Advanced Programme - Planning, Design _ Construction of Long Span Bridges- (Batch I) - 22

Seismic Effects on Design & Performance of Long Span Bridges

National Rural Infrastructure Development Agency

Ministry of Rural Development

Engineering Staff College of India (ESCI)

Hyderabad

Lecture 3

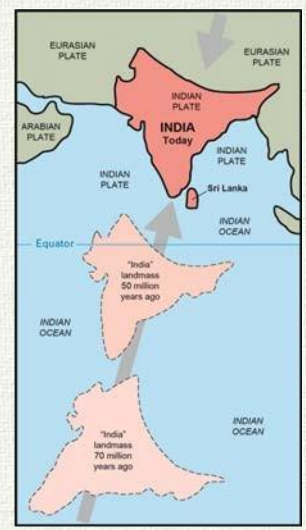
Seismic Effects on Design & Performance of Long Span Bridges

Seismic Design Principles…

- 1. Seismic Shaking
- 2. Concept of Hertz or Cycles/Sec
- 3. Joint Safety
- 4. Behaviour of RC & PSC Beams

Seismic Shaking…

Seismic Shaking…



Seismic Shaking…

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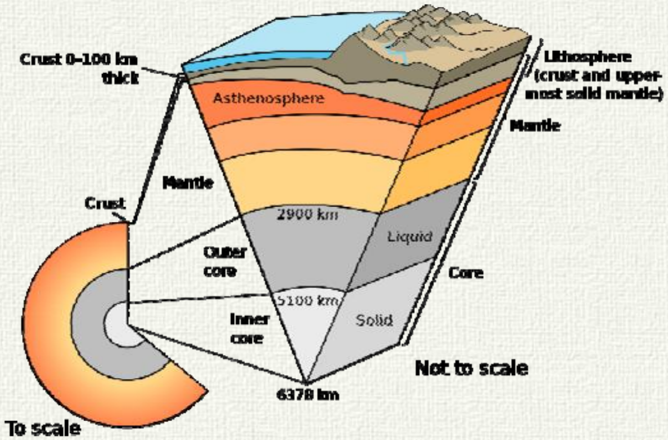


Terminologies in Earthquake Engineering….

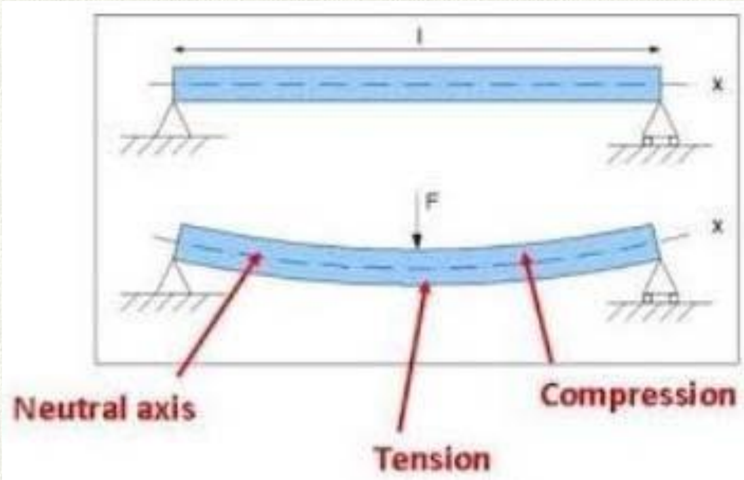
Focus
Epicenter
Magnitude
Moment Magnitude
Damping
Natural Period
Intensity

Basics of Seismic Design

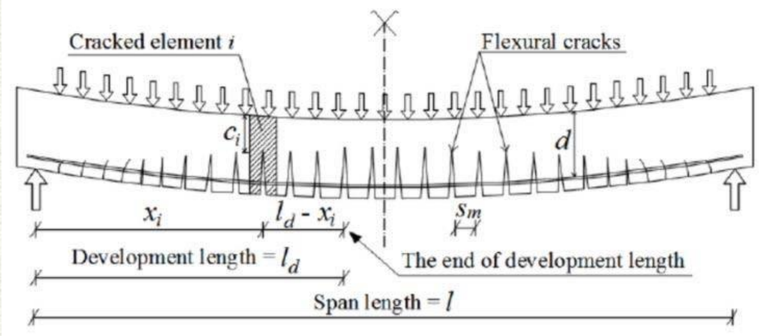
Some important Terms

- Cracking of concrete
- Over strength
  Concrete
  Steel
- Redundancy
- Confinement
-

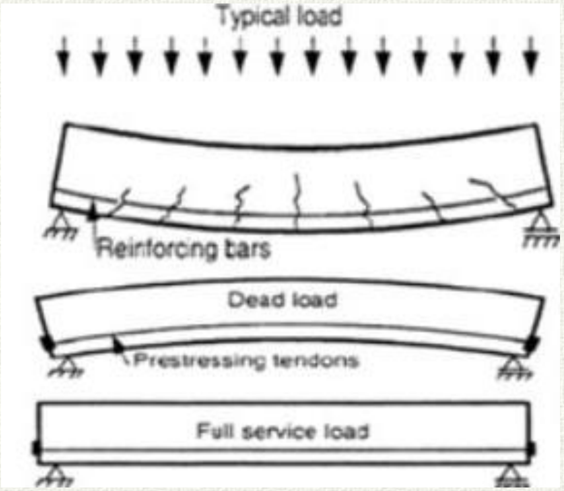
Cracked and Uncracked Sections



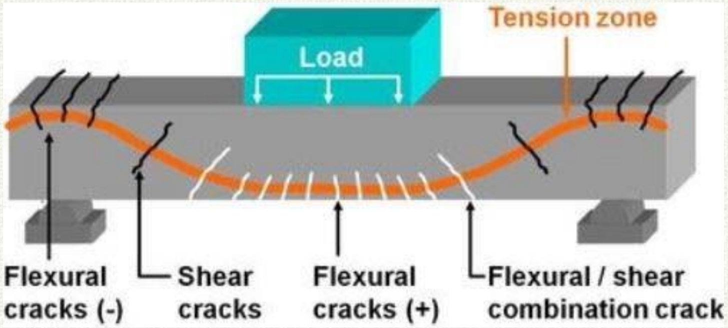
Cracked Sections



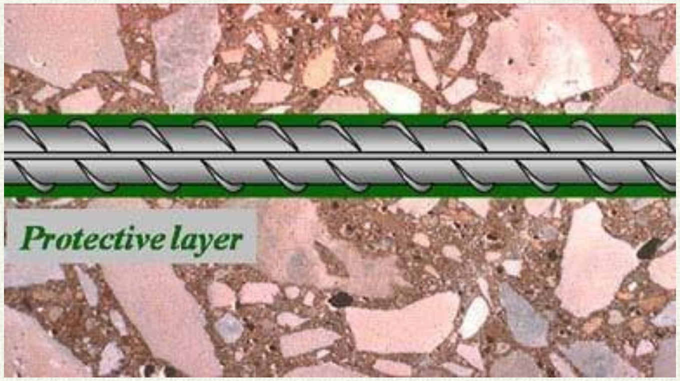
RC & PSC Sections



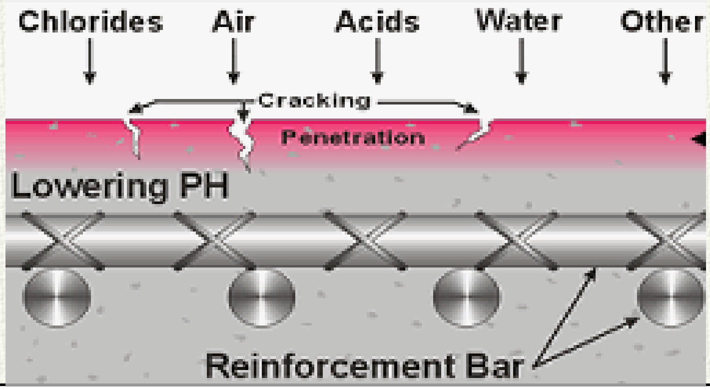
RC & PSC Sections



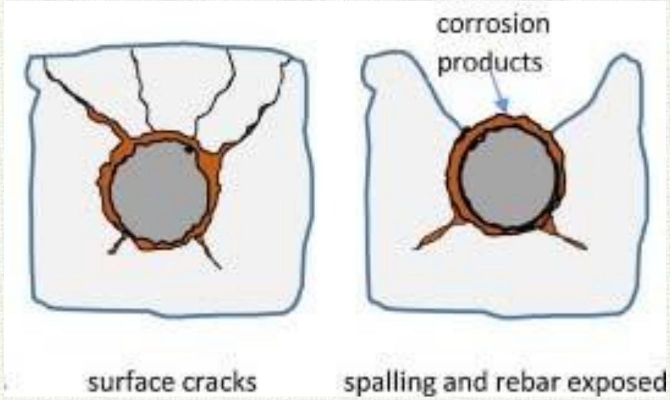
When fresh concrete used in RCC



Carbonation reduces ph of concrete & protective film gets dissolved



Cracks further widen resulting in spalling

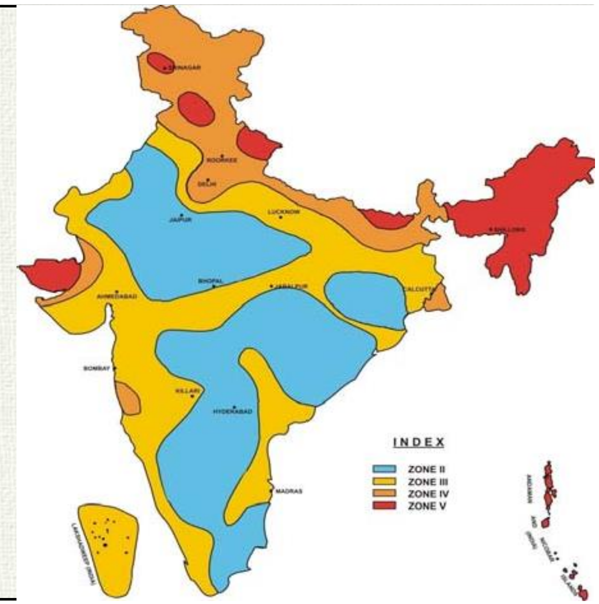


Spalling at slab bottom

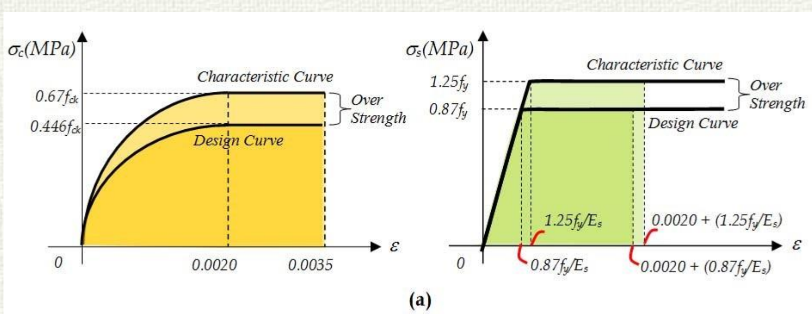
EQ Prone Areas….

Indian Seismic Code IS:1893 (1)

- Seismic areas broadly identified
  - Four zones

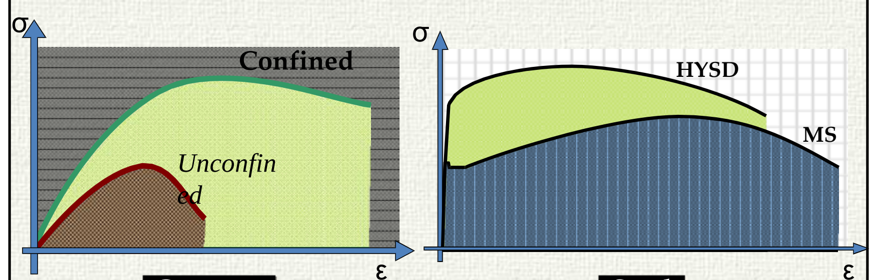


Overstrength



Concrete **Steel**

Performance of RC & Steel



Concrete **Steel**

Redundancy…

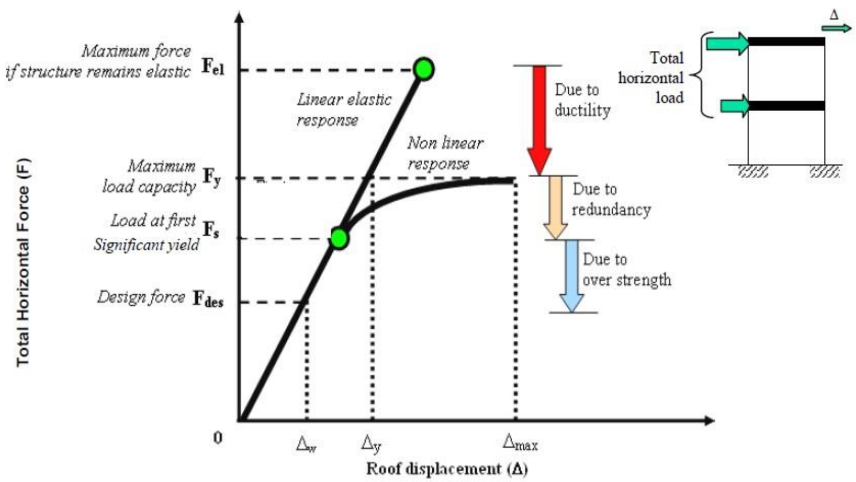


Figure C 8- Concept of Response Reduction Factor

Which one is better…? 4 or 8 columns?

