitch plate  
29. Pin extractor  
30. Choker  
31. Tail crane  
32. Tail sled
Miscellaneous Lugs, \( W_L < 60 \) kips

### Calculations

Due to bending:

\[
t_L = \frac{6P_T B}{A^2 F_b}
\]

Due to shear:

\[
t_L = \frac{P_T}{(A - D_1) F_s}
\]

Due to tension:

\[
t_L = \frac{P_L}{(A - D_1) F_t}
\]

### Notes

1. Table 10-6 is based on an allowable stress of 13.7 ksi.
2. Design each lug for a 2:1 safety factor.
3. Design each lug for a minimum 10% side force.

### Hertzian Stress, Bearing

\[
\sigma_p = 0.418 \sqrt{\frac{E \left( \frac{P}{t_L} \right) (R_1 - R_2)}{R_1 R_2}} < 2F_y
\]

### Shear Load in Weld

Type 1: greater of following:

\[
\tau_w = \frac{6P_T B}{2A^2}
\]

\[
\tau_w = \frac{P_L}{2A}
\]

Type 2: Use design for top head lug.

---

### Table 10-6

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Figure 10-6. Dimensions and forces.