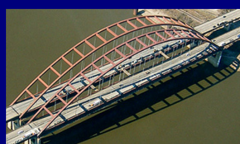
Innovations in Tied Arch Bridges

R. Shankar Nair
Chicago