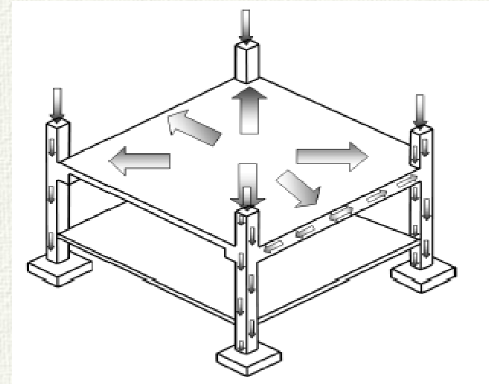
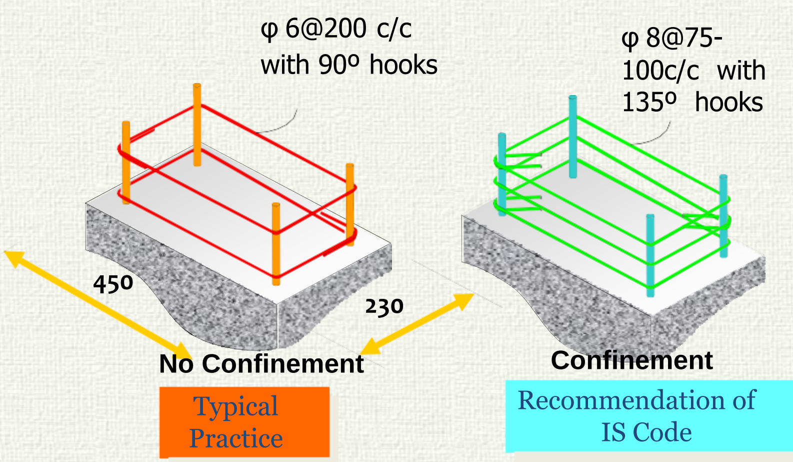
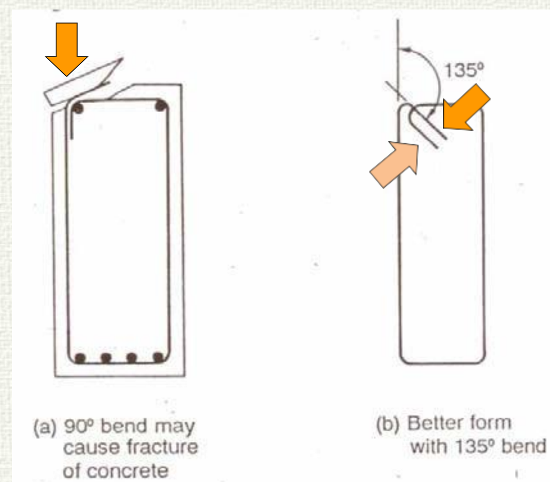


Figure C1: Load path

Confinement of concrete



Importance of 135º Hook ….?



Indian Seismic Code IS:1893 (1)

- Seismic areas broadly identified
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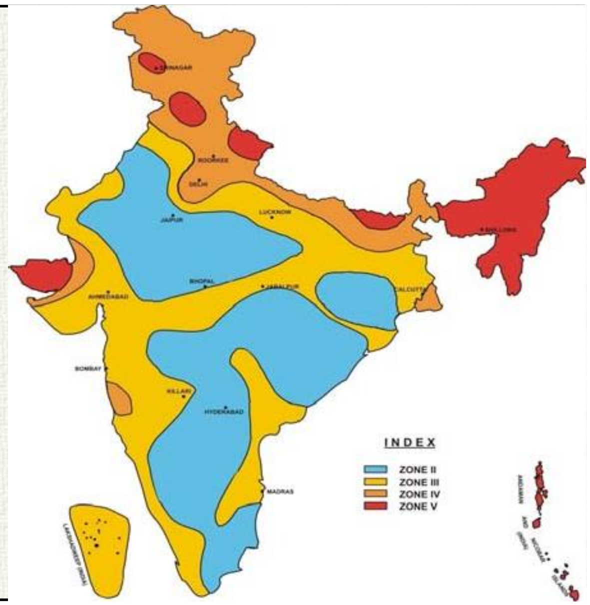


Design Concepts of Bridges & Culverts…

- 1. Horizontal & Vertical Geometry
- 2. Superstructure Type
- 3. Pier / Support Placement & Span Arrangements
- 4. Abutment Placement & Heights

Design Concepts of Bridges & Culverts…

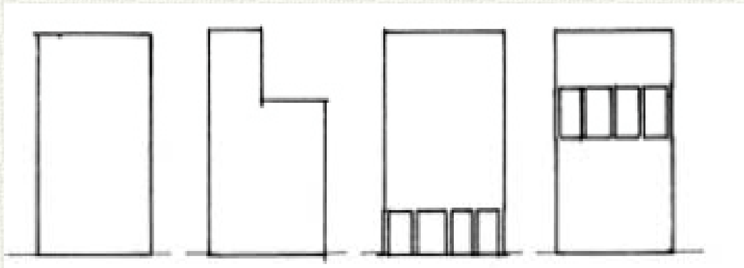
- 5. Superstructure Shape (Including parapets, Overhang & Railings)
- 6. Pier Shape
- 7. Abutment Shape
- 8. Colour

Design Concepts of Bridges & Culverts…

- 7. Texture, Ornamentation, and Details
- 8. Lighting, Signing, and Landscaping

Architectural & Structural Concepts of EQ Resistant Building Configuration

The elevations should be regular (uniform), i.e. top-heavy facades where mass is concentrated at upper storey's should be avoided.



Adequate Forms to be avoided

Inadequat

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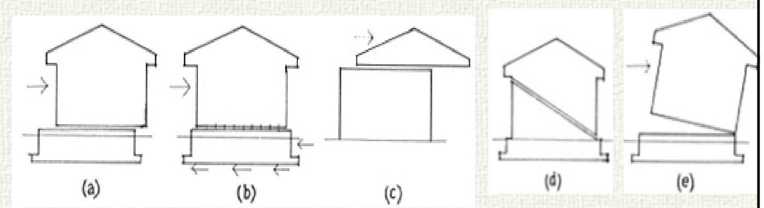
Architectural & Structural Concepts of EQ Resistant Building Configuration

Transmission of the seismic (inertia) forces to the ground should be direct Common Modes of Structural Failure as shown below shall be avoided

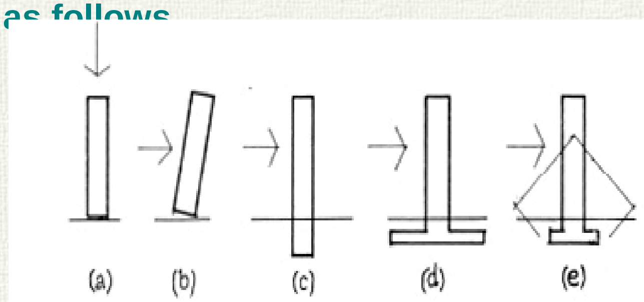


Sliding at plinth Sliding at Sliding at roof

Diagonal Cracks at foundation level

Architectural & Structural Concepts of EQ Resistant Building Configuration

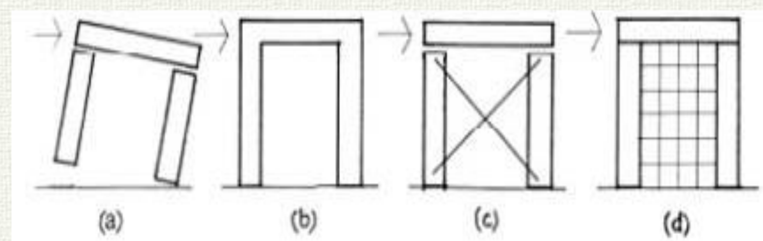
Resistance to overturning can be improved as follows



Stable Unstable Stability by embedment Stability by bracing

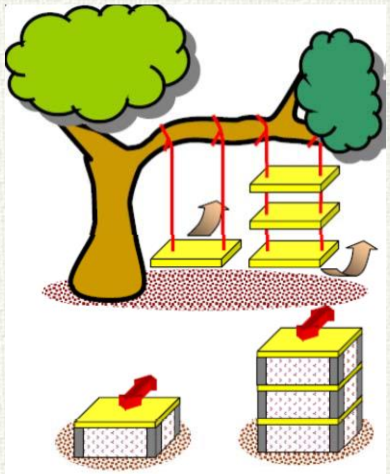
Architectural & Structural Concepts of EQ Resistant Building Configuration

Improving resistance to lateral force as follows



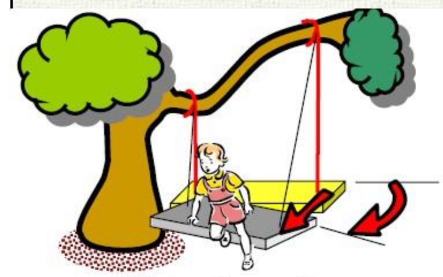
Making rigid connections between Stability by X bracing or elements by rigid infill wall

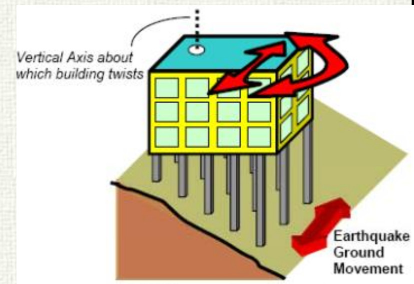
Torsion & Swing Analogy



Courtesy EQ Tips-7

When foundations are at different levels Undesirable effect during earthquake!

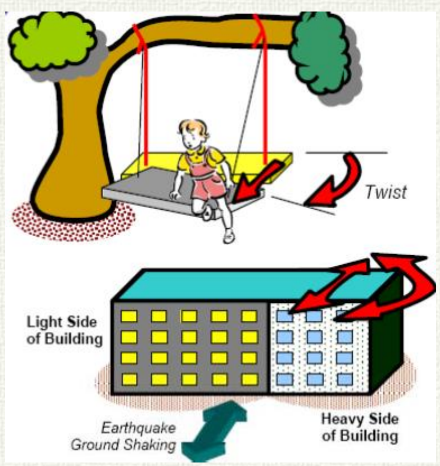

(a) Swing with unequal ropes



(b) Building on slopy ground

Courtesy EQ Tips-7

Torsion



Courtesy EQ Tips-7

Why Seismic Design?

Bridge designers make changes in seismic design or construction practice based on lessons learnt:

- from bridge damage due to earthquakes,
- through tests in labs and
- from analytical studies.

Purpose of this lecture

To identify and classify types of damage to bridges that earthquakes commonly induce.

- Primary damage,
- Secondary damage

It must be noted that in many cases the difference between primary and secondary damage is unknown because

- Bridge geometry is complex
- In case of collapse it is difficult to reconstruct sequence of failure.

Parameters influencing Ground shaking

- Geotechnical
- Structural
- Residual Bridge Capacity

Geotechnical Parameters

- Proximity to fault:
  Bridges close to fault suffer higher levels of ground shaking
- Greater Magnitude:
  Increase ground shaking
- Relationship between fault mechanism and level of ground shaking
  i) Bridges on hanging wall of fault are designed for higher ground motion
  ii) Dipping faults can cause higher ground motion

Geotechnical Parameters

- Shear velocity of top 30m of ground
- Softer soils far from fault rupture are amplified
- Longer period structures experience higher acceleration on soft soil.
- Short period structures resting on rock experience higher acceleration
- Deep (2.5 km) basins filled with alluvial soils experience higher acceleration
- Topographical features also have effect on ground motion

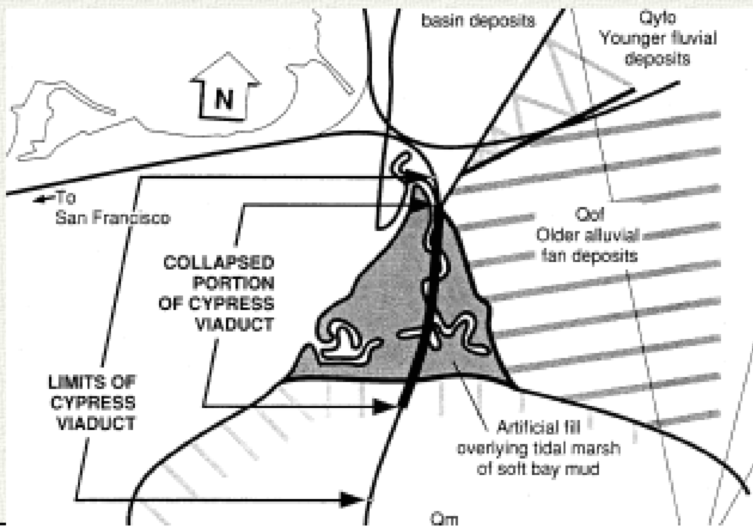
Near fault effect (within 15 km)

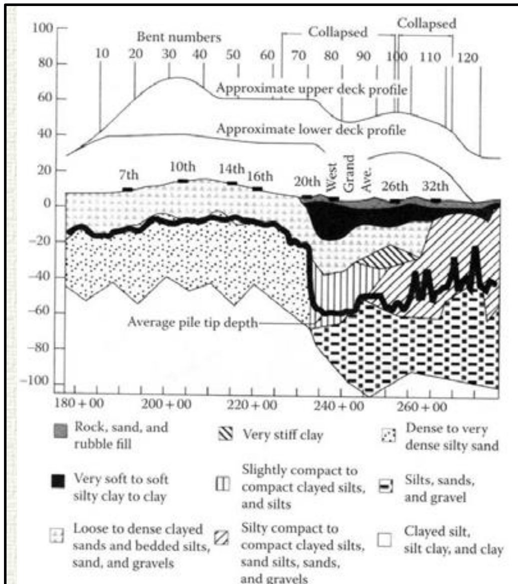
- The long period "velocity pulse" caused the collapse of an 18-span viaduct section of Hanshin Expressway

Site condition & Ground Shaking

- 1.4 km of Cyprus Viaduct on weak soil (with low shear velocity) collapsed, whereas a portion of structure on good soil (higher shear wave velocity) was undamaged (Loma Prieta-1989 M 6.9)

Site condition & Ground Shaking





Structural Parameters

- Poor development length of reinforcement or "continuity" can prevent concrete bridge elements from being pulled apart during an earthquake
- Provision of ample seating space for to support end of girders.
- Provision of ample "confinement" in concrete columns allowing them to displace without failing in flexure or shear.

Structural Parameters

Higashi-Nada Viaduct collapse in 1995 Hyogo-Ken Nambu Earthquake, Jan 17, 1995.

Welded Splices and Mechanical Splices

- Welded Joint efficiency is taken to 100% if welding is supervised and at any cross section not more than 20% of the tension reinforcement is welded
- Otherwise efficiency is considered to be 80%
- Mechanical Splices 100% efficiency

Structural Parameters

- Lack of "Regularity" makes bridge vulnerable
- Excessive deformation demand in a few brittle elements
- Complex structural configuration.
- Lack of redundancy.

Examples of Irregularity

- Tall and short columns in the same bent
- Tall and short bents in a frame
- Tall and short frames in a bridge.

Above cases cause shorter elements to fail since they cannot displace as much as the longer elements .

It is important

a) for the elements on a bridge to be regular and balanced, but also

b) Parts of bridge elements should also be regular.

Examples of Irregularity

- Non-prismatic elements like flared columns often fail during earthquake
- The strong flare forces plastic hinging into short column below it.
- The shorter column gets a bigger shear force (V_p=M_p/L), which can fail column

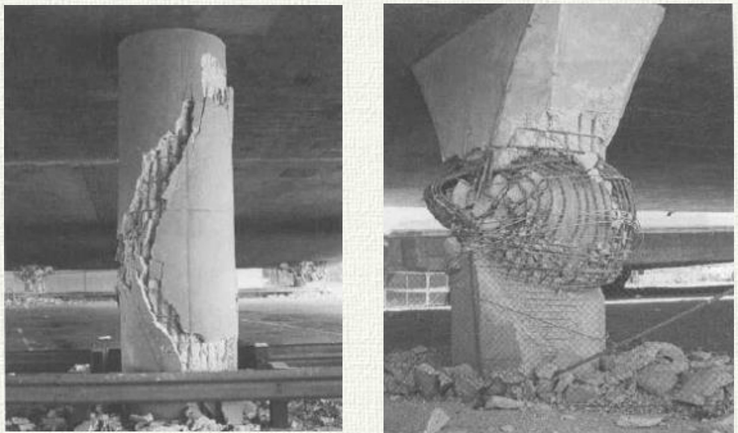
Examples of Irregularity

- Bridge elements arranged in parallel need to have about same stiffness, carry about the same mass, and have about the same period.
- Bridge elements arranged in series need to have the same strength and stiffness to prevent the weaker elements from failing prematurely.

Structural

Weld failure of column longitudinal reinforcement: 1995 Kobe Earthquake.

Structural Parameters

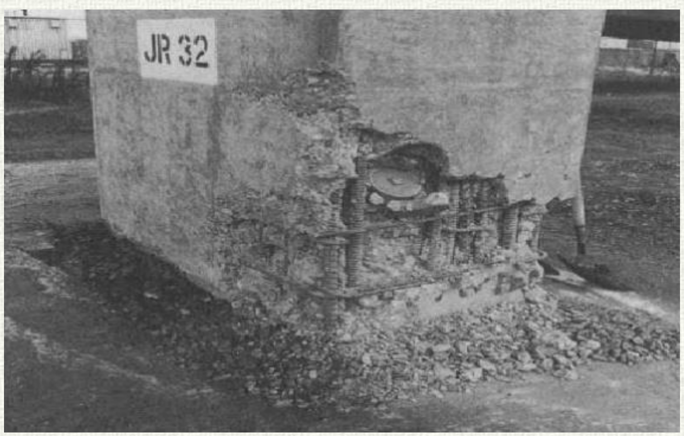


- Shear failure – within plastic hinge region, 1971 San Fernando earthquake

Structural Parameters

Nishinomiya-Ko Bridge approach span collapse in 1995 Hyogo-Ken Nambu Earthquake.

Structural Parameters



Shear failure outside plastic hinging region, San Fernando Earthquake.

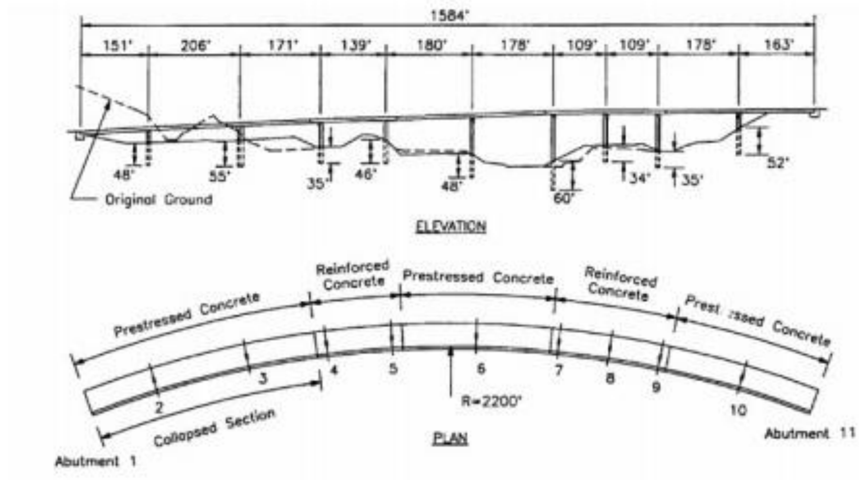
Structural Parameters

Bridge collapse during Northridge Earthquake in California.

Structural Parameters

Reinforced concrete channel wall unintentionally shortened the effective length of bridge column...!!

Structural Parameters



Structural Parameters

Expansion joint introduced catastrophic irregularity causing unseating & finally collapse..!!.

How to reduce bridge damage during seismic shaking?

By introducing following parameters:

- Continuity
- Confinement
- Regularity.

Damages

- Standard Girder Bridges damages can be to:
  i) Superstructure
  ii) Sub-structure
  iii) Connections
  iv) Foundation
  v) Retrofit

Damages to superstructure

- Usually superstructure damage occurs at discontinuity like expansion joint etc.

- Expansion joint releases stresses caused by
  a) Thermal movement of superstructure
  b) Post-tensioned superstructure shortening
  c) Creep and shrinkage
  d) Relative settlement of supports

Damages to superstructure

- Expansion joints are located:
  a) over abutment seats,
  b) bent caps, and
  c) at in-span hinges

- When ends of girder sit on a narrow seat, the bridge is vulnerable to collapse.

Damages to superstructure

- After the 1971 San Fernando earthquake, engineers began putting cable restrainers at expansion joints.

- However this practice is discouraged today.

- It is unlikely that enough cables can be provided to prevent unseating or to support superstructure if it falls..!!

Damages to superstructure

- Since unseating is related to column displacement, the seats at expansion joint must be longer that the combined earthquake displacement of adjacent bents and frames.

- Sometimes girders fall of the bearings, but not the seat. This is difficult to repair, but much better than having girders fall off the seat and dropping the span.

Damages to superstructure

- Girders falling off bearings can destroy the expansion joint device, which is a danger to inattentive drivers.

Damages to superstructure

- If the superstructure is continuous, then the superstructure can move off the bearings without much danger of becoming unseated.

- Generally, only the deck is made continuous over simply supported girders.

- An extremely well designed deck can sometimes support girders as they become unseated, but downward force is usually enough to break the deck in to two.

Damages to superstructure

- Unseating at Piers 41 and 40 during Kobe EQ.

What went wrong…?

What went wrong…?

What went wrong…?

Four Stages of a Bridge Design …

a) Conceptual
b) Preliminary
c)Detailed
d)Construction Design

Four Stages of a Bridge Design …

a) Conceptual Design

The purpose of conceptual design is to come up with various feasible bridge schemes and decide on one or more final concepts for further consideration.

Four Stages of a Bridge Design …

b) Preliminary Design

The purpose of preliminary design is to select the best scheme from these proposed concepts and then to ascertain the feasibility of selected concept and finally to refine cost estimates .

Four Stages of a Bridge Design …

c) Detailed Design

The purpose of detailed design is to finalize all the details of the bridge structure so that the document is sufficient for tendering and construction.

Four Stages of a Bridge Design …

d) Construction Design

The purpose of construction design is to provide step-by-step procedures for building the bridge.

Characteristics of Bridge Structure….

Bridge Type:

a) Girder Bridges.
b) Arch Bridges
c) Cable-Stayed Bridges
d) Suspension Bridges

Characteristics of Bridge Structure….

Girder Bridges:

a) Good for short to medium spans.

Characteristics of Bridge Structure….

Arch Bridges:

a) Good for short to medium spans.

Characteristics of Bridge Structure….

Cable-Stayed Bridges:

a) Good for medium to longer spans.

Characteristics of Bridge Structure….

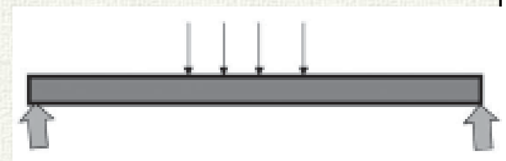
Suspension Bridges:

a) Good for very long spans (up to 1000m).

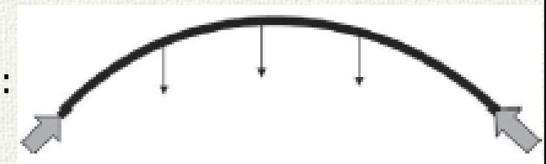
Basic Structural Elements….

By axial force:

By bending:

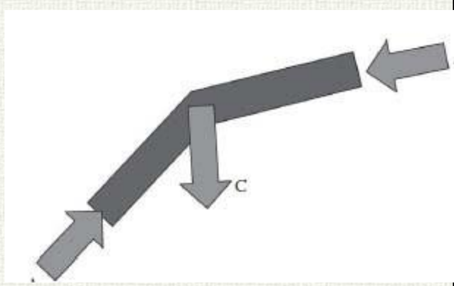


By curvature:



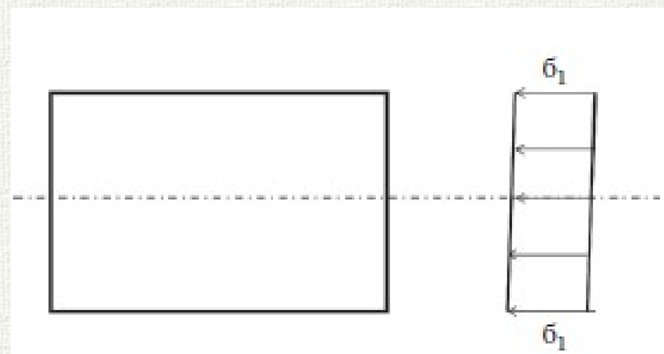
Basic Structural Elements….

Formation of Curve Element:



If the lateral loads are sufficiently closely spaced, the structural element becomes a curve, resulting in a curved structural element, the C element.

Basic Structural Elements Type-A….



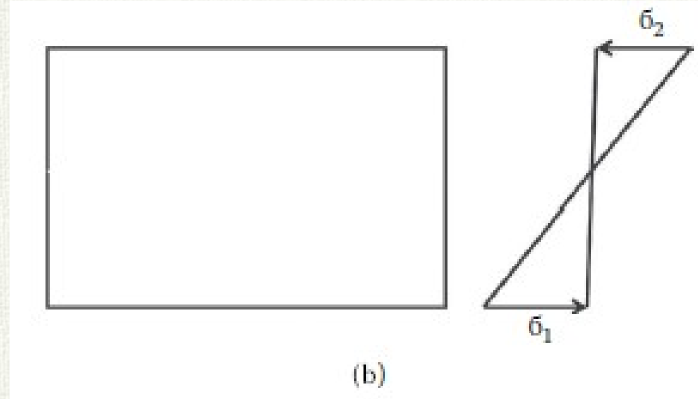
(a)

Basic Structural Elements….

In a design, we proportion the structural elements to remain within the allowable stress limits.

In an A element, the entire cross section can be utilized to its fullest extent because the entire cross section can reach the allowable stress at the same time.

Basic Structural Elements Type-B….



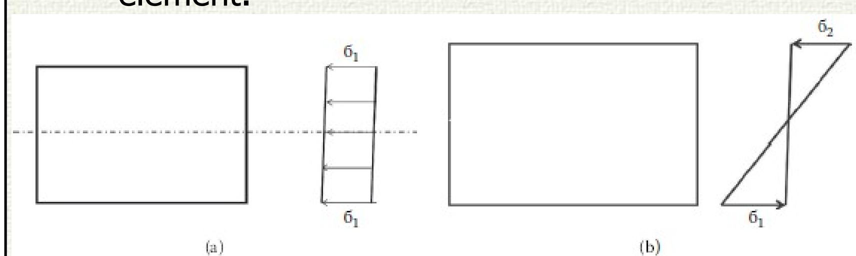
Basic Structural Elements….

By contrast, in a B element, only the extreme fiber can reach the allowable stress, while the stress in the rest of the cross section is less than the allowable stress.

Although both of them must be considered in the design, the predominant factor is still the bending moment and it therefore can be characterized as a B element.

Basic Structural Elements Type-C….

So in a B element, most of the cross sectional area is not fully utilized and is consequently less efficient. The C element is similar to the A element and it is more efficient than the B element.



Basic Structural Elements….

When a portion of the element is not participating in carrying loads, or if it is not used to its fullest extent, more material is required to carry the same load, thus increasing its dead weight, which is a big disadvantage in bridges, especially in long-span bridges.

Basic Structural Elements….

The girder bridge is the only bridge type that relies mainly on bending to carry the loads. It is a B element. B elements are less efficient.

Therefore, a bridge that consists mainly of a B element is less efficient and thus its maximum span is smaller

Know the limits….

We must know the limitations, or the boundaries within which we must remain.

There are many different kinds of boundaries such as
a) environmental,b) financial, c) social,
d) historical, and e) technical boundaries.

All these boundaries are project specific, which means they cannot be applied universally, with the exception of technical problems.

Know the limits….

Through the course of designing a bridge, engineers must deal with many technical problems that fall into two categories:

a)Technical difficulties which are problems that can be solved, even though the solution may cost time and money e.g. span length and

b)Technical limitation is an upper bound that cannot be exceeded.

Know the limits….

Through the course of designing a bridge, engineers must deal with many technical problems that fall into two categories:

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b)Technical limitation is an upper bound that cannot be exceeded.

Know the limits….

For a very long span bridge most prominent problems are:

1. Girder stiffness in the transverse direction
2.Reduction in cable efficiency of very long cables in a cable-stayed bridge
3. Torsional stiffness of the main girder
4.Allowable stresses of the construction materials

Know the limits….

For several thousands of years until the nineteenth century, basically all longer span bridges were built with stones and bricks and were all arch bridges.

Stones and bricks have good compressive strength but almost no tensile strength, so the only type of bridge that can be built using stones and bricks is an arch bridge.

Know the limits….

Currently, for long-span bridges, the predominant materials used are steel and concrete, as has been the case in the past 150 years.

As far as very long-span bridges are concerned, concrete only plays a secondary role, and steel is the predominant construction material to be used, with the exception of girder bridges.

Lateral Stiffness of the Main Girder….

The minimum width of a bridge is determined by its specified traffic pattern.

As an example, the deck width of a regular six-lane bridge with pedestrian paths is usually approximately 34 m.

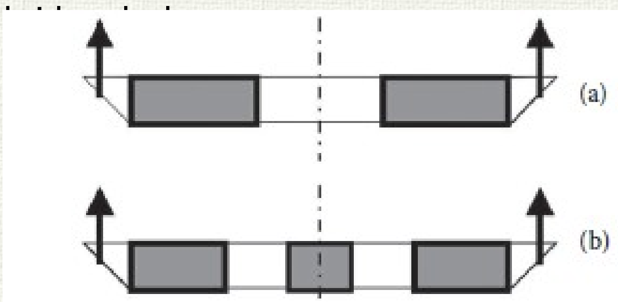
Thus, for a 1000-m span, six-lane bridge, the span to width ratio is approximately 29.4, safely resisting lateral loads caused by wind, earthquakes, and other natural phenomena.

Lateral Stiffness of the Main Girder….

However, if the span is increased to 2000 m, the ratio increases to 59, and the bridge may have a problem resisting lateral loads.

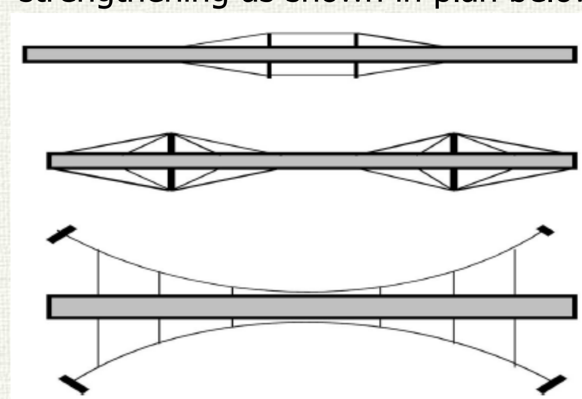
Lateral Stiffness of the Main Girder….

If the span is even longer, the problem becomes more serious. To increase the bridge's stability, the simplest solution is to increase the width of bridge, e.g. separating



Lateral Stiffness of the Main Girder….

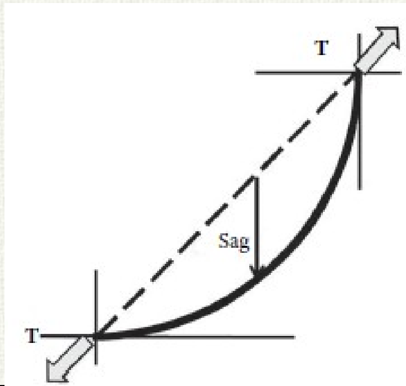
A bridge's stability can be increased by cable strengthening as shown in plan below:



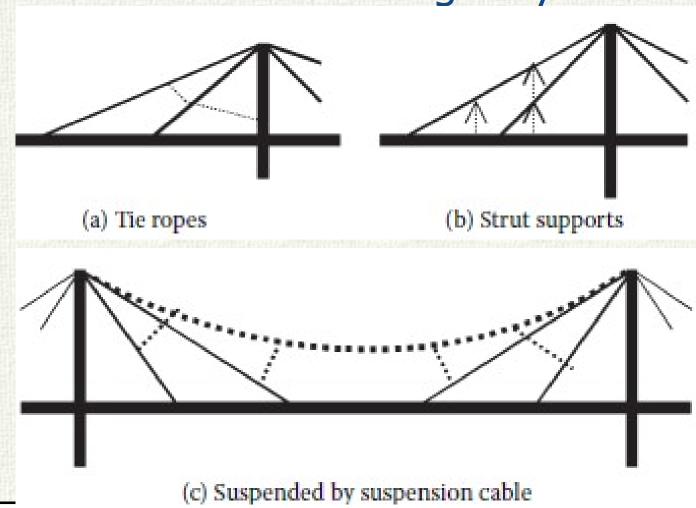
Effectiveness of a Long Stay Cable….

A cable that sags under its own weight will decrease the efficiency of the cable.

If we can shorten the cable span, L, the sag will be reduced, avoiding this problem



Effectiveness of a Long Stay Cable….



Torsional Stiffness of the Main Girder….

The torsional stiffness is important under eccentric loads and aerodynamic actions.

In most cases, the use of a box cross section for the girder will provide sufficient torsional stiffness to resist eccentric loads.

Otherwise, increasing the distance between the two cable planes of the bridge is one way to increase the torsional rigidity of the girder.

Torsional Stiffness of the Main Girder….

Spatial arrangement of the cables will also help.

Another solution is to use a local cable stay system to stiffen up the girder.

At worst, installing dampers will suppress the torsional oscillations.

Allowable Stresses….

The allowable stress of construction materials is a technical limitation.

For very long-span bridges, steel is the main construction material used. There are two kinds of steel for bridge construction—the regular steel and cold-drawn steel wires. Wire has a much higher strength than regular steel plates.

Allowable Stresses….

Various countries may have different steel products.

The yield strength, the breaking strength, and consequently, the allowable stress, may vary.

Nevertheless, the allowable stress for any specific steel is fixed and is proportional to its yield strength or breaking strength.

It is not possible for us to increase its strength,

Allowable Stresses….

Likewise it is impossible to increase the allowable stress of that same steel. Certainly, the quality of the steel we use in construction today is continuously being improved; the allowable stress of steel has significantly increased in the last century.

Therefore, the maximum possible span of bridges has also increased.

Maximum Possible Spans….

Suspension Bridges:

The critical members with respect to allowable stress in a suspension bridge are the main cables and we can use a wire in cable with higher breaking strength, which is available today, for instance, fu = 1890 MPa.
With a safety factor of 2.2,
the allowable stress fa will be 860 MPa.

Maximum Possible Spans….

Suspension Bridges:

Thus, if we assume wg+wLL to be approx equal to 20% of wc, that is, $\alpha = 0.20$, *we can solve the equation and the maximum* span length would be approximately 8000 m.

Maximum Possible Spans….

Suspension Bridges:
Currently, the world's longest span suspension bridge, Akashi Kaikyo Bridge in Japan, has a 1991-m span. It is <30% of span of 8000 m.

The Messina Strait Bridge in Italy, which is under construction, will have a center span of 3300 m; it is still <50% of the 8000 m, so we do not have to worry about span length when we conceptualize a long-span suspension bridge

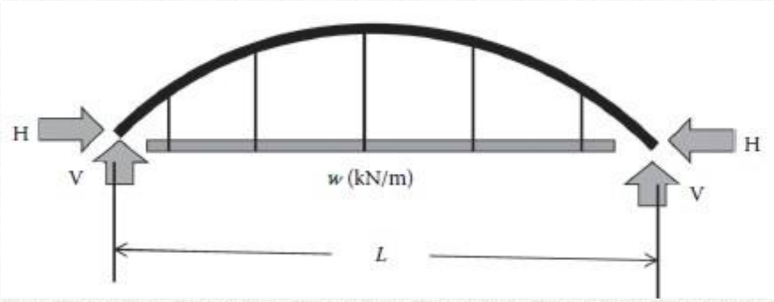
Maximum Possible Spans….

Arch Bridges:
An arch rib is the reverse of a suspension cable. here are three distinct differences between an arch rib and a suspension cable even though they are both "curve" elements.

First, the arch is a compression member and requires stiffness to be stable. It cannot use wires; rather, it employs steel plates, so the allowable stress is lower.

Maximum Possible Spans….

Arch Bridges:



Maximum Possible Spans….

Arch Bridges:

The allowable stress of the steel plates we commonly use in bridge construction, is less than half of the allowable stress of the wires. As the allowable stress in the arch rib is smaller, the proportion of girder weight and live load will be higher, which may rise to approximately 30% of wc, or $\alpha = 0.3$, *where wc denotes the weight of the arch rib for a super-long arch span.*

Maximum Possible Spans….

Arch Bridges:

Second, because the arch rib is in compression instead of tension, the arch requires additional steel for bracing to ensure its stability. In effect, the effectiveness of the steel is reduced. Third, the arch usually has a rise to span ratio between 1/5 and 1/8, which is more efficient than a suspension cable.

Maximum Possible Spans….

Arch Bridges:

If we use steel with a yield strength of 560 MPa, which is currently available, the allowable stress should be approximately 336 MPa. Assuming $\alpha = 0.3$, *the maximum span of an arch should be* approximately 4200 m. The above analysis assumes that the cross section of the arch is constant. In reality, the crosssection of the arch ribs may vary according to the axial force.

Maximum Possible Spans….

Arch Bridges:

Maximum Possible Spans….

Arch Bridges:
In fact, practical limitations in an arch span are a function of their construction. Because the arch rib itself is not stable until it is completely built, the structure is more difficult to build as the span gets longer.
Therefore, even though the arch is very efficient in terms of the quantity of materials, very long-span arch bridges are still too expensive to build. This explains why much longer span arches have not been built to date

Maximum Possible Spans….

Cable Stayed Bridges:
In both the suspension bridge and the arch bridge, the girder is not a main load carrying member of the entire structure. It only carries the local loads and transfers them to the suspension cables or the arch ribs.

Therefore, in the above analysis, we only deal with the main load carrying members of the bridge- the suspension cables or the arch ribs.

Maximum Possible Spans….

Cable Stayed Bridges:

The critical member that determines the maximum possible span of cable stayed bridge is the girder, the compressive stress of which is the limiting factor.

The allowable stress in the towers and the cables does not pose a limitation to span length. Only the girder does.

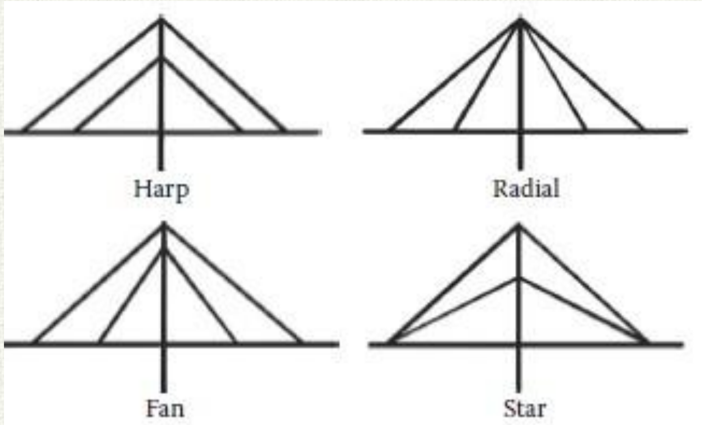
Maximum Possible Spans….

Cable Stayed Bridges:

The cables in a cable-stayed bridge can be arranged in a harp, fan, star, or a radial pattern.
The harp pattern cable arrangement will result in the highest possible compression force in the girder, which is not suitable for long spans, whereas the radial pattern cable arrangement will leave the lower portion of the tower un-braced.

Maximum Possible Spans….

Cable Stayed Bridges:



Maximum Possible Spans….

Cable Stayed Bridges:

A fan pattern is usually preferred in a long-span cable-stayed bridge because it is a compromise of the other two extremes, with less axial force in the girder while providing cable supports for the tower legs.

Maximum Possible Spans….

Cable Stayed Bridges:

A fan pattern is usually preferred in a long-span cable-stayed bridge because it is a compromise of the other two extremes, with less axial force in the girder while providing cable supports for the tower legs.

Maximum Possible Spans….

Cable Stayed Bridges:

For a very long-span cable-stayed bridge, the stress because of local bending is not significant and may be assumed to be approximately 20% of the allowable stress. Thus, for an allowable stress of 336 MPa, the maximum possible span length would be approximately 5500 m for a cable-stayed bridge.

Maximum Possible Spans….

Cable Stayed Bridges:

Currently there are three super-long cable-stayed bridge spans in the world: the 1104-m span Vladivostok Bridge in Russia, 1088-m span Sutong Bridge in Jiangsu, China, and the 1018-m span Stonecutters Bridge in Hong Kong, China. whose spans are only approximately 20% of the maximum possible span length or less.

Maximum Possible Spans….

Cable Stayed Bridges:
Above calculation is based on the assumption that the girder cross section is constant along the entire span.

In a cable-stayed bridge, the axial force in the girder is close to zero at mid span and increases to its maximum near the tower.

Maximum Possible Spans….

Cable Stayed Bridges:
Thus, if we increase cross section of the girder - as the axial force increases, the allowable axial force in the girder can be increased and, consequently, the maximum span can also be increased.

This way, the theoretical maximum span length could be increased by almost 100%, to more than 10,000 m.

Maximum Possible Spans….

Girder Bridges:
There is no clear cut criterion for estimating the maximum span of a girder bridge. Presently, girder bridges are the only bridge type in which some of the longest spans were entirely or partially built with concrete.

The current longest span steel girder bridge is the 300-m span Rio Niteroi Bridge in Brazil, which was completed in 1974. Longer spans have not been built since then.

Maximum Possible Spans….

Girder Bridges:
Currently, the world's longest girder span is the 330-m span Shibanpo Bridge, in Chongqing, China this is a hybrid structure with a 103-m steel box section in the middle of the 330-m span that reduces weight.

Maximum Possible Spans….

66-2 Rich Street Bridge:

Maximum Possible Spans….

Girder Bridges:
Currently, the world's longest girder span is the 330-m span Shibanpo Bridge, in Chongqing, China this is a hybrid structure with a 103-m steel box section in the middle of the 330-m span that reduces weight.

Maximum Possible Spans….

Girder Bridges:
Experience from designing the Shibanpo Bridge indicates that extending the steel portion to 250 m and the concrete portion on each side to approximately 150 m is possible, making a 550-m span a feasible solution in future.

Maximum Possible Spans….

Girder Bridges:
A very long-span concrete girder is excessively heavy and a very long-span steel bridge will require very thick flange plates that are extremely difficult to fabricate.

The long-term deformation due to creep and shrinkage of concrete is still hard to predict, making very long-span concrete bridges vulnerable to excessive deflections.

Design Process….

Conceptual Design: Reduced cost & improved appearance

Design Process….

Conceptual Design: Paying attention to proportions and detailing resulted in good

Design Process….

Conceptual Design: Elegant Robert Maillert’s Salginotobel Bridge.

Design Process….

Conceptual Design: Thomas Telford’s Craigellachie Bridge

Design Process….

Conceptual Design:

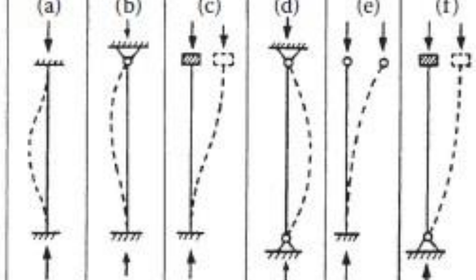
Christian Menn’s Sunniberg Bridge

Design Process….

Conceptual Design: A successful collaboration between an engineer and an architect/urban designer: Clearwater Memorial Causeway, Clearwater, Florida

Design Process….

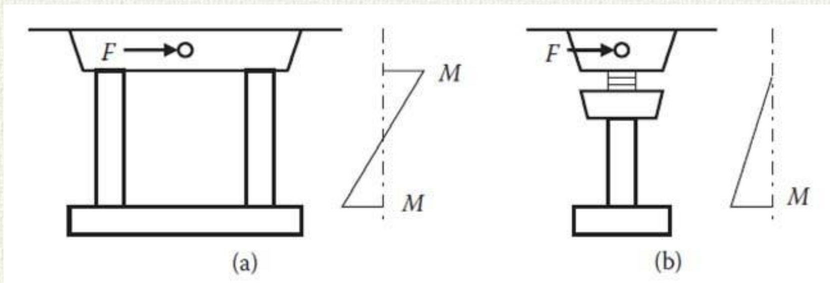
Effective Length of compression members:



	(a)	(b)	(c)	(d)	(e)	(f)
Buckled shape of column is shown by dashed line						
Theoretical K value	0.5	0.7	1.0	1.0	2.0	2.0
Recommended design value when ideal conditions are approximated	0.65	0.80	1.2	1.0	2.10	2.0

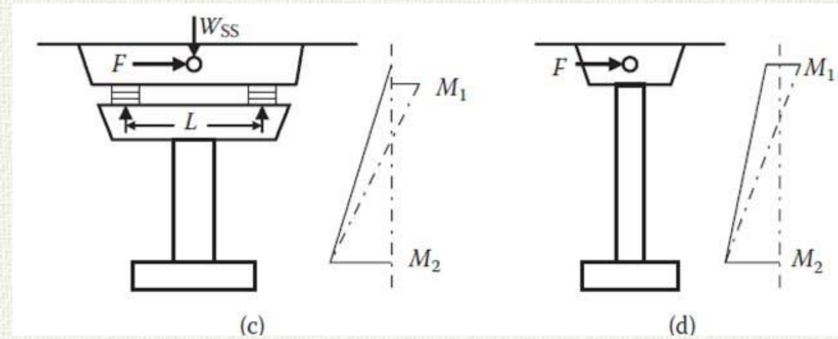
Design Process….

Transverse Response of Bridge Pier:



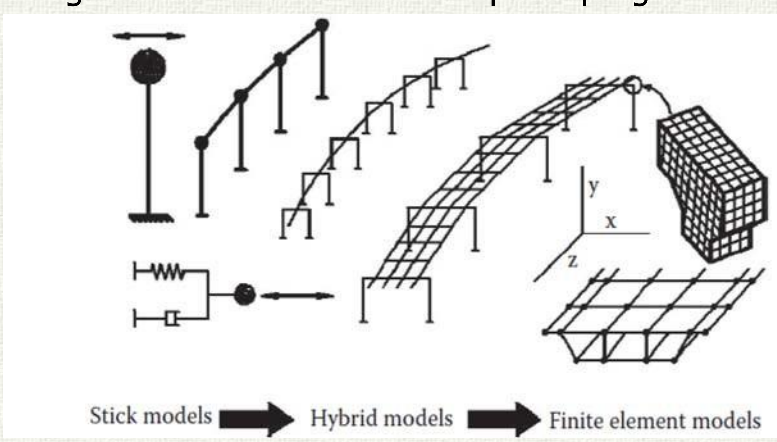
Design Process….

Transverse Response of Bridge Pier:



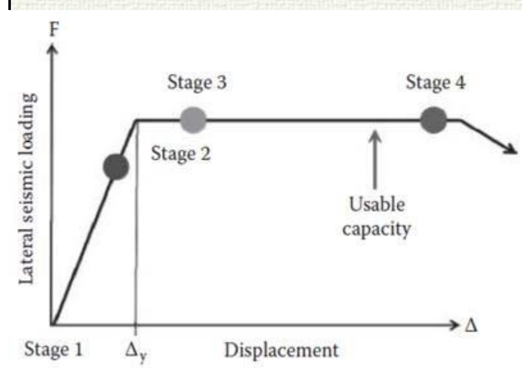
Design Process….

Bridge models available on computer programs:

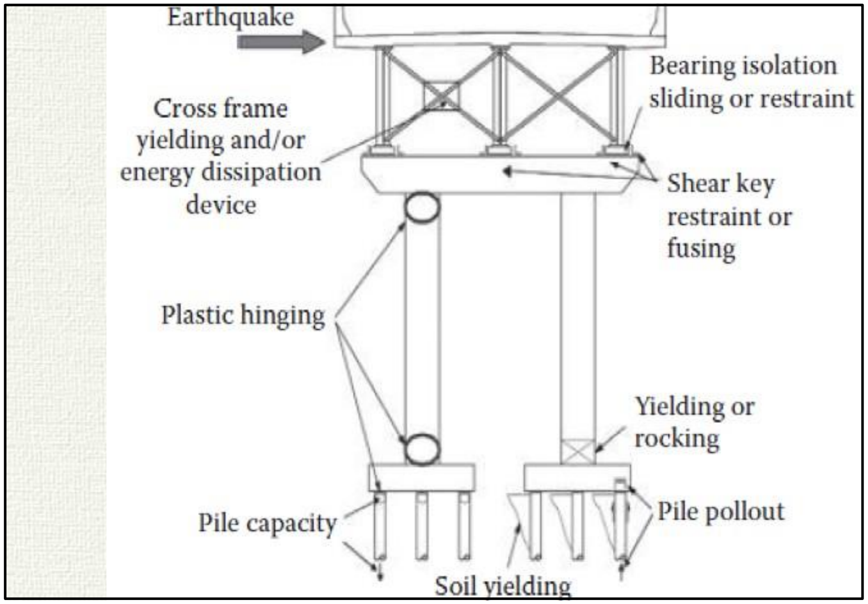


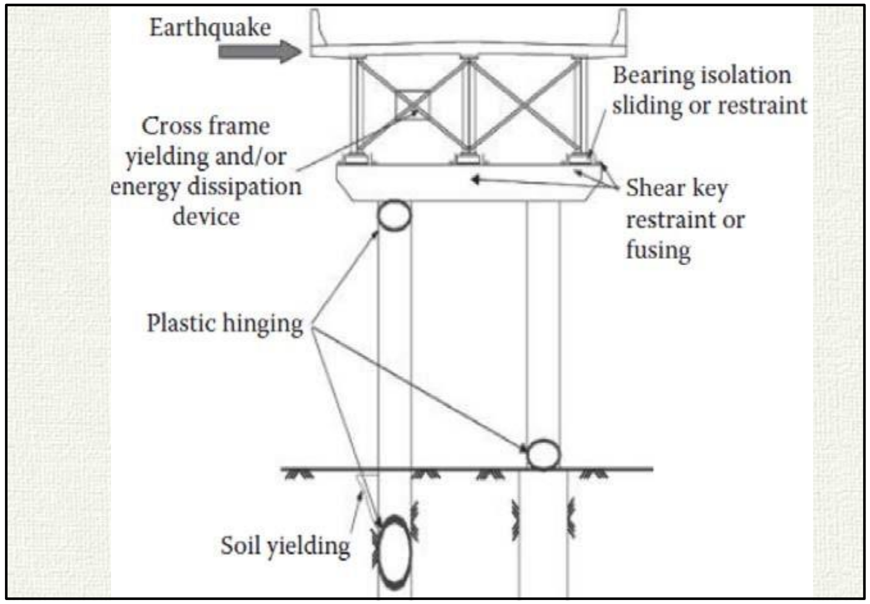
Design Process….

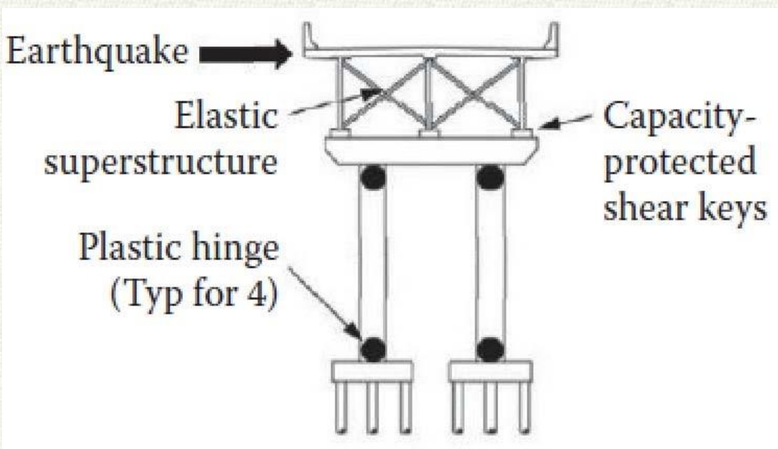
Idealised lateral Seismic loading versus displacement plot:



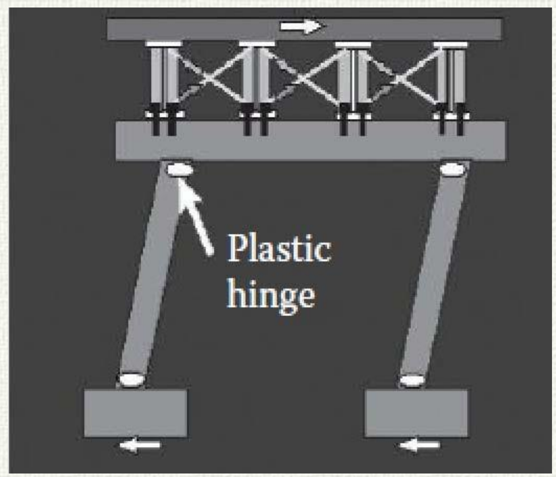
Stages	Description
1	Zero lateral load
2	Just before yielding
3	Just following formation of the plastic hinge
4	Just before plastic hinge capacity-degradation



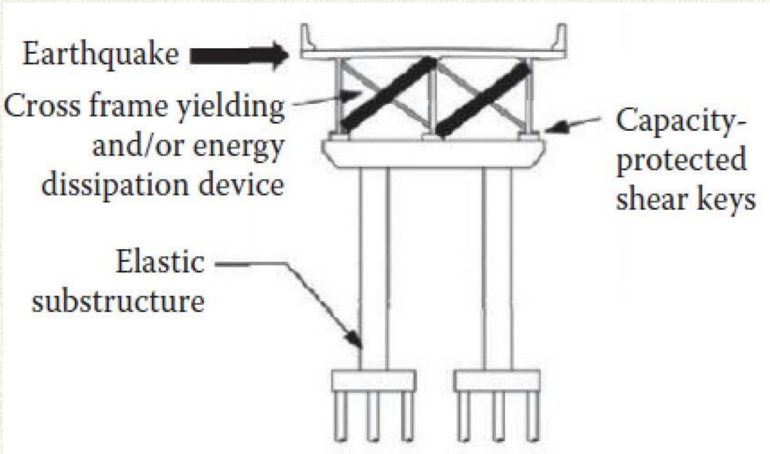




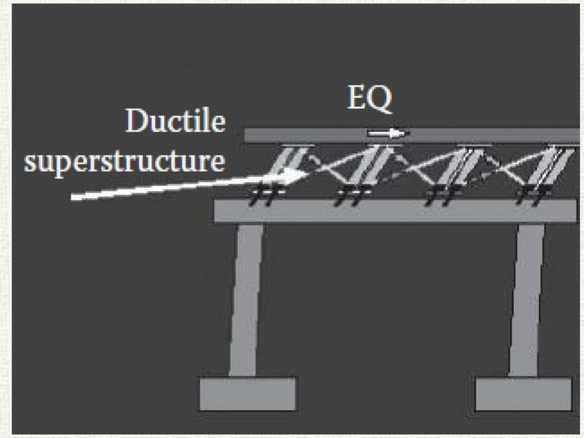
Ductile Substructure



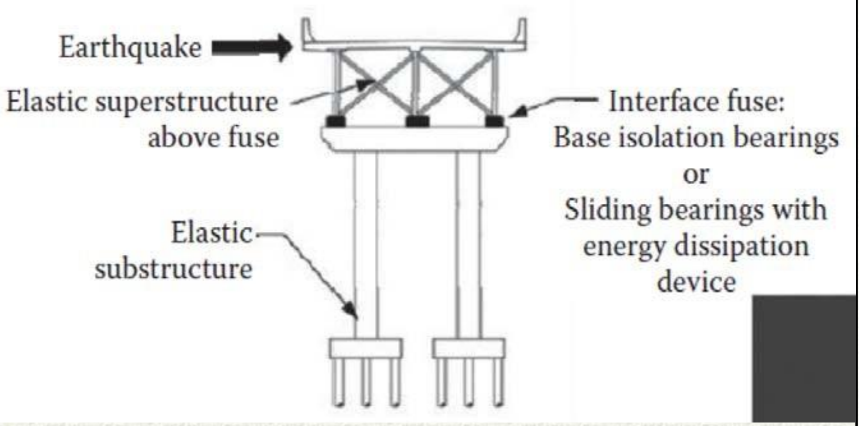
Ductile Substructure



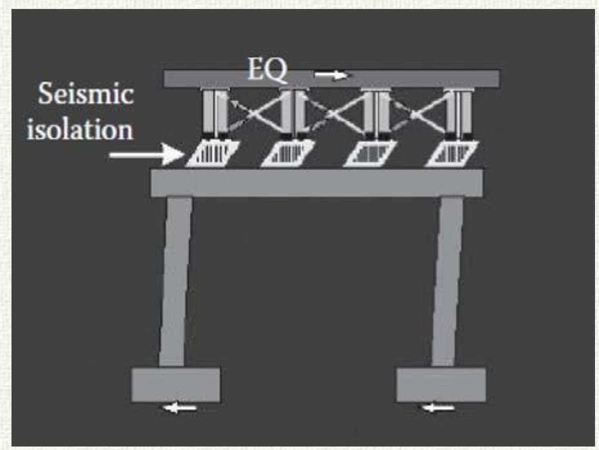
Ductile Superstructure



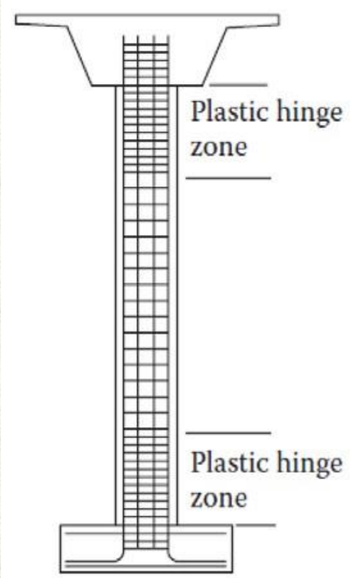
Ductile Superstructure



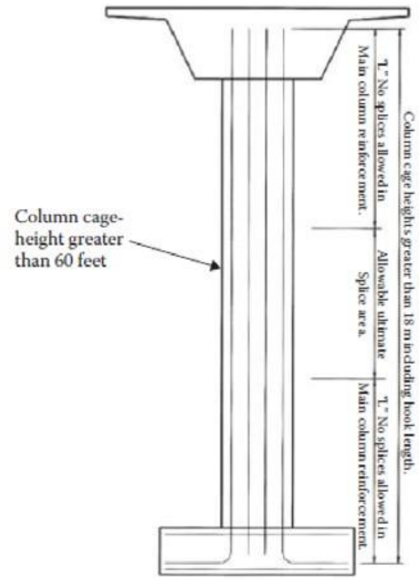
Fusing Mechanism



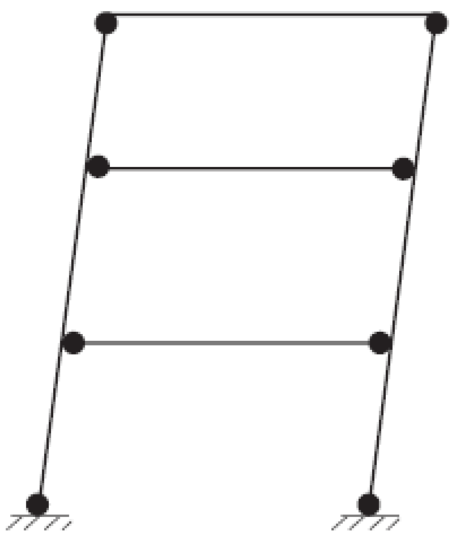
Seismic Isolation



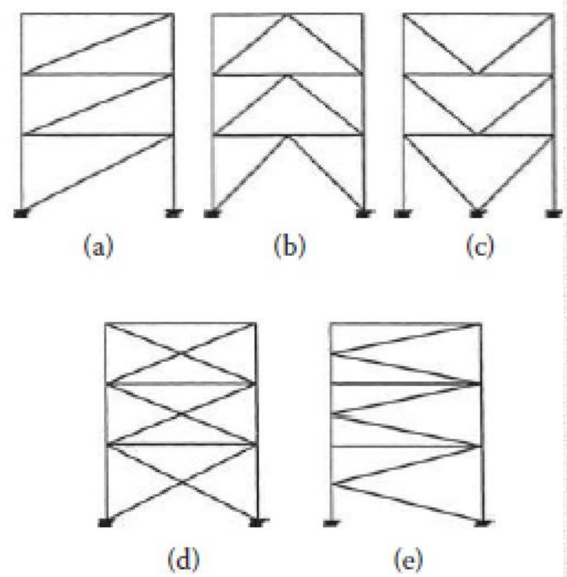
Single column reinforcement in plastic hinge region



Reinforcement Splicing in Single column bent

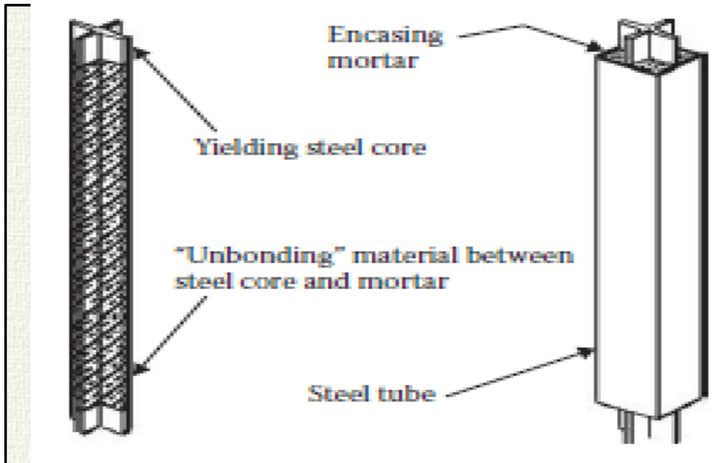


Acceptable plastic hinge mechanism in Multi Pier Bent

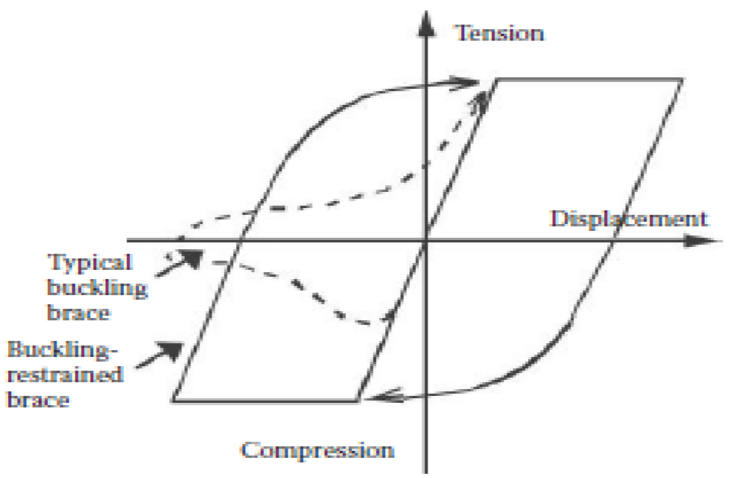


Acceptable Bracing configuration except (e)

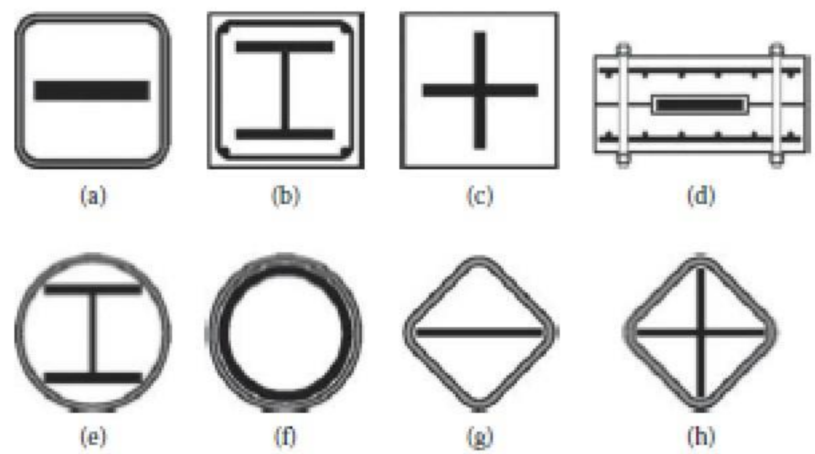
Buckling restrained brace BRB



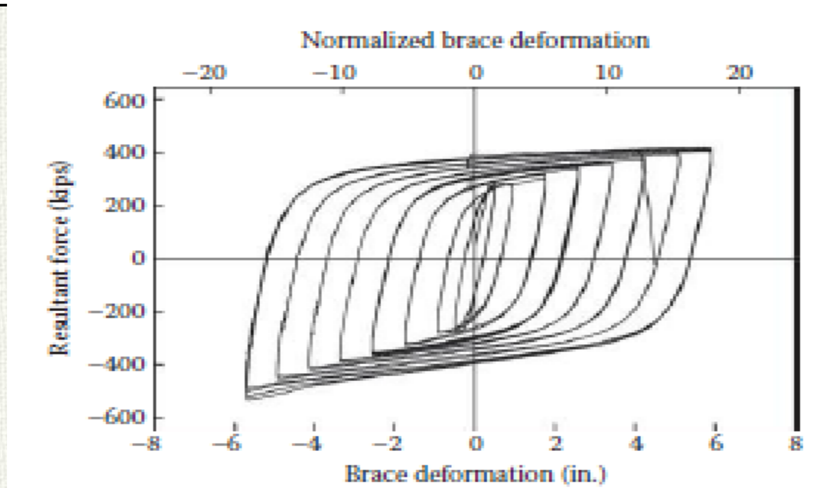
Buckling restrained brace BRB



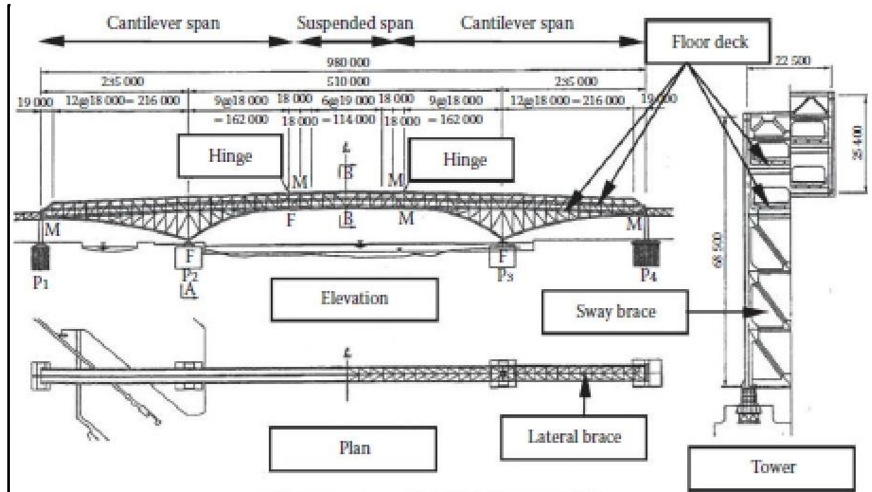
Cyclic Response of Conventional versus Buckling restrained brace BRB



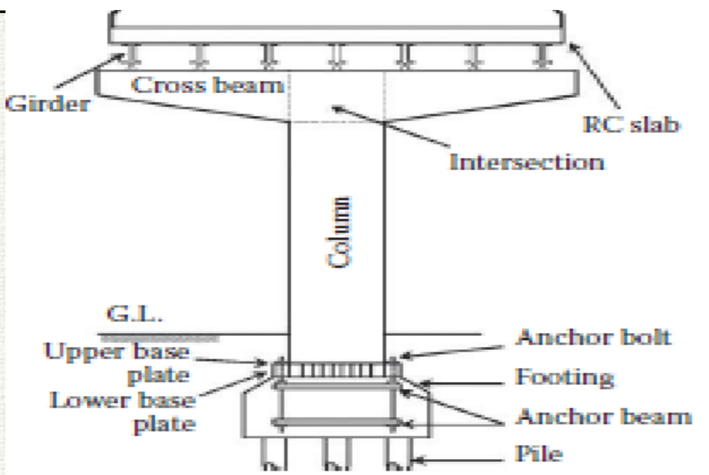
Cross Sections of Buckling restrained brace BRBs



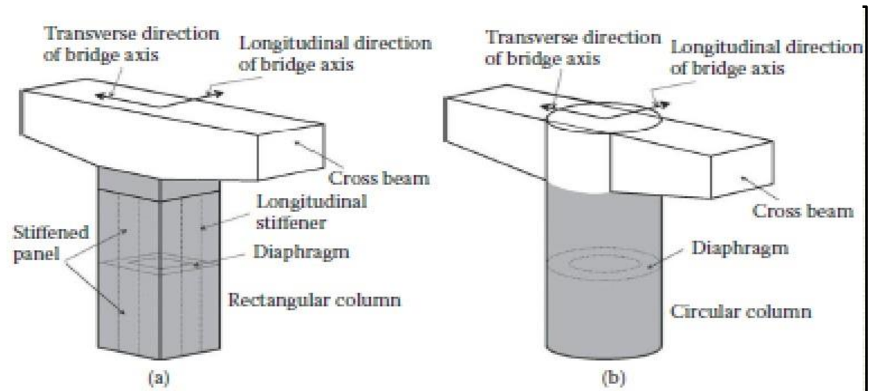
Typical response of Buckling restrained brace BRBs



Minato Bridge retrofitted with BRBs

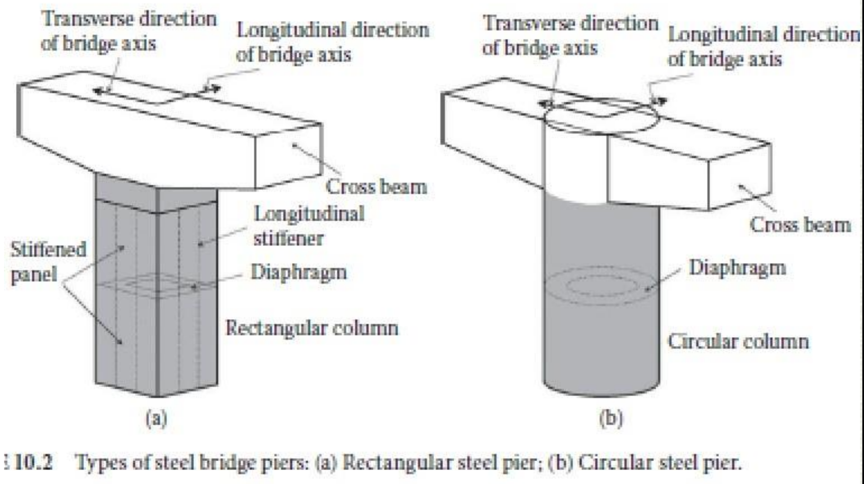


Thin walled steel bridge piers

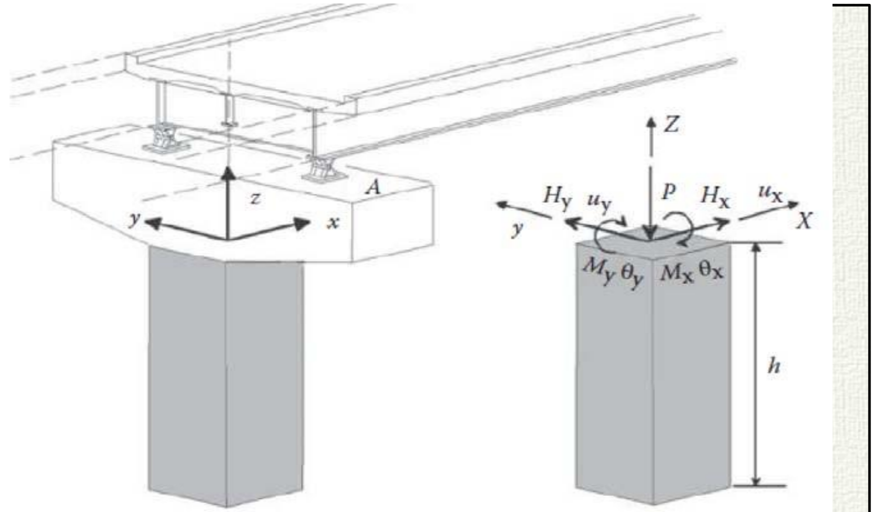


10.2 Types of steel bridge piers: (a) Rectangular steel pier; (b) Circular steel pier.

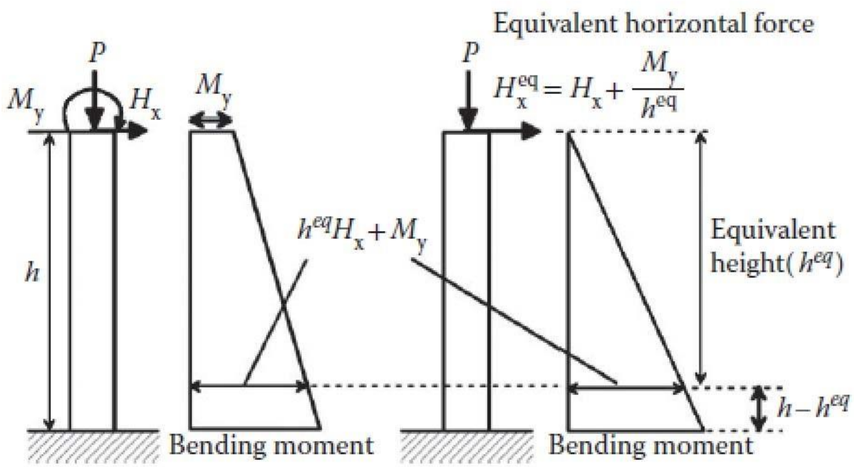
Rectangular & Circular piers



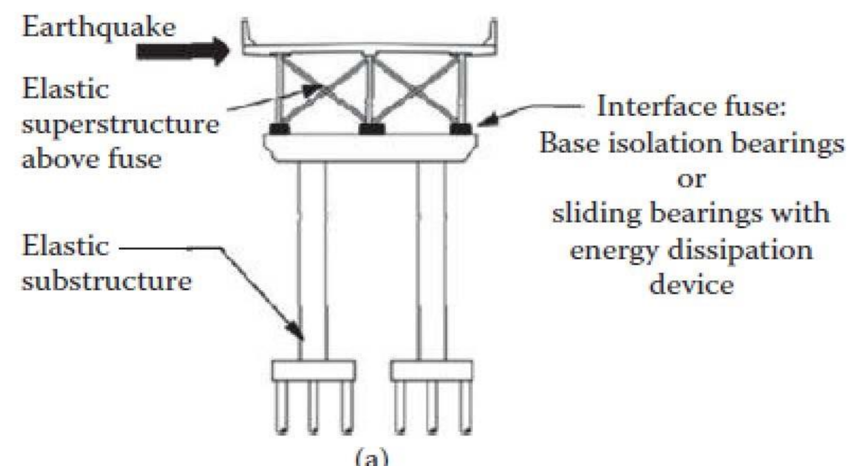
Rectangular & Circular piers



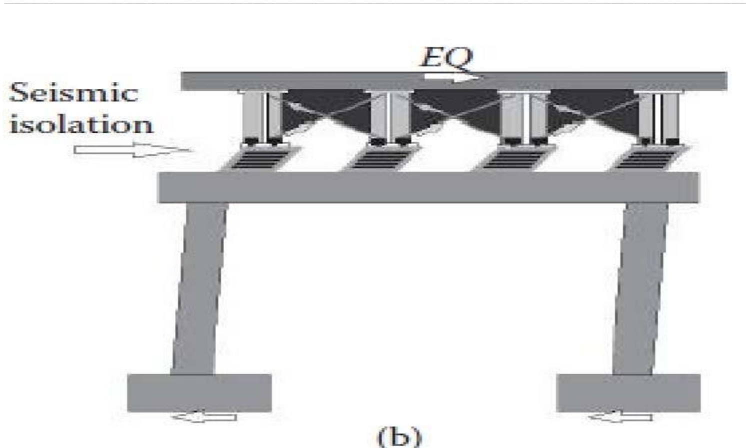
Forces and Moments on top of bridge piers



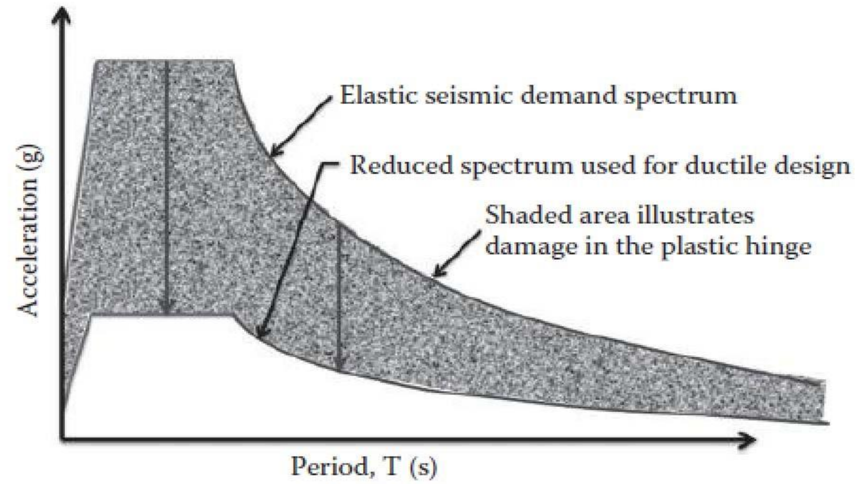
Forces and Moments at bottom of bridge piers



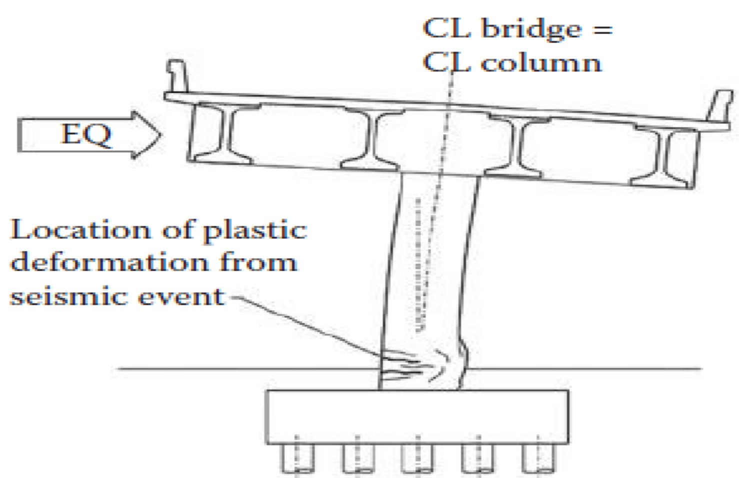
Seismic Isolation



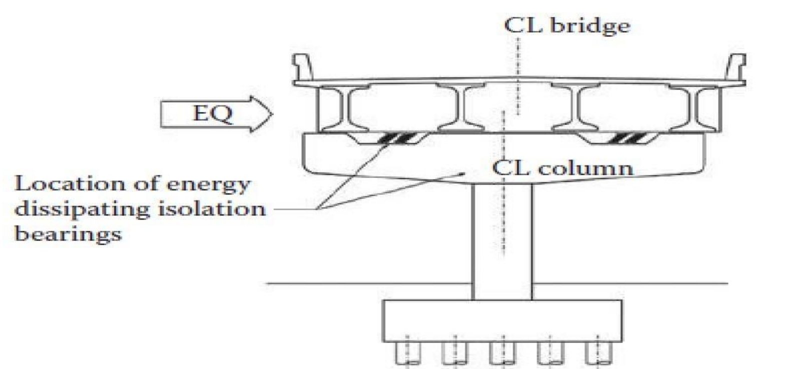
Seismic Isolation



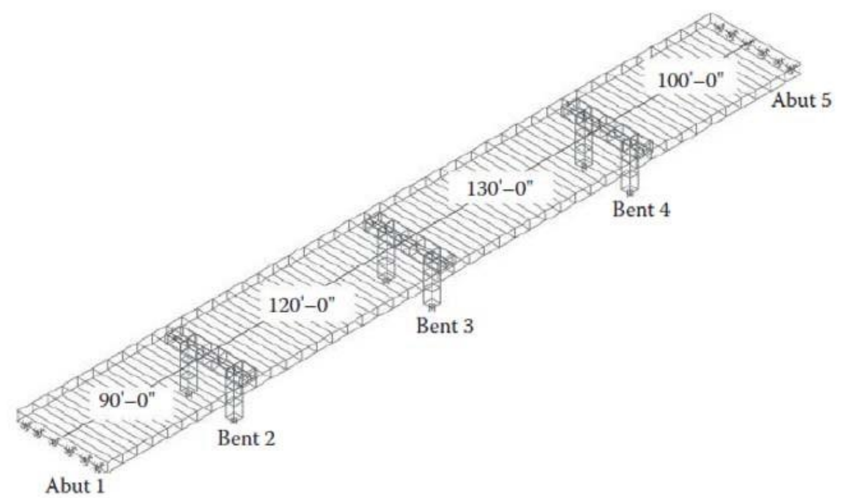
Life Safety Performance



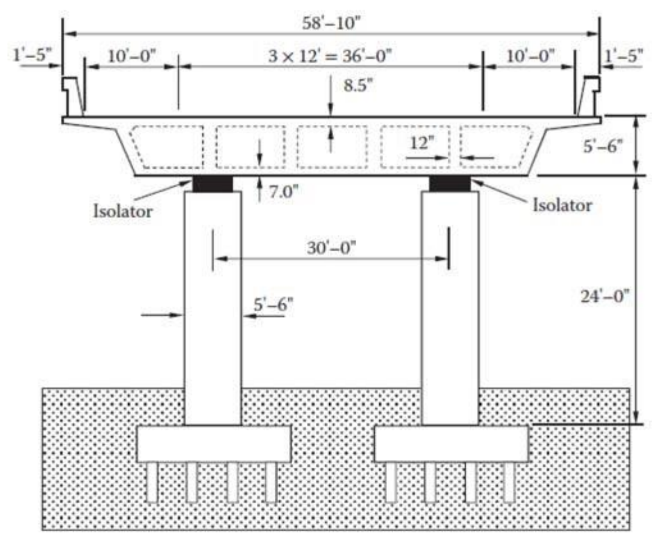
Non-isolated Bridge Structure



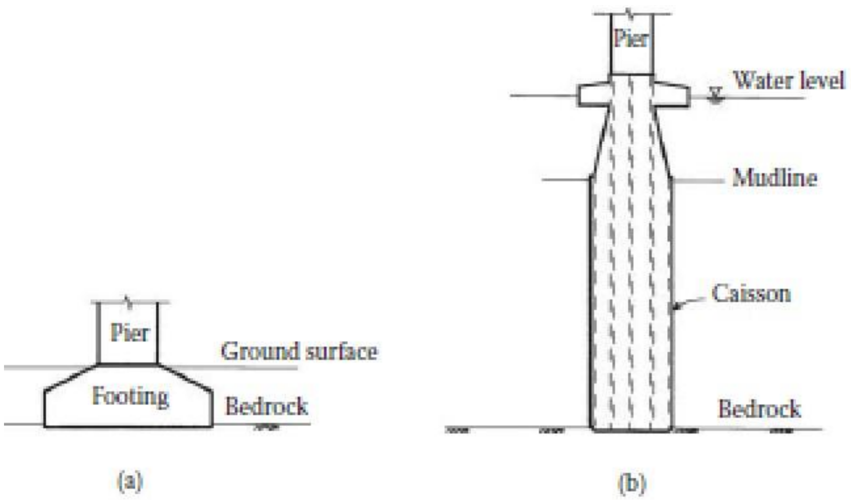
Isolated Bridge Structure



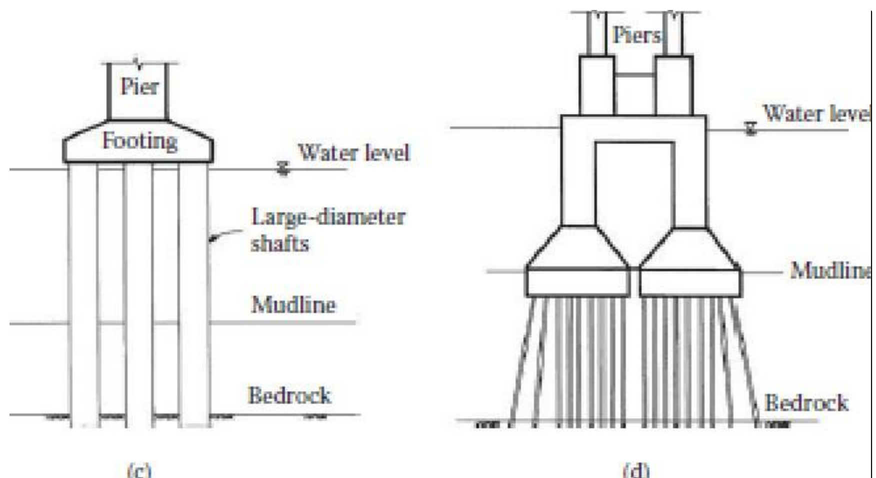
Bridge Layout Four Span Two Column Bent



Section Two Column Bent



Bridge Foundation Types a) Spread Footing b) Cassion



Bridge Foundation Types c) Large diameter shaft d) Slender pile-group

Failure of Bridge deck slab

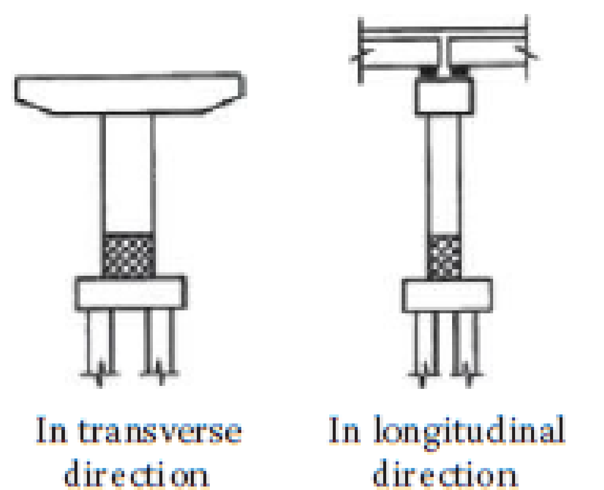
Shear Failure of Bridge pier

Failure of Shiwei Bridge

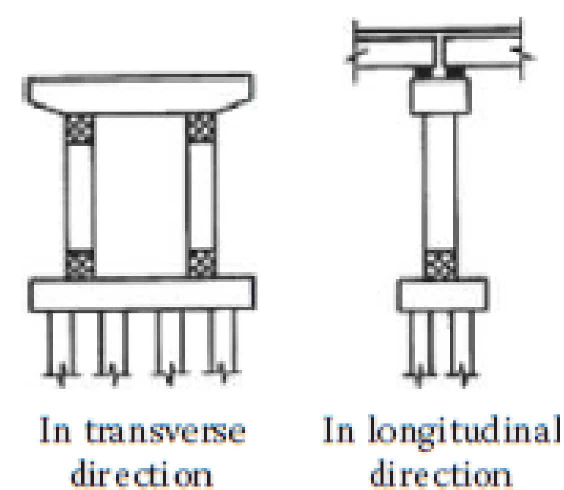
Failure of Luanhe Highway River Bridge Spans from 2 to 24 fell (8°)

Yiwanshui Bridge Collapse by stone hitting

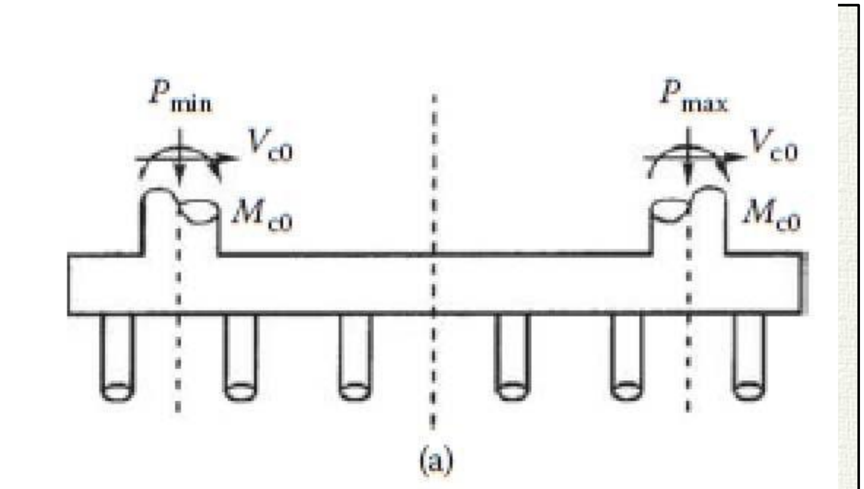
Chediguan Bridge 1-3 Span Collapse by stone hitting



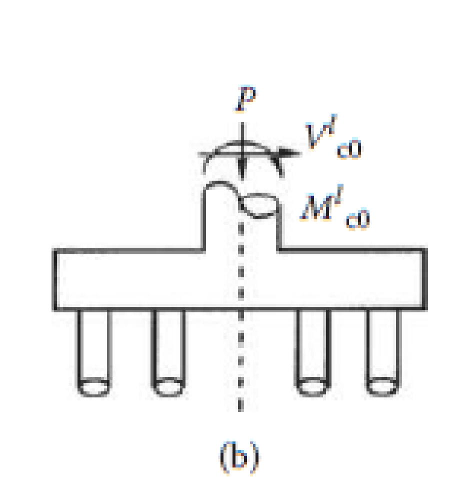
Distribution of Plastic Hinge



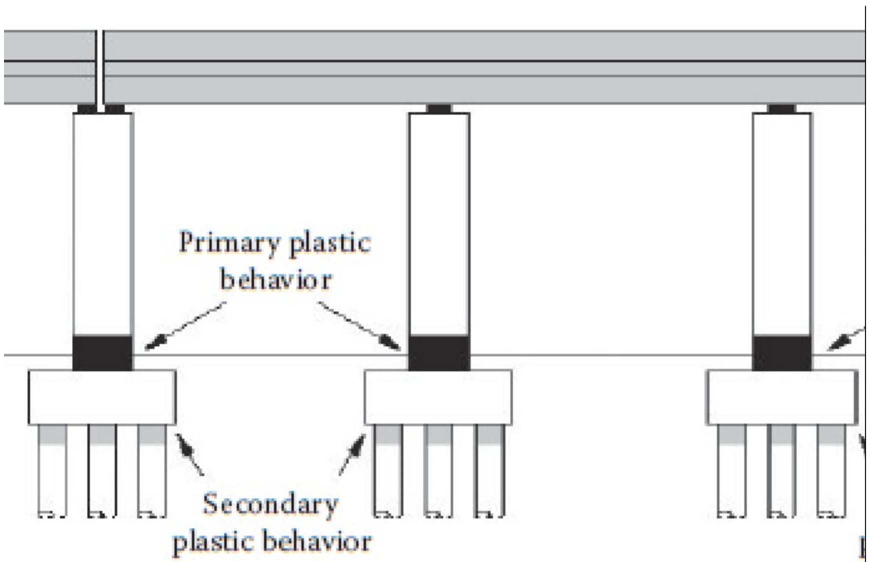
Distribution of Plastic Hinge



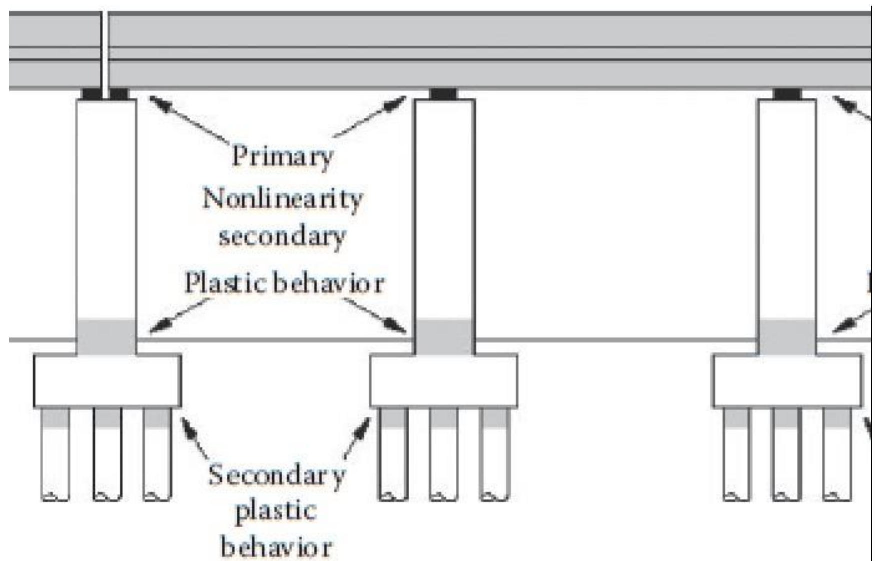
Schematic plan of design loads in foundations



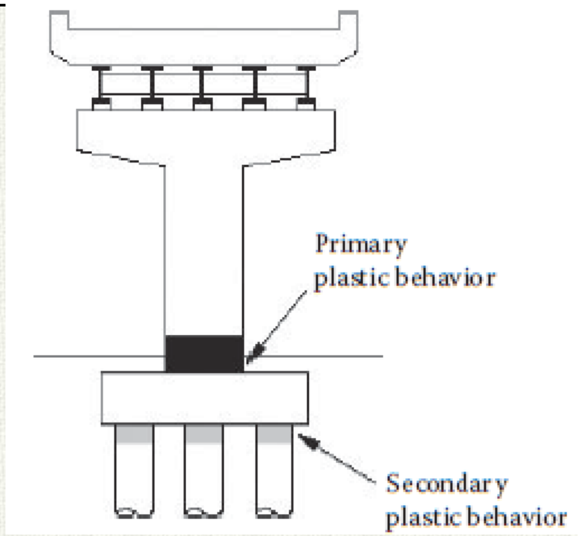
Schematic plan of design loads in foundations



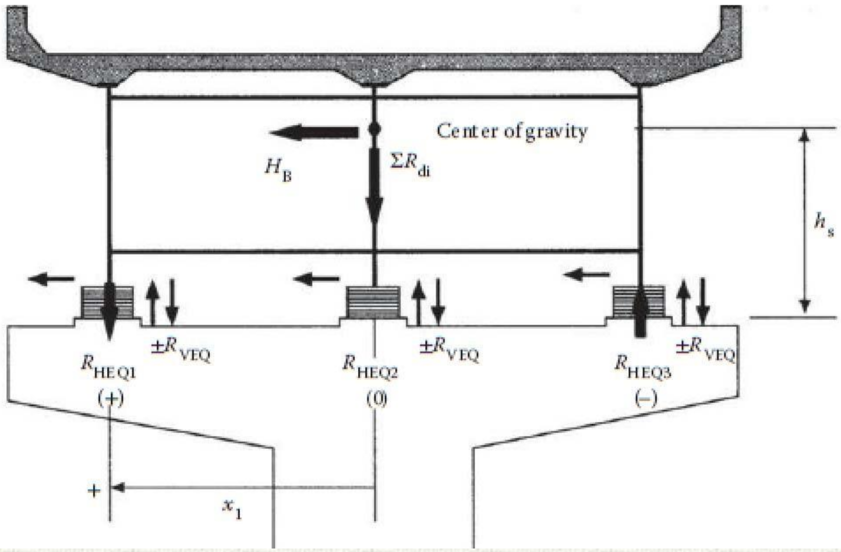
Single pier column in longitudinal direction



Single pier column in longitudinal direction



Single pier column in Transverse direction



Design forces for bearing supports

Discussion