Lecture – 1

Design Philosophy

**Working Stress Method of Design**
Concrete is strong in compression and crushing strength is determined by test on standard cubes. Large deformation is noticed at the failure load. Deformation is permanent in nature. This suggests for the adoption of a factor of safety.

Permissible bending & direct compression are as fraction of crushing strength. For example:

M15 concrete, the value of $\sigma_{cbc} = 5 = (15/3)$ and $\sigma_{cc} = 4 = (15/3.75)$

**Assumptions in working stress method**
1. Plane section before bending will remain plane after bending.
2. Stress-strain relations obey Hooks law (linear)
3. Tensile stresses are taken by steel only.
4. The Modular ratio $m = \frac{280}{3\sigma_{cbc}}$ not as $\left( m = \frac{E_s}{E_c} \right)$
5. $f_{ch}$ = Compressive stress of concrete; $\sigma_{cbc}$ = Permissible stress of concrete; $f_{st}$ = Tensile stress in steel; $\sigma_{st}$ = Permissible stress of concrete


**Limit State Method of Design**

This is based on the behavior of structure at different limit states ensuring adequate safety against each limitation.

1. **Ultimate Limit State**: With respect to strength in shear, flexure, torsion, bond or combined effects.
2. **Serviceability Limit State**: With respect to deflection & cracking. The appearance, durability and performance of the structure must not be affected by deflection & cracking.

**Assumptions in limit state method:**

1. Plane section before bending will remain plane after bending.
2. Tensile strength carried by of concrete is zero.
3. Does not obey Hook’s law.
4. Ultimate strain of concrete is 0.0035
   \[ \sigma_c = 0.67 f_{ck} \]
   Partial safety factor for concrete \( \gamma_m = 1.5 \)
   Hence, design strength of concrete \( = 0.67 f_{ck} / 1.5 = 0.446 f_{ck} \)
5. Maximum strain in tensile reinforcement at failure shall not be less than
   \[ \frac{0.87 f_y}{E_s} + 0.002 \]
6. Partial safety factor for steel \( \gamma_m = 1.15 \). Thus the design strength will be:
   \[ f_y / 1.15 = 0.87 f_y \]
**Design Stress-Strain Curve for Concrete**

**Stress-Strain Curve for Mild Steel**

\( E_s = 200000 \ \text{N/mm}^2 \)
Balanced section:  
- Compression strain in concrete = 0.0035
- Tensile strain in steel = yield strain

Under Reinforced Section:  
- Compression strain in concrete < 0.0035
- Tensile strain in steel = yield strain

Over Reinforced section:  
- Tensile strain in steel < yield strain
- Compression strain in concrete = 0.0035

**Under Reinforced Section is Preferable**
**Lecture Note – 2**

**Modeling of Wind Loads**

IS-875  
Part-I DL  
Part-2 LL  
Part-3 WL  
Part-4 Snow Load  
Part-5 Special loads & load combinations

IS:1893 → Earthquake load
- Exceptional load → Due to cyclone, earthquake.
- Dynamic super imposed load → Vibration & impact caused by machinery & mobile equipments such as crane etc.

IRC → Bridge code
- Load due to imposed deformations.
  1. Shrinkage, temperature & prestressing.  
  2. Movements of supports

Factored Designed load = Load × Partial safety factor.  
For DL & LL Partial safety factor = 1.5 → Ultimate limit state  
= 1.0 → For Serviceability limit state

**Wind load**

In 1700 Century,  
WL = 0.28 kN/m² (V = Up to 45 mph)  
= 0.43 kN/m² (V = 45-60 mph)  
= 0.56 kN/m² (V = over 60 mph)

In early 1900 Century

\[ p = \frac{1}{2} \rho v^2 \] → Bernoulli’s equations

Where,
- \( p \) → Pressure  
- \( \rho \) → Density of air \( \approx 1.2 \) Kg/m³  
- \( v \) → Steady velocity of air
Indian Code for wind loads
There are 6 zones in India having basic wind speed of 33, 39, 44, 47, 50 & 55 m/s.

