ORDINE DEGLI INGEGNERI PROVINCIA DI PERUGIA

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PROGETTO DI STRUTTURE IN ACCIAIO

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col patrocinio di:

Ordine degli ingegneri della provincia di Perugia e Fondazione Promozione Acciaio

Problematiche costruttive, strutturali e funzionali di serbatoi e sili in acciaio

Parte 4: Progetto di silos

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Calculation of Loads from the Stored Material according to EC1

Eurocode 1 and Eurocode 3 (EN1993-4-1 - Silos) give detailed rules for the **calculation of loads from the stored material** on bins subject to the following limitations:

- *The eccentricity of inlet and outlet is limited to 0,25 d_c where d_c is the bin diameter or shortest side length.*
- *Impact loads during filling are small.*
- *Discharge devices do not influence the pressure distribution.*
- *The stored material is free flowing and has low cohesion.*

Rules are given for calculating loads on slender, squat and homogeneous bins. The following four loads are specified:

- *horizontal wall load and wall friction*
- *patch load*
- *hopper load*
- *kick load.*

The initial horizontal (p_{hf}) and wall friction (p_{wf}) loads are **uniform at any depth** in the bin. They are multiplied by a **constant factor** to allow for **pressure variations during discharge**. A **patch load** is added to the symmetric load to allow for the effects of **non-symmetric loading.** Due to the complexities of structural analysis of shells incorporating a patch load, Eurocode 1 permits the use of a **symmetrical pressure distribution** for the design of all bins with diameters less than 5m. The symmetrical pressure is increased to compensate for the patch pressure. This gives bins that are safe but more conservative than those bins designed for the patch pressure and the lower symmetrical pressure.

The **hopper loads consist of a linear pressure distribution and a kick load (switch)**. The kick load is applied at the junction of the transition of mass flow hoppers only.

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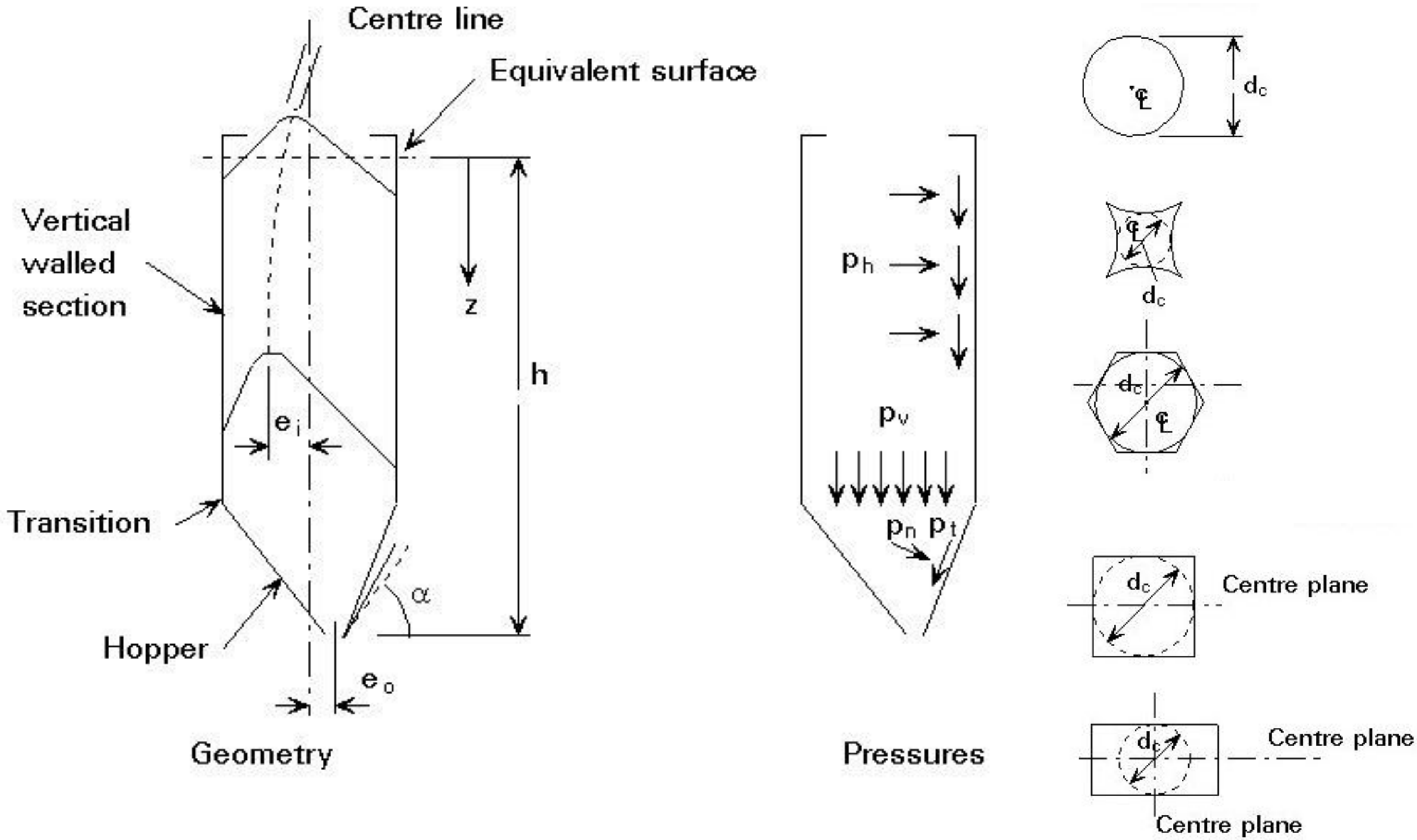
Main silo forms according to EC1



Horizontal pressure and wall frictional pressure

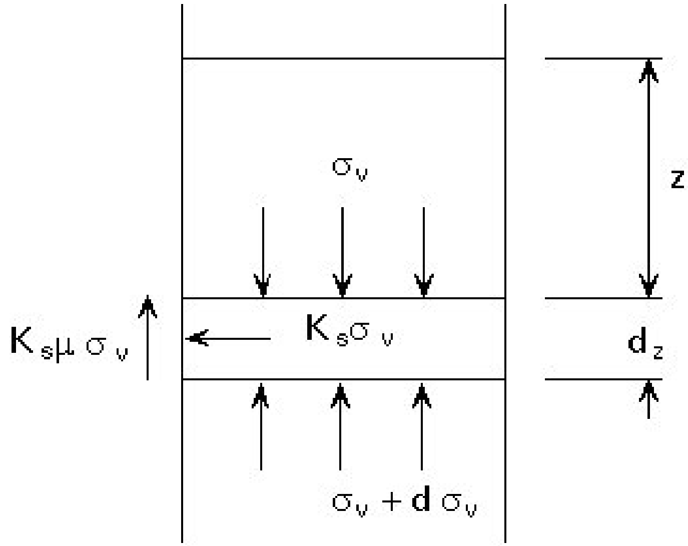
The horizontal pressure at any depth in the bin is calculated using the classical Janssen theory. Janssen considered the vertical equilibrium of a horizontal slice through the stored material in a bin (see Figure) and obtained the following relationship:

$A(s_v + ds_v) + U\ \mu\ K_s\ s_v\ dz = g\ Adz + A\ s_v$ (1)

Rearranging and solving the first order differential equation gives the Janssen equation for vertical pressure p_v at depth z, the horizontal pressure p_{hf} and the wall frictional pressure p_{wf}:

$p_v = [gA/U\mu K_s][1 - e^{-KsmzU/A}]$ (2)
$p_{hf} = K_s\ p_v$ (3)
$p_{wf} = \mu\ p_{hf}$ (4)

The accuracy of the method depends on the selection of a value for the **ratio of horizontal to vertical pressure K_s and the coefficient of wall friction μ.**



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Most bin wall pressures vary because the bins are filled with materials of different properties at different times. Other pressure changes may occur as the bin becomes polished or roughened by stored solids. Bins should therefore be designed with a variety of conditions in mind. Eurocode 1 recognises this situation and gives a **range of properties for common stored materials**. Material properties are selected to give the **most adverse loading condition**. **The most adverse horizontal pressure occurs when K_s is at its maximum value and μ is at its minimum**. **The most adverse wall friction load arises when μ and K_s are both at maximum values**. Material properties may be determined by testing or by taking values given in Eurocode 1.

For bins with corrugated walls, allowance must be made for higher values of μ due to the effect of the stored material within the corrugations.

For convenience Eurocode 1 gives a formula for the calculation of the **axial compression force due to the wall friction** pressure at any depth in a bin. The axial compression per unit perimeter at depth z is equal to the integral of the wall friction pressures on the wall above and is obtained as below:

$$P_w(z) = \int_0^z P_{wf}(z)\,dz = \gamma \frac{A}{U}\left[z - z_0\left(1 - e^{-z/z_0}\right)\right]$$

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Pressure increase for filling and discharge according to EC1

The pressures calculated using the Janssen theory are multiplied by **empirical factors to give filling and discharge pressures** for the following conditions:

1. **Patch load for filling.**
2. **Uniform pressure increase for discharge.**
3. **Patch load for discharge.**
4. **For simplicity of structural design, EC 1 also includes a simplified alternative rule to the patch load for filling and discharge.**

1.a The patch load for filling: non-membrane bins

Pressures determined using the Janssen equation are increased by a **localised load or 'patch' load** to allow for **unsymmetrical pressure distributions**. The patch load is prescribed to **account for unsymmetrical pressures** which experiments have shown occur in all bins. The non-uniformity of pressure depends mainly upon the eccentricity of the bin inlet, the method of filling and the anisotropy of the stored material. The patch load increases with the eccentricity of filling. The eccentricity of filling results from the horizontal velocity of the stored material. It depends upon the type of filling device and must be estimated before calculating the patch load.

The **patch load is different** for unstiffened steel (**membrane**) and stiffened steel and concrete (**non-membrane**) bins to allow for the differences in the response of these structures to loading. **The maximum stress in the walls of non-membrane bins depends upon the magnitude of the pressure whereas membrane steel bins are more sensitive to the rate of change of pressure**.

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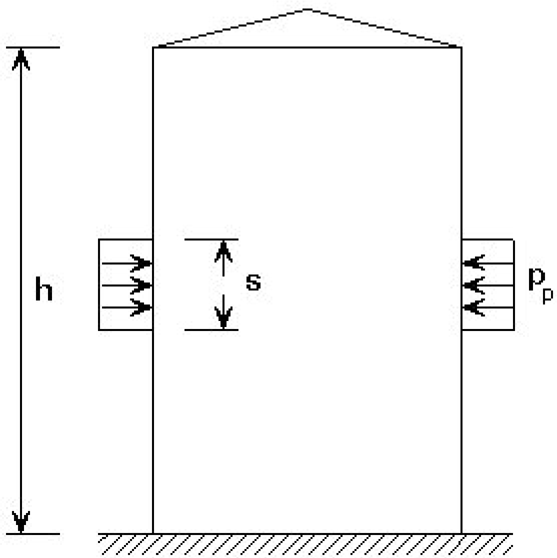
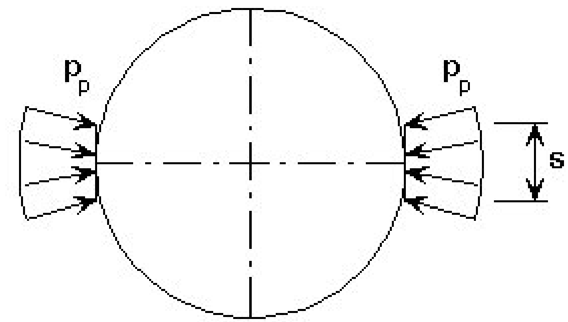
The patch load for filling: non-membrane bins



(a) Side elevation



(b) Plan view of thick walled circular silo

For **stiffened steel bins**, two patch loads are applied on diametrically opposite square areas of wall, each with side length $s = 0{,}2d_c$ (see Figures a and b). The loads are symmetrical and allow a relatively simple calculation of the bending moments induced in the structure. The patch pressure is calculated as $p_p = 0{,}2\beta\ p_{hf}$ (5). The pressure acts over a height s, where $s = 0{,}2d_c$ (6) and $\beta = 1 + 0.2\ e$.
The patch should be applied at **different levels on the bin wall** to find the worst loading case resulting in the highest wall stress. For simplicity, Eurocode 1 allows the patch load in **non-membrane** bins to be applied at the **mid-height** of the vertical walled section and uses the percentage increase in the wall stresses at that level to increase the wall stresses throughout the silo. The simplified rule does not apply to groups of silos.

Main source ESDEP

2.b The patch load for filling: membrane bins

Membrane steel bins are **sensitive to the rate of change of the patch pressure** and so a cosine pressure distribution is specified. The pressure pattern shown in Figure c extends all around the bin. Pressure is outward on one side and inward on the other.

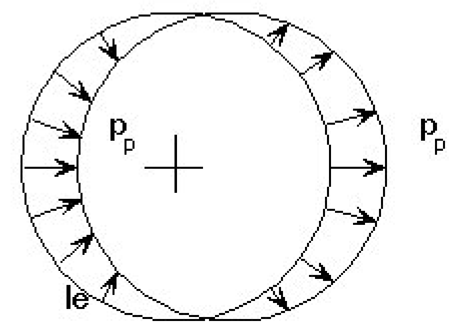
The most important influence of the patch is the **increase in axial compression at the base** of the bin. The increased axial compressive force can easily be calculated using beam bending theory and assuming global bending of the bin. In order to calculate the axial compressive force, the total horizontal force from the patch load should be calculated from:

$$F_p = \frac{\pi}{2} s \, d_c \, p_{ps}$$

Where $p_{ps} = p_p \cos q$ and p_p and s are calculated using Equations (5) and (6) respectively.

The patch should be taken to **act at a depth z_0 below the equivalent surface** or at the **mid-height** of the vertical walled section, whichever gives the higher position of the load, where

$$z_0 = \frac{A}{K_s \, \mu U}$$



(c) Plan view of thin walled circular silo

The patch pressure introduces **local bending stresses** in the bin at the level of the patch. These bending stresses are difficult to calculate and a **finite element analysis of the structure is required**. To simplify the calculation it is easier to design using the **increased pressure distribution** described in the next as an alternative to the patch pressure.

Main source ESDEP

2. Uniform pressure increase for discharge

The **static pressures are multiplied by two constant coefficients** (C_w and C_h) to design for **uniform discharge pressures**. C_h increases the horizontal pressure and C_w increases the vertical pressure. C_h varies depending upon the stored material and Eurocode 1 gives a value that ranges from 1,3 for wheat to 1,45 for flour and fly ash. C_w is taken as 1,1 for all stored materials. These factors were selected from experience gained from satisfactory bin design and test results.

3. Patch load for discharge

The patch load for **discharge** is calculated in the **same way** as the patch load for filling. Horizontal pressures calculated for discharge (described in 2.) are used to calculate the patch load. In addition, the eccentricity e, is taken as the greater of the eccentricities of the filling and the outlet.

4. Increased uniform load - an alternative to the patch for filling and discharge

For simplicity in structural design, Eurocode 1 permits the use of another constant factor on the uniform discharge pressures to allow for stress increases due to unsymmetrical pressure. The factor is calculated from the patch load magnifier and results in a simple but conservative rule which may be used instead of the patch pressure. For filling and discharge the normal wall pressure calculated using Equation (3) is multiplied by $1 + 0{,}4\ \beta$ and the wall friction is multiplied by $1 + 0{,}3\ \beta$.

Main source ESDEP

Hopper and bottom loads

Flat bottoms are defined as bin bottoms where $\alpha < 20°$. The vertical pressure p_{vf} varies across the bottom but for slender bins it is safe to assume that the pressure is constant and equal to:

$p_{vf} = 1{,}2\ p_v$ (8)

where:

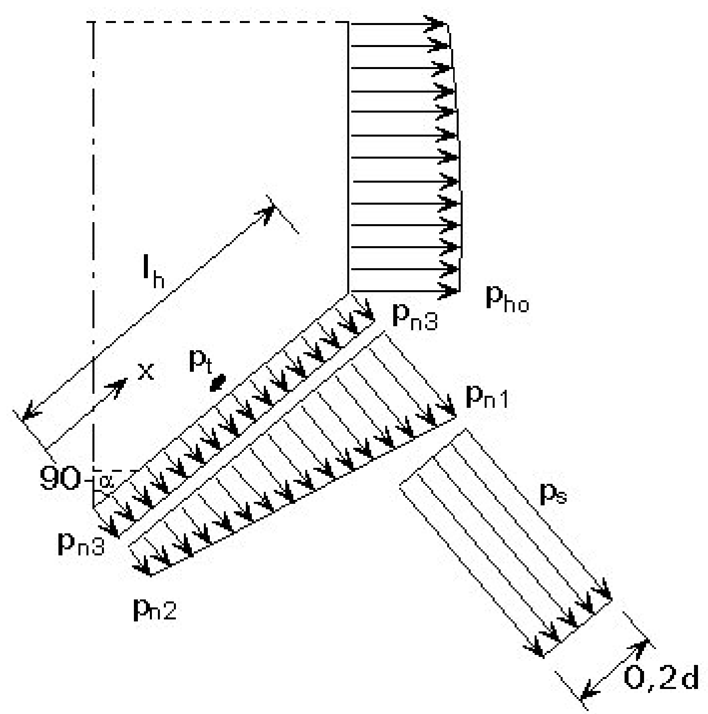
p_v is calculated using Equation (2).

It should be noted that for squat bins, the pressure variation at the bin bottom may influence the design and so flat bottomed squat bins may be designed for non-uniform pressures.

Loads on slopping walls of hopper

Eurocode 1 considers the sloping wall (where $\alpha > 20°$) to be subject to both **normal pressure**, p_n, and **friction force** per unit area p_t (see Figure). The hopper walls carry all **the weight of the stored material** in the bin other than that carried by wall friction in the vertical section. Knowledge of the **vertical pressure** at the transition between the vertical walled section and the hopper is required to define the loading on the hopper. Empirical formulae have been adopted in Eurocode 1 for the calculation of normal and frictional wall pressures on the hopper wall following a series of tests on pyramidal hoppers. The tests showed that it was sufficient to assume that the pressure distribution upon a hopper wall subjected to surcharge from the vertical walled section **decreases linearly from the transition to the outlet**. The pressure **normal to the hopper wall**, p_n, as shown in the Figure may be obtained as follows:

$$p_n = p_{n3} + p_{n2} + (p_{n1} - p_{n2})(x/l_h) \qquad (9)$$



where:

x is a distance measured from the edge between 0 and l_h

$p_{n1} = p_{vo} (C_b \cos^2 \alpha + 1{,}5 \sin^2 \alpha)$ (10)

$p_{n2} = C_b \, p_{vo} \cos^2 \alpha$ (11)

$$p_{n3} = 3{,}0 \, \frac{A}{U} \frac{\gamma K_s}{\sqrt{\mu}} \qquad (12)$$

Where

C_b is a constant and is equal to 1,2

p_{v0} is the vertical pressure acting at the transition calculated using the Janssen equation.

The value of the wall frictional pressure p_t, is given by $p_t = p_n \; \mu_m$ (13)

Main source ESDEP

Kick load

High pressures have been measured in **mass flow hoppers** at the start of discharge due to a change in the stress state of the stored material. The change is often referred to as the **'switch'** and results in a **'kick load'** at the transition. It occurs when the material moves from a static (**active pressure**) to a dynamic (**passive pressure**) state. An empirical and approximate value for the kick load, p_s, in Eurocode 1 is given as follows:

$p_s = 2\ p_{h0}$ (14)

where

p_{h0} is the **horizontal pressure at the base of the vertical walled section** (see previous Figure) and p_s is taken to act normal to the hopper wall at a distance equal to 0,2 d_c down the hopper wall.

The kick load is **only applied to mass flow bins**. This is because it will be partially or totally absorbed by the layer of stationary material in **funnel flow hoppers**. The transition between the hopper and the vertical section is subjected to a **compressive inward force** from the inclined hopper. The kick load acts against this compressive force and so, it may actually increase the outward load from the stored material (p_n) which may be carried by the hopper during discharge (although the kick cannot be guaranteed and should not be used to reduce the design stresses).

Main source ESDEP

Other Loading Considerations

Pressure distributions can be affected by factors which may either increase or decrease wall loads. Such factors are difficult to quantify, and are more significant in some bins than others. A limited list is given below.

Temperature variation

Thermal contraction of a bin wall is restrained by the stored material. The magnitude of the resulting increase in lateral pressure depends upon the temperature drop, the difference between the temperature coefficients of the wall and the stored material, the occurrence of temperature changes, the stiffness of the stored material and the stiffness of the bin wall.

Consolidation

Consolidation of the stored material may occur due to release of air causing particles to compact (a particular problem with powders), physical instability caused by changes in surface moisture and temperature, chemical instability caused by chemical changes at the face of the particles, or vibration of the bin contents. The accurate determination of wall pressures requires a knowledge of the variation with depth of bulk density and the angle of internal friction.

Moisture Content

An increase in the moisture content of the stored material can increase cohesive forces or form links between the particles of water soluble substances. The angle of wall friction for pressure calculations should be determined using both the driest and wettest material likely to be encountered.

Increased moisture can result in swelling of the stored solid and should be considered in design.

Main source ESDEP

Segregation

For stored material with a wide range of density, size and shape, the particles tend to segregate. The greater the height of free fall on filling, the greater the segregation. Segregation may create areas of dense material. More seriously, coarse particles may flow to one side of the bin while fine cohesive particles remain on the opposite side. An eccentric flow channel may occur, leading to unsymmetrical loads on the wall. The concentration of fine particles may also lead to flow blockages.

Degradation

A solid may degrade on filling. Particles may be broken or reduced in size due to impact, agitation and attrition. This problem is particularly relevant in bins for the storage of silage where material degradation may result in a changing pressure field which tends to hydrostatic.

Corrosion

Stored material may attack the storage structure chemically, affecting the angle of wall friction and wall flexibility. Corrosion depends on the chemical characteristics of the stored material and also the moisture content. Typically, the design wall thickness may be increased to allow for corrosion and the increase depends upon the design life of the bin.

Abrasion

Large granular particles such as mineral ones can wear the wall surface resulting in problems similar to those described for corrosion. A lining may be provided to the structural wall, but care should be taken to ensure that wall deformation does not cause damage to the lining. The linings are usually manufactured from materials such as stainless steel or polypropylene.

Main source ESDEP

Impact Pressures
The charging of large rocks can lead to high impact pressures. Unless there is sufficient material to cushion the impact, special protection must be given to the hopper walls. The collapse of natural arches which may form within the stored material and hold up flow, can also lead to severe impact pressures. In this case, a preventative solution is required at the geometric design stage.

Rapid Filling and Discharge
The rapid discharge of bulk solids having relatively low permeability to gasses can induce negative air pressures (internal suction) in the bin. Rapid filling can lead to greater consolidation, and the effects are discussed above.

Powders
The rapid filling of powders can aerate the material and lead to a temporary decrease in bulk density, cohesiveness, internal friction and wall friction. In an extreme case, the pressure from an aerated stored material can be hydrostatic.

Wind Loading
Methods for the calculation of wind loads on bins are given in Eurocode 1. Design against wind loads is especially critical during bin construction.

Dust Explosions
Eurocode 1, Part 4 recommends that bins storing materials that may explode should either be designed to resist the explosion or should have sufficient pressure relief area. Eurocode 1 lists materials that may lead to explosions. Eurocode 1 recommends proper maintenance and cleaning, and the exclusion of sources of ignition to prevent explosions.

Differential Settlements

Large settlements often occur as bins are filled, particularly the first time. The effects of differential settlement of groups of bins should be considered. Differential settlements may lead to buckling failure of membrane steel bins.

Seismic Actions

Rules for seismic design are given in Eurocode 1 and Eurocode 8.

Mechanical Discharge Equipment

Mechanical discharge equipment can lead to unsymmetrical pressure distributions even when it is considered to withdraw the stored material uniformly. The influence of mechanical discharge equipment on wall pressures should be considered during design.

Roof Loads

Bin roofs impose an outward thrust and axial compression on bin walls and should be considered during wall design.

Load Combinations

Many bins are filled to their full design loads for most of their life. Eurocode 1 states that 100% of the predominant load should be added to 90% or 0% of other loads to give the most onerous design load at both ultimate and serviceability limit states respectively.

STRUCTURAL ANALYSIS AND DESIGN

Selection of the Bin Form

At the conceptual stage of design, the geometry of the bin is selected and consideration is given to the relative economy of different structural forms. The costs of materials, fabrication, erection and transport all influence the selection of the structural form. Steel bins usually have **rectangular** or **circular** cross-section shapes. **Circular** bins are usually **more economical than rectangular** bins because the circular walls carry loads in membrane tension whereas rectangular bins carry load less efficiently in bending. Rectangular bins typically require 2,5 times the material required for circular bins of the same capacity.

Rectangular bins tend to be heavily stiffened structures whereas circular bins are often unstiffened except at the top and the transition of the vertical walled section and the hopper. Rectangular bins tend to have large reserves of strength. This is not generally the case with circular bins for which care is needed in design to prevent overstress or buckling of the bin wall.

Design of Non-Circular Bins

A typical non-circular bin is shown in the Figure. The structural design consists of the following main procedures:

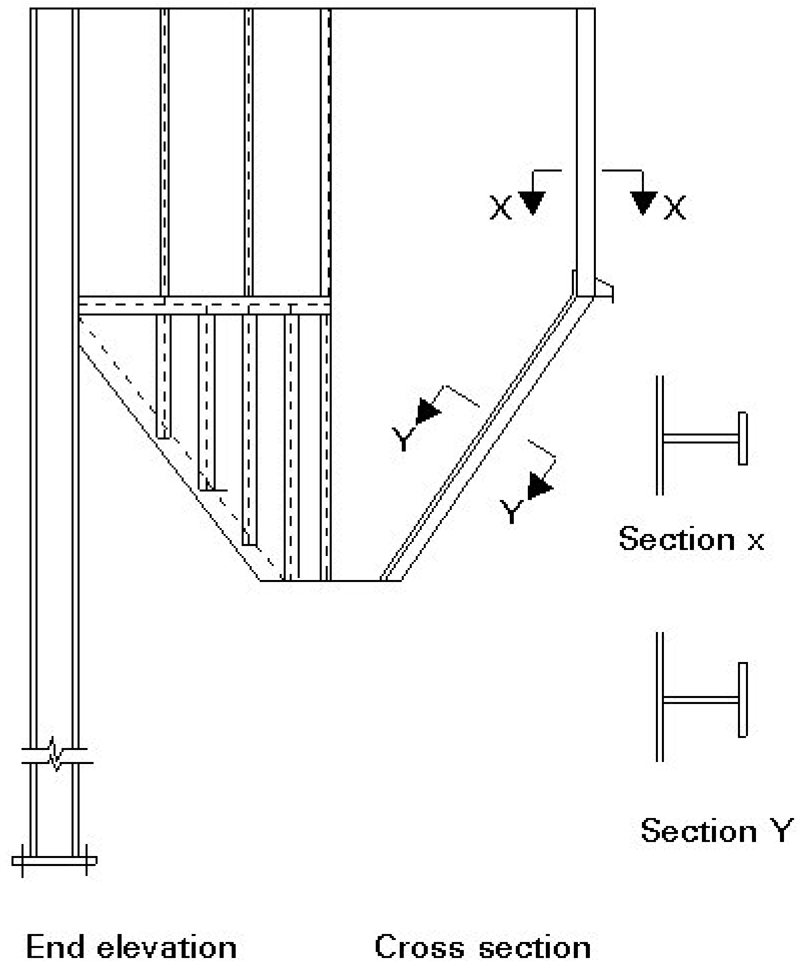
•*select the support layout, stiffener layout and connections,*

•*design the wall plates,*

•*design the vertical and horizontal stiffeners including the transition ring beam,*

•*design the supports.*

The pressures on the vertical and inclined walls are calculated using the rules outlined previously. The structural design is discussed below.



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Wall plates

Non-circular bins tend to be **heavily stiffened** structures. Material loads in the bin are applied directly to the wall plate, and transferred via the plate to the stiffeners. The walls are subject to **bending** and tensile **membrane** stresses. Frictional forces result in vertical compression of the wall and, because of the stiff cores and column supports, cause in-plane bending of the wall. There are two main approaches to model the structural system. Either the bin is analysed as many isolated components or it is considered as a continuous folded plate structure. Most existing guides recommend the first approach. The walls are designed with assumed boundary conditions and interaction between individual plates is ignored. The guidance given is for flat plated bins. A more economical solution may be to use **corrugated** wall plates. In this case the bin wall is designed using the section properties of the corrugated sheet.

Wall pressure is carried partly by flexural action of the plate in bending and partly by membrane action. Bin walls are generally analysed using small deflection theory. The wall deflections are small (less than the thickness of the plate) and so for design purposes it is acceptable to assume that the load is carried entirely by plate bending. Two methods of analysis are commonly used.

1. Wall plates between stiffeners with an aspect ratio greater than two to one are analysed as **beams bending in one direction only**. The beam is assumed to span continuously over stiffeners and may be fully fixed at the ends.
2. Plates with an aspect ratio less than two to one are designed with **tabular data**. The maximum bending moment for plates with simply supported or fixed edges is given by:

$M_{max} = \alpha \, pa^2 \, b$ (15)

where:

a and *b* are the shorter and longer plate dimensions respectively

p is the average normal pressure.

α is tabled in the code as a function of the a/b aspect ratio of the plate.

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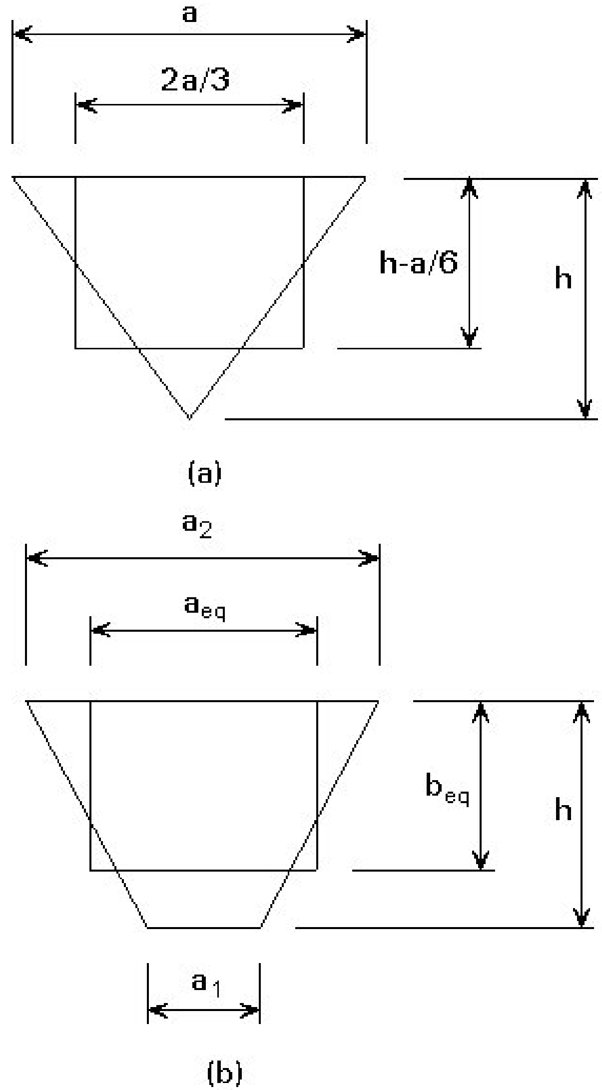
Tabulated data is not available for the analysis of trapezoidal plates and so the hopper wall is analysed as an idealised rectangular plate. The dimensions may be calculated from formulae given in the Figure. Both of the methods described lead to conservative designs due to the assumed plate geometry and boundary conditions. Higher accuracy can be achieved using numerical techniques, such as the finite element method, to analyse the interaction of the various plate members subjected to in-plane and out-of-plane loads.



$$a_{eq} = \frac{2a_2(2a_1 + a_2)}{3(a_1 + a_2)}$$

$$b_{eq} = h - \frac{a_2(a_2 - a_1)}{6(a_1 + a_2)}$$

Main source ESDEP

Plate Instability

Buckling is unlikely to control the design of the wall thickness of plates analysed using small deflection theory. Thus a conservative stability analysis is usually adopted and the critical elastic buckling load is calculated assuming that the loads are acting in the plane of the plate. The elastic critical buckling load can be calculated from the following equation:

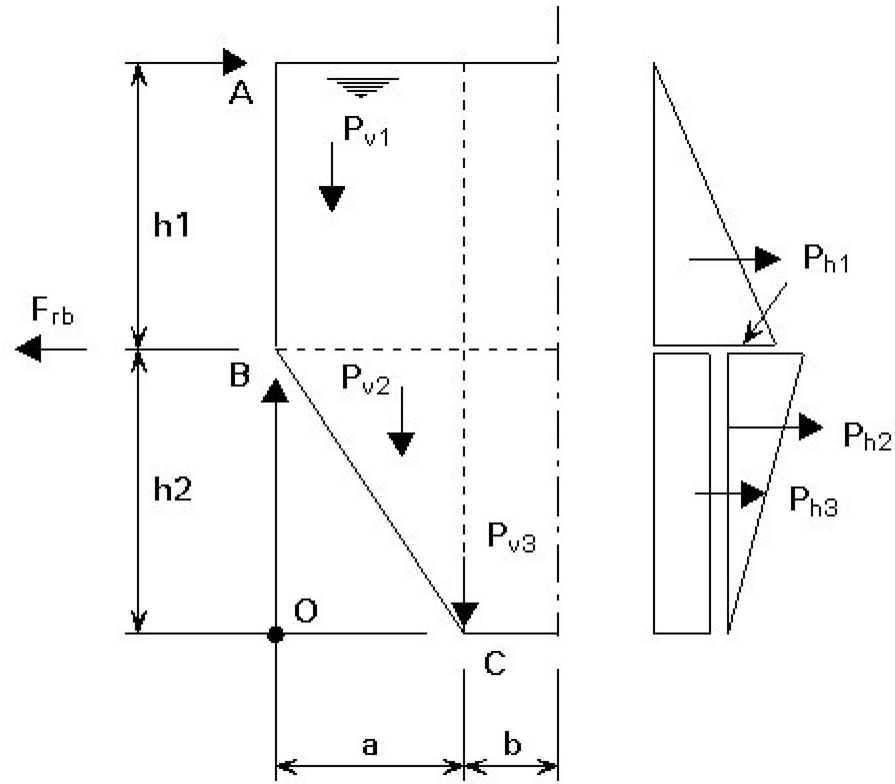
$$f_{cr} = \frac{k\,\pi^2 E}{12(1-\mu^2)\left(\frac{b}{t}\right)^2} \qquad (16)$$

The plate is assumed to be simply supported on all four edges and subject to a uniform or linearly increasing load. If necessary, the buckling resistance of a flat plate can be calculated allowing for additional strength due to lateral pressure from the stored material and post buckling strength.

Stiffener design

A typical stiffened arrangement consists primarily of vertical stiffeners but with horizontal stiffeners at the transition and at the top of the bin. Vertical stiffeners in the vertical walled section are simply designed to carry horizontal and vertical wall friction loads from the adjoining wall plates. Stiffeners in the hopper are designed as beams with end reactions and loads normal to the wall from the stored material as shown in the Figure. Tension forces along the beam may also need to be considered.

The horizontal stiffener at the top of the bin is designed to carry the reaction at A from the horizontal loads on the vertical wall. Horizontal loads include those from the stored material and the wind loads.



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Hopper loads are usually carried by a ring beam at the transition. The ring beam has to carry the hopper weight and distribute the bin loads to the supports. **At the start of filling the ring beam acts as a compression frame. It resists inward forces from the suspended hopper. As filling continues, the compressive forces are offset by tension from the lateral pressure exerted by the stored material in the bin.** The previous Figure shows the load resultants. The ring beam force is found by taking moments about point O.

$$F_{rb} = \frac{1}{h_2}\left[p_{v1}\frac{a}{2} + p_{v2}\frac{2a}{3} + p_{v3}a - p_{h2}\frac{2h_2}{3} - p_{h3}\frac{h_2}{2}\right] \qquad (17)$$

p_{h2} and p_{h3} are the horizontal components of pressure calculated normal to the hopper wall using Equation (9). The ring beam may also have to carry loads from the following:

Vertical load from wall friction in the bin.

Axial compressive forces that arise from in-plane bending of the wall plates.

Axial tension due to forces from adjacent walls.

Torsion due to eccentricity of any of the above forces.

Support structure

The support structure for small bins is usually terminated at the ring beam. The walls of the structure above carry all the loads from the bin. This form of support is common in circular bins but in square bins the supports are usually continued from the transition ring beam to the top of the structure. Their function is to carry the vertical loads in the bin and provide resistance to buckling. A small ring beam is often positioned at the top of the bin to give additional restraint against horizontal forces. The support structure is braced to provide stability against externally applied lateral forces or non-symmetrical internal forces.

Main source ESDEP

Design of Circular Bins

Introduction

The wall thickness of circular bins is selected after checks to **prevent yielding** due to circumferential tension forces and **buckling**. The wall thickness of most bins is governed by buckling although hoop tension controls the design of very shallow bins. Most cylindrical bins have only two stiffeners, one at the transition and one at the top of the vertical walled section. Additional stiffeners may be used to resist wind loads. Conical hoppers are usually unstiffened.

This section describes the basic design procedure and discusses the design of critical components. The main elements of design are:

Preliminary sizing of bin and hopper walls.

Bin wall buckling.

Stiffener design considering the influence on wall stresses and buckling.

Support design considering the influence on wall stresses and buckling.

Recent research has investigated the limitations of simplified design rules and highlighted areas of design which may require careful consideration. These areas include high localised stresses around bin supports and boundaries, and the influence of unsymmetrical loads on wall stress. For very large bins a detailed finite element analysis of the structure is recommended. For most bin designs this may not be possible due to economic restrictions and so the design is carried out using simplified procedures. In many cases these procedures do not model the bin behaviour accurately and careful design is required to prevent failure.

Main source ESDEP

Cylinder wall stress

The circumferential wall stresses in bins less than 5 m diameter can be first estimated simply but conservatively using the symmetrical pressure distribution alternative to the patch load discussed above and the membrane theory of shells. Membrane theory assumes that the bin wall is subject to tensile forces only. The 'hoop' tension should be calculated at the bottom of the cylinder as follows:

$t_h = p_{he}\, r$ (18)

The resulting wall thickness may have to be increased to ensure adequate connection strength, corrosion and wear resistance and to prevent buckling. Membrane theory is only accurate for the predication of wall stresses away from discontinuities such as changes in wall thickness, supports and stiffeners. Particular precautions are required depending upon the type of support.

Main source ESDEP

Wall buckling

The most common failure mode of cylindrical steel bins is the buckling of the bin wall under axial compression. Axial compression may be due to combined loads of wall friction, roof loads and loads from attached equipment. The elastic buckling stress of a bin wall is influenced by the following:

- *magnitude and shape of wall imperfections;*
- *distribution of the wall friction load;*
- *magnitude of internal pressure;*
- *elastic properties of the stored material;*
- *connections;*
- *bin supports.*

Buckling can be prevented using simple hand calculation methods provided that the bin walls, supports and connections are detailed carefully to prevent significant out-of-plane displacements.

Many methods have been proposed for the calculation of the critical elastic buckling stress. A simple and conservative approach is to adopt the classical elastic critical stress multiplied by an empirical safety factor γ.

$$f_{cr} = \gamma \, 0{,}605 E_t / r \qquad (19)$$

where $\gamma = 0{,}15$

The influence of lateral pressure is ignored and the shell is assumed to be uniformly axially compressed. Equation (19) may be used safely provided that the load distribution is uniform (i.e. the conservative pressure distribution in Eurocode 1 is used) and the supports are designed to prevent significant out-of-plane stresses and deflections in the shell.

Main source ESDEP

Buckling from Wind Loads

The ECCS [15] and BS 2654 [16] give recommendations for the design of cylinders to resist external pressure. Generally, restraint to the top of the bin is provided either by a fixed roof or a stiffener at the top of the cylinder. In large bins, it may be economical to stiffen the sheeting of circular bins. Stiffening generally increases the resistance to wind buckling, but not to circumferential tension or meridional compression, except locally. Circumferential stiffeners should be placed on the outside of a bin to avoid flow restrictions. Steel bins are more susceptible to wind buckling during construction than in service because restraint is provided by the roof and ring beam in service.

The following points should be considered when designing cylindrical bin walls to prevent buckling.
Bins can be designed less conservatively using the patch pressure distribution. The patch load results in an unsymmetrical pressure distribution around the bin wall corresponding to rapid circumferential changes in stress. A rigorous shell analysis of the bin wall is required as simple hand calculation methods are not available for an accurate analysis.
Further economy may result from utilising the increased strength of the bin wall due to lateral pressure from the stored material. Hoop tension resulting from lateral pressure reduces the imperfection sensitivity of buckling under axial compression and increases the buckling strength. Methods have been developed to include the influence of internal pressure on the buckling strength. Designers have been reluctant to use the rules because of the high number of buckling failures of steel bins and the need to ensure that the stationery layer of stored material adjacent to the bin wall has adequate thickness. In eccentrically discharged bins, the lateral support cannot be guaranteed over the entire wall and so there may not be any increase in buckling strength.
Cylindrical walls are not normally stiffened with vertical stiffeners. The physical size of local buckles is small and so longitudinal stiffeners would need to be closely spaced to prevent buckling. Circumferential stiffeners serve no useful purpose in resisting buckling under axial compression.
The critical buckling stress is reduced by surface imperfections. The number and size of imperfections is influenced by the fabrication process. Apparently identical cylinders fabricated using different processes may have very different buckling strengths. The critical stress should be reduced for bins with large imperfections. Eurocode 3 (and Eurocode 9 for aluminium shells) give rules for the strength reduction depending upon the type and size of imperfection.
Where bolted construction is used on bins and the plates are lapped together, the buckling strength is reduced below the value for butt jointed construction. Circumferential joints lead to eccentricities in the line of axial thrust resulting in destabilizing axisymmetric deflections, compressive circumferential membrane stresses and local bending stresses.
Column supports can induce high bending stresses in the bin wall. They can influence stresses up to a distance equal to many times the diameter from the support. The problem can be alleviated by extending the columns to the full height of the bin (the columns can then carry the roof loads directly). If the columns are not continued to the top of the bin, a shell bending analysis could be used to determine the stresses induced in the shell wall and associated ring beams and stiffeners.

Main source ESDEP

Bottom and hopper

High stresses occur near the base of a bin wall if it is rigidly connected to a flat floor. They may be reduced by detailing a suitable movement joint or by design of the bin wall to prevent overstress. Flat bottoms should be designed to carry the vertical pressure calculated from Equation (8).

Conical hoppers are designed as membrane structures in tension. For the calculation of the hopper wall thickness and connection detailing, it is necessary to calculate the meridional tensile stress and the circumferential hoop stress. The meridional tension, t_m, is calculated from the resultant of the vertical discharge pressure p_v at the transition and the combined weight of the material in the hopper and the hopper wall, W.

$$t_m = \frac{p_v r}{2 \cos(90 - \alpha)} + \frac{W}{2 \pi r \cos(90 - \alpha)} \qquad (20)$$

The hoop tension t_h is calculated from the pressure normal to the hopper wall during discharge and is equal to:

$$T_h = \frac{p\, r}{\cos(90 - \alpha)} \qquad (21)$$

The effects of mechanical discharge aids or column supports on the hopper wall stress should be considered. Again reliable hand methods for the calculation of stresses due to column supports are not available and so an accurate prediction is only possible using a finite element analysis.

Main source ESDEP

Transition ring beam

The transition between the cylinder and the cone may be made using a variety of connection details (some are shown in the Figure in the next page). The hopper applies an inward and downward force on the transition which induces a **circumferential compression** in the ring beam. The ring beam should be checked to prevent **plastic collapse and buckling**. It is a usual practice to design continuously supported rings to resist the horizontal components of the hopper meridional tension t_m. This may be reduced to allow for hoop tension from the horizontal pressure in the cylinder. The ring beam may also have to carry vertical loads for column supports.

A summary of **forces on the ring beam** is as follows:

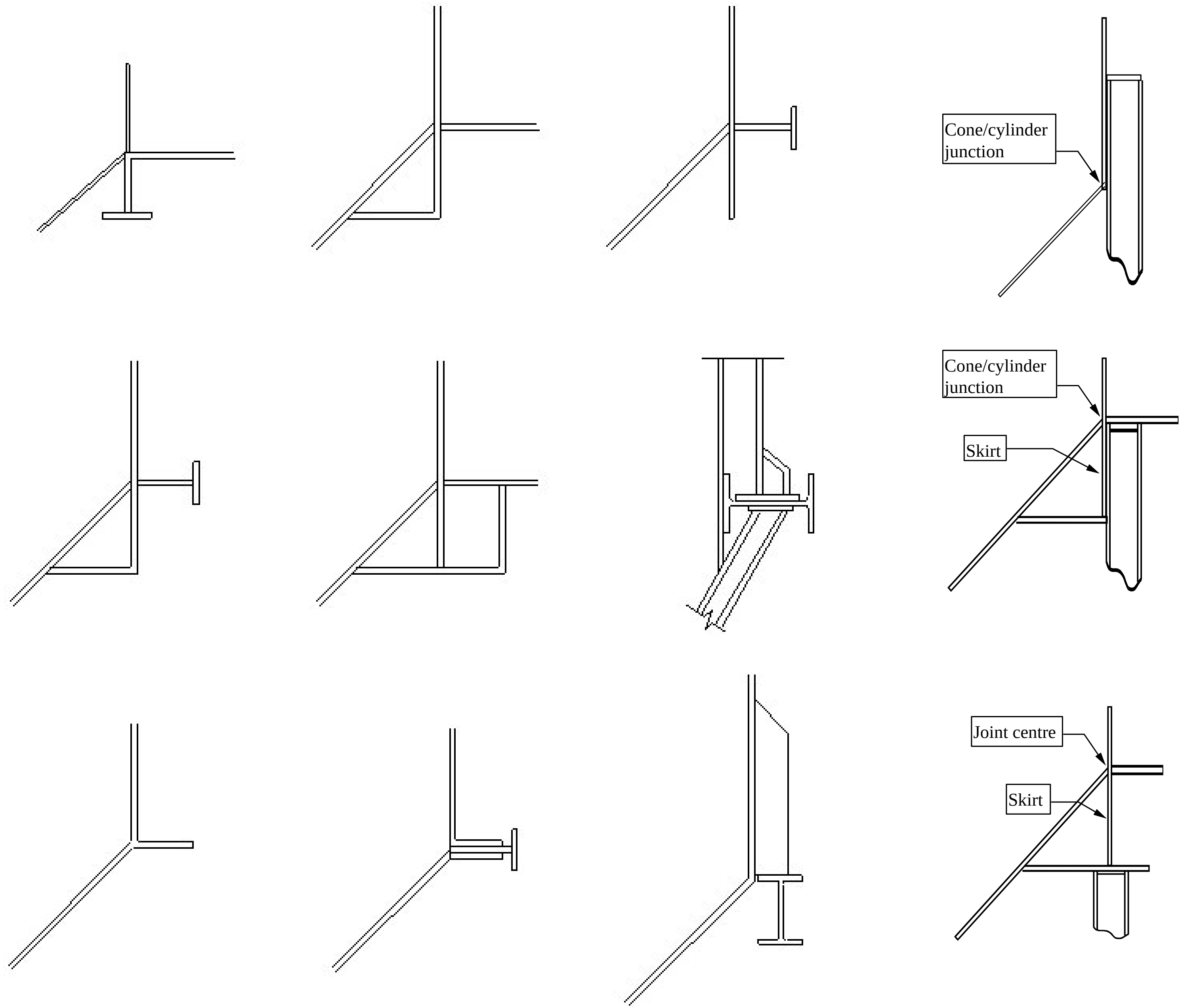
- *vertical load from wall friction in the cylinder;*
- *outward load from horizontal pressure in the cylinder;*
- *membrane forces from the hopper;*
- *torsion due to eccentricity of any of the above forces;*
- *upward load from the supports.*

  These forces result in:
  - *axial compression from net outward and inward forces;*
  - *shear and bending between support columns;*
  - *local shell bending;*
  - *torsion due to eccentricity of shell and column loads.*

Circumferential compressive stresses in the ring beam at the transition of the mass flow hoppers is **relieved** by the **kick load**. Due to uncertainty of the exact magnitude of the kick load, the beneficial effects should not be used in design.

For many ring beam details, part of the hopper and the cylinder walls are effective in carrying the ring beam forces and should be designed accordingly. For skirt supported bins, the shell provides sufficient strength and a ring beam is not usually required.

Main source ESDEP



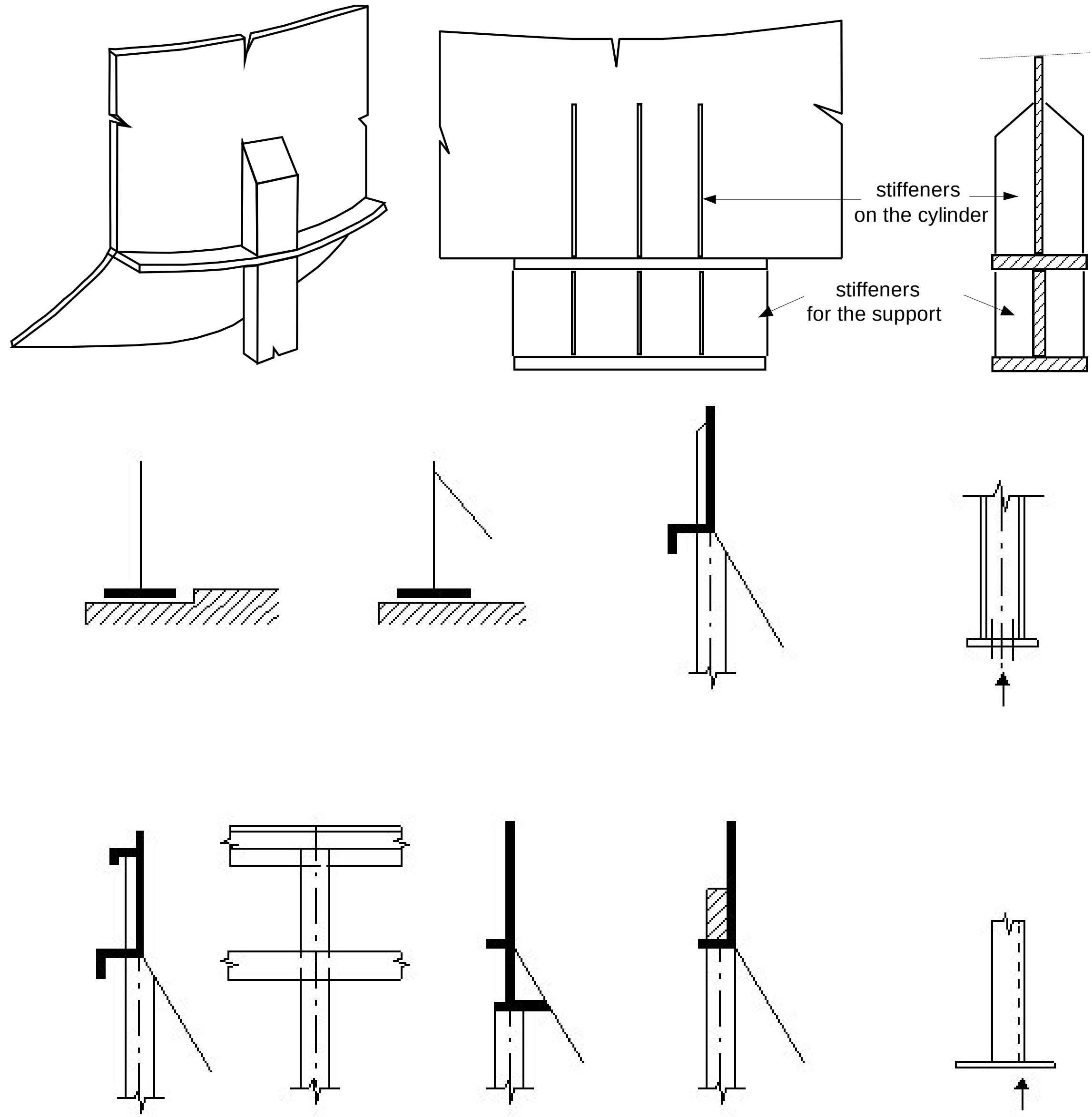
Typical transition ring details suggested by EC3

Main source ESDEP

Supports

Different types of bin support are shown in the Figure. Column supported bins result in a complicated stress pattern in the bin wall around the column. The stress pattern is less complicated when the columns are continued to the top of the bin. Increased stresses in the shell wall can be reduced by sensible design of the column support. The distance of the column from the bin wall should be kept to a minimum and loads from the column supports can be distributed by stiffeners.

In the case of small-diameter bins and bunkers (d_c < 7m), the metal walls may extend down to the foundation and support the entire structure.



Typical column supports suggested by EC3

Main source ESDEP

Connections
Sheeting may be connected by welding or bolting. When bolted connections are used, designers should be aware of the reduced buckling strength of the bin wall due to lap joints. Connections are designed to carry the meridional and circumferential stresses in the cylinder and the hopper as described above.

5. CONCLUDING SUMMARY

Eurocode 1 gives simplified rules for the calculation of loads and the structural design of common bin types.
Non-uniform loading needs to be carefully considered in design.
Non-circular bins are heavily stiffened structures designed to carry loads in bending. In general, they are designed conservatively.
The design of circular bins is usually governed by the buckling of the bin wall.
Circular and non-circular bins may be designed conservatively using simple hand calculation methods.
Supports, connections, stiffeners and fittings should be detailed to minimise out-of-plane stresses and deflections.