55 m/s. → Only Silchar & Ladakh
→ Hilly Area

Design Wind speed

\[ V_z = V_b k_1 k_2 k_3 \]

Where, \( V_z \) → Design wind speed in m/s at height \( Z \)
\( V_b \) → Basic wind speed.
\( K_1 \) → Probability factor or risk factor.
\( K_2 \) → Factor for the combined effects of terrain height & size of the component on structure.
\( K_3 \) → Factor for local topography (i.e. hills, valleys etc.)

\( K_1 \) → Table -1 of IS-875 part-3
\( K_2 \) → Depends on
  a) Type of terrain.
  b) Height of building
  c) Size of structure
\( K_2 \) is given in Table-2

Type of terrain
Category 1: Exposed open terrain with no obstruction.
Category 2: Open terrain with scattered obstruction of height between 1.5m to 10m.
Category 3: Terrain with numerous low rise (10m) obstructions.(Outskirts of City)
Category 4: Terrain with numerous high rise obstructions.(City centre)

Size of Structure – Depends on the largest dimension of structure for different Class
Class A: Structure & components such as cladding, glazing, roofing etc. having maximum dimensions less than 20m.
Class B: Structure & components as above with maximum dimension 20m to 50 m.
Class C: Structure & components as above with maximum dimension greater than 50 m.

In USA, UK following formula is used to calculate the velocity
\[ V_h = V_g \left( \frac{h}{h_o} \right)^a \]

Where,
- \( V_h \rightarrow \) Velocity at height \( h \).
- \( V_g \rightarrow \) Velocity at ground.
- \( h_o \rightarrow \) Height of the ground.
- \( h \rightarrow \) Height of the structure.
- \( a \rightarrow \) From 1/10 to 1/12 depending upon site conditions.

**Value of the topography factor \( K_3 \)**

Topographical features such as hills, valleys, cliffs, significantly alter the wind speed.

\[ K_3 = 1.0 \text{ if } \theta < 3^0 \]
\[ = 1.0 \text{ to } 1.36 \text{ if } \theta > 3^0 \]

From IS:875
$L_e =$ Effective horizontal length

$L_e = L$ when $\theta = 3^0$ to $17^0$

$= \frac{Z}{0.3}$ when $\theta > 17^0$

Where,

$L =$ Horizontal length of the upwind slope.

$Z =$ Effective height of the feature.

$\theta =$ Upwind slope in the wind direction.

$K_s = 1 + C_s$

$C = 1.2 \frac{Z}{L}$ (for $\theta = 3^0$ to $17^0$)

$= 0.36$ (for $\theta > 17^0$)

$S =$ A function of distance ratio $\frac{X}{L_e}$ and the height ratio $\frac{H}{L_e}$ of the point being considered.
### Wind Effects on Structure

#### Static & Dynamic effects of wind on Structure

<table>
<thead>
<tr>
<th>Type of Structure</th>
<th>Effect of Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Very stiff structure like low rise building.</td>
<td>A. No deflection.</td>
</tr>
<tr>
<td></td>
<td>B. Pressure quasi-static.</td>
</tr>
<tr>
<td>2. Flexible structure like chimneys, tall buildings with natural frequency greater</td>
<td>A. Structure deflects.</td>
</tr>
<tr>
<td>than that of wind.</td>
<td>B. Pressure dynamic.</td>
</tr>
<tr>
<td></td>
<td>C. Resonance effect nil. Both along &amp; across wind effects are possible.</td>
</tr>
<tr>
<td>3. Flexible structure with natural frequency equal to that of the fluctuating</td>
<td>A. Structure undergoes large deflection.</td>
</tr>
<tr>
<td>part of the wind.</td>
<td>B. Effects of deflection can be larger than wind effect.</td>
</tr>
<tr>
<td></td>
<td>C. Resonance with damping. Both along &amp; across wind effects are possible.</td>
</tr>
</tbody>
</table>

#### Clause 7.1 of IS 875 Part-3

7. **DYNAMIC EFFECTS**

7.1 General - Flexible slender structures and structural elements shall be investigated to ascertain the importance of wind induced oscillations or excitations along and across the direction of wind.
In general, the following guidelines may be used for examining the problems of wind induced oscillations:

a) Buildings and closed structures with a height to minimum lateral dimension ratio of more than about 5.0.

b) Buildings and closed structures whose natural frequency in the first mode is less than 1.0 Hz.

Any building or structure which does not satisfy either of the above two criteria shall be examined for dynamic effects of wind.

NOTE 1 - The fundamental time period \( T \) may either be established by experimental observations on similar buildings or calculated by any rational method of analysis. In the absence of such data, \( T \) may be determined as follows for multi-storeyed buildings:

a) For moment resisting frames without bracing or shear walls for resisting the lateral loads

\[
T = 0.1 \times n
\]

Where, \( n \) = number of storeys including basement storeys; and

b) For all others

\[
T = \frac{0.09H}{\sqrt{d}}
\]

Where,

\( H \) - total height of the main structure of the building in metres,
\( d \) = maximum base dimension of building in metres in a direction parallel to the applied wind force.

**Design wind pressure**

\[
p_z = 0.6V_z^2
\]

\( p_z \) \( \to \) Design wind pressure in \( N/m^2 \) at height \( Z \).

\( V_z \) \( \to \) Design wind velocity in \( m/s \) at height \( Z \).

**Wind pressure and force on structure**

The wind load on a structure shall be calculated for:

a) The building as a whole \( \to \) Using pressure coefficient.

b) Individual structural elements as roofs & walls. \( \to \) Using force coefficient.
Effect of Wind on Structure

The internal pressure depends on the locations & size of the openings.

1. Pressure coefficients for components
Pressure coefficients are given in Table 4 to 22.

\[ \text{Force} = (C_{pe} - C_{pi}) p A \]  \[ \Rightarrow \text{Clause 6.2.1 (pp-13)} \]

2. Force coefficient for structure as a whole
Force = $C_f \rho A_e$

- $C_f \Rightarrow \text{Force coefficient –Table-23}$
- $p \Rightarrow \text{Pressure}$
- $A_e \Rightarrow \text{Effective area of the building.}$
Lecture Note – 3

Wind Load on Buildings

Example: A reinforced framed building is 45 ×15 m in plan and 60 m in height consisting of storeys 4m in height. It is braced in the longitudinal direction by rigid frame action and by a reinforced concrete infill wall in the transverse direction. Determine the design wind force on the framed building.

Assume that the building is situated in terrain category 3 with basic wind speed of 50 m/s in a fully developed velocity profile.

Solution:

Step 1:
Data Plan of building = 45×15 m; height =60 m
Basic wind speed =50 m/s

Step 2:
Find the design wind speed $V_z$

$$V_z = V_b k_1 k_2 k_3$$

Risk factor $k_1 = 1.0$; Topography factor $k_3 = 1.0$

Factor $k_2$ depends upon the following:

i) Terrain category 3

ii) Structural size factor – greater horizontal or vertical dimensions is larger than 50 m. 15 m gust size is appropriate. Hence class C.

Read off $k_2$ for terrain category 3 and class C for varying heights, the value of $k_2$.

For convenience, the heights is divided into three divisions & the greater value for each division is used, i.e. (0-20 m, 20-40 m, and 40-60 m)

Step 3:
Determine dynamic pressure for different heights

Pressure

$$p_z = 0.6V_z^2$$ [Ref. clause 5.4 of IS:875]

<table>
<thead>
<tr>
<th>Interval</th>
<th>$k_2$ (max)</th>
<th>$V_z$ (m/s)</th>
<th>$p(N/m^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-20</td>
<td>0.91</td>
<td>45.5</td>
<td>1242</td>
</tr>
<tr>
<td>20-40</td>
<td>1.00</td>
<td>50.0</td>
<td>1500</td>
</tr>
<tr>
<td>40-60</td>
<td>1.04</td>
<td>52.0</td>
<td>1622</td>
</tr>
</tbody>
</table>
Step4:
Calculate the force coefficients $C_f$

Let, Wind be normal to 45 m base = wind at $0^\circ$.
Wind be normal to 15 m base = wind at $90^\circ$

$a$ = Depth of plan dimension=15 m

$b$ = Dimensions on which wind at $0^\circ$ acts =45 m

$h$ =Height=60 m

<table>
<thead>
<tr>
<th>Dimension</th>
<th>wind at $0^\circ$</th>
<th>wind at $90^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a/b$</td>
<td>15/45=0.33</td>
<td>45/15=3.0</td>
</tr>
<tr>
<td>$h/b$</td>
<td>60/45=1.33</td>
<td>60/15=4.0</td>
</tr>
<tr>
<td>$C_f$</td>
<td>1.3</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Table 2 (from fig. 4 of IS:875)

Step5:
Determine forces of wind at $0^\circ$.

Wind force = $pC_f$ (Area)

Area = 45 (Floor height of 4m)

UDL on floor slab = \( \frac{1.3 \times 45 \times 4}{45} \times p = 5.2 \times p \) for each meter of length.

Tabulating for the intervals adopted.

<table>
<thead>
<tr>
<th>Interval</th>
<th>$p(N/m^2)$</th>
<th>Force (KN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-20</td>
<td>1242</td>
<td>5.2p=6.46</td>
</tr>
<tr>
<td>20-40</td>
<td>1500</td>
<td>5.2p=7.80</td>
</tr>
<tr>
<td>40-60</td>
<td>1622</td>
<td>5.2p=8.43</td>
</tr>
</tbody>
</table>

Table 3

Step 6:
Determine wind forces in $90^\circ$ direction.

As above = \( \frac{1.1 \times p \times 45 \times 4}{45} = 4.4 \times p \) for each meter of length.

Step7:
Nature of action of Wind forces:
These uniformly-distributed forces from the edge of the slab are transferred to the frames and shear walls. The floor slab acts as rigid diaphragms between the walls and the frame.
Material Characteristics

Cement
The most common types of Portland Cements are as follows:

<table>
<thead>
<tr>
<th>Portland Cement</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPC</td>
</tr>
</tbody>
</table>

1. **Ordinary Portland Cement (OPC):** 3 different grade denoting compressive strength C33, C43, C53 corresponding to 28 days characteristic strength & conforming to IS269, IS8112 & IS 12269 respectively.

2. **Rapid Hardening Portland Cement (RHPC):** Conforming to IS8041. Similar to OPC except more tricalcium silicate \( (C_3S) \) & less dicalcium silicate \( (C_2S) \).

3. **Portland Slag Cement (PSC):** Conforming to IS455. Suitable to use in environments exposed to sulphates.

4. **Portland Pozzolana Cement (PPC):** Conforming to IS1489. Flyash based or calcined clay based. It is comparatively cheaper.

5. **Hydrophobic Portland Cement (HPC):** Conforming to IS8043. It has water resistant property.

6. **Low Heat Portland Cement (LHPC):** Conforming to IS12600

7. **Sulphur Resistant Portland Cement (SRPC):** Conforming to IS12330

8. **Portland White Cement (PWC):** Conforming to IS8042

Other Cements
1. **High Alumina Cement (HAS):** It is recommended in marine environments.
2. **Supersulphate Cement (SC):**
Test on Cements
1. Chemical Composition
2. Fineness
3. Normal Consistency
4. Initial & final setting time
5. Soundness
6. Strength

Aggregate
Aggregates are classified as Fine aggregate & Coarse Aggregate. It contributes to strength, durability & volume stability.

Aggregate Properties & Tests
1. Particle size, shape, & surface texture.
2. Geological classification:- It based on the mineral type of the parent rock.
3. Specific gravity & bulk density
4. Moisture content, water absorption & bulking of sand.
5. Strength
6. Toughness
7. Hardness
8. Soundness
9. Deleterious constituents:- Such a presence of iron pyrites, coal, mica, clay, silt, salt.

Water
The PH should not be less than 6
Sea water is unsuitable for mixing.
The ‘Optimum’ water content in a mix is that at which the sum of volume of entrapped air and that of entrapped water is minimum & for which the density achievable is the maximum.
Water Cement ratio controls the strength & it is in the range of 0.35 to 0.65.
Admixtures
It is an additive to modify the properties of concrete.

**Type of Chemical Admixtures**

1. **Accelerator**: It accelerates the hardening or the development of early strength.
2. **Retarders**: It retards the setting of concrete & thereby to reduce the generation of heat.
3. **Water Reducers or Plasticizers**: It improves the plasticity in the fresh concrete. These are used to achieve higher strength by reducing the w/c ratio for improving workability.

4. **Super plasticizer or High range water reducer**: Superior to conventional water reducer.
5. **Air-entraining agent**: Organic compounds which introduce discrete & microscopic air bubble cavities.
6. **Bonding admixture**: Polymer emulsions to improve the adherence of fresh concrete to hardened concrete. They are ideally suited for repair work.
**Grade of concrete**

Ordinary Concrete: - M10 – M20  
Standard strength Concrete: - M25 - M55  
High Strength Concrete: - M60 and Above

**Characteristic Strength:** - It is defined as the strength of the material below which not more than 5% of the test results are expected to fall.

![Idealized normal distribution of concrete strength](image)

**Fig:2** Idealized normal distribution of concrete strength

**Design Mix of Concrete**  
{IS 10262:1982 & SP 23:1982}

**Steps:**
1. Find Mean target strength, $f_{cm}$ from the designed characteristic strength $f_{ck}$
   
   $f_{cm} = f_{ck} + 1.65 \sigma$

   $\sigma$ - The standard deviation depends on quality control. This may be assumed for design in the first instance as listed in the table 8 of the code.

2. Determine w/c ratio based on 28 days strength of concrete & the mean target strength of concrete using appropriate chart. This is shown in Fig. 1. This ratio should not exceed the limits specified in the Table 5 of the code.

3. Find the water content based on workability requirements and select the ratio of fine aggregate to coarse aggregate by mass based on the type and grading of the concrete.
4. Calculate Cement content in kg/m$^3$. Ensure that the cement content is not less than that specified in the code in the Table 4 & 5 for durability consideration.

5. Calculate masses of fine aggregates $M_{fa}$ and coarse aggregate $M_{ca}$ based on the absolute volume principle.

$$\frac{M_c}{\rho_c} + \frac{M_{fa}}{\rho_{fa}} + \frac{M_{ca}}{\rho_{ca}} + v_w + v_v = 1.0$$

Where $\rho_c, \rho_{fa}, \rho_{ca} \rightarrow$ mass densities of cement, fine & coarse aggregate respectively

$v_w \& v_v \rightarrow$ Volume of water content & volume of voids per cubic meter concrete.

6. Calculate the weight of ingredients for batch, based on the capacity of the concrete mixer.

**Properties of Concrete**

**Test of concrete strength in compression**

Cube $\rightarrow$ 150mm $\times$ 150mm $\times$ 150mm

Cylinder $\rightarrow$ 150mm $\phi$ $\times$ 300mm height

Cylinder strength is lower than cube strength.

**Fig. 3 Influence of height/diameter ratio on the apparent strength of a cylinder**
Fig: 4 Influence of diameter on the apparent strength of a cylinder

Fig: 5 Typical stress-strain curves of concrete in compression

Higher concrete grade → Initial portion is steeper
→ Peak is sharpen
→ Failure strain is less.
For lower strength concrete ⇒ Higher failure strain
⇒ Curve is relatively flat top

Maximum stress reached approximately at a strain of 0.002

Strain at failure is from 0.003 to 0.005
Stress-strain relation for the compression zone of a RC flexure number is nearly identical to that obtained for uniaxial compression.

**Dynamic modulus of elasticity**: It can be measured from initial tangent modulus. This is applicable for cyclic loading such as wind, earthquake, where long term effects are negligible.

**Static modulus of elasticity**: This is used for long term duration of load like DL, LL
\[ E_c (MPa) = 5000\sqrt{f_{ck}} \] (Clause 6.2.3.1 of IS 456:2000)

Earlier, \[ E_c = 5700\sqrt{f_{ck}} \] (Over estimation of \( E_c \))

ACI code suggest \[ E_c = 0.0427\sqrt{\left(\rho_c f'_c\right)} \]
Where, \( \rho_c \) is the mass density of concrete in kg/m\(^3\) = 2400 kg/m\(^3\) generally

\( f_c' \) = Cylinder strength

Thus, \( E'_c = 4500 \sqrt{f_{ck}} \), Where \( f_c' = 0.8 f_{ck} \)

**Influence of duration of loading**

![Influence of duration of loading on stress strain curve of concrete](image)

**Concrete Under Tension**

- Stress-strain is linear.
- Maximum strain under uniaxial tension is 0.0002 to 0.0003

**Modulus of Rupture \( (f_{cr}) \)**

\[ f_{cr} = \frac{M}{Z} \]

Assuming a linear stress distribution along the cross section.

IS code: \( \rightarrow \) Clause no 6.2.2 \( \rightarrow f_{cr} = 0.7 \sqrt{f_{ck}} \) in MPa

ACI code: \( \rightarrow f_{cr} = 0.623 \sqrt{f_c'} \)
**Splitting Tensile strength**

Splitting tensile strength, \( f_{st} = \frac{2P}{\pi dL} \).

Generally, \( f_{st} \approx \frac{2}{3} f_{cr} \).
Lecture Note – 5

Properties of Concrete

Creep of concrete
Time dependent component of total strain is termed creep.

- Exact mechanism of creep in concrete is still not clear.
- It is generally attributed to internal movement of absorbed water, viscous flow or sliding between the gel particles, moisture loss & growth in micro cracking.

Effect of creep
- Increased deflection of beam and slabs.
- Increased deflection of slender columns (possibly leading to buckling)
- Gradual transfer of load from concrete to steel in compression.
- Loss of prestress in prestressed concrete.

Factor influencing Creep
1. Material properties
2. Composition
3. Curing
4. Loading condition
5. Environmental condition
Creep increases if
1. Cement content is high
2. Water Cement ratio is high
3. Aggregate content is low
4. Air entrainment is high
5. Relative humidity is low
6. Temperature is high (causing moisture loss)
7. Size/thickness of member is small.
8. Loading occurs at early stage
9. Loading is sustained over a long period

Creep coefficient for design
IS code: Clause 6.2.5.1
Ultimate creep coefficient \( (\theta) \) \( \rightarrow \) 2.2 for ages of loading =7 days
\( \rightarrow \) 1.6 for ages of loading =28 days
\( \rightarrow \) 1.1 for ages of loading = 1 Year

Effective modulus of Elasticity, \( E_{ce} = \frac{E}{1+\theta} \) (Clause 4.1)

Durability
If concrete is to serve the purpose for which it is designed during its intended lifetime, it has to be durable.

Loss of durability results a reduced life of structure.
Loss of durability happens due to chemical attack.

Durability of concrete can be increased by
1. Reducing permeability by
   - Providing high grade of concrete
   - Using adequate cement content
   - Using well graded, dense aggregate
   - Using low water cement ratio
   - Using appropriate admixture
   - Achieving maximum compaction
   - Achieving effective curing
   - Using appropriate surface coatings & impermeable membranes.
   - Avoiding sharp corners & locations where compaction is difficult.
   - Taking care while designing to minimize possible cracks
2. Providing appropriate type of cement having the desired chemical resistance to sulphates & chlorides.
3. Avoiding the use of alkali-reactive aggregates
4. Providing direct protection to embedded steel against corrosion by
   • Using appropriate corrosion resistant coated steel.
   • Providing adequate clear cover
   • Using sophisticated techniques such as cathodic protection
5. Controlling the chloride & sulphate contents in the concrete mix constituents.
6. Providing air-entering admixture when resistance against freezing & thawing is required.
7. Providing adequate thickness is required.
8. Providing adequate reinforcement designed to contain crack widths within acceptable limits.
9. Providing adequate drainage on concrete surfaces to avoid water retention.

Environmental exposure & code Requirements (Clause 8.2.2)
The code identifies 5 category of environmental Exposure, Viz
i) Mild
ii) Moderate
iii) Severe
iv) Very severe
v) Extreme

**Minimum requirements**
- Minimum grade of Concrete (M20 to M40)
- Minimum clear cover to reinforcement (20mm to 75mm)
- Minimum cement content ratio (300-360kg/m$^3$ for 20 mm size aggregate)
- Maximum water cement ratio (0.55 to 0.40)
- Acceptable limits of surface s width of cracks (0.1 mm to 0.3mm)
**Reinforcing Steel**

**Assumption:** Stress – strain behavior of steel in compression is similar to that in tension.

![Graph showing stress-strain behavior of different steel grades](image)

$E_s = 2 \times 10^5 \text{ MPa for all steel}$

**Stress-strain behavior of different steel**

![Diagram illustrating Bauschinger effect & Hysteresis](image)

**Bauschinger effect & Hysteresis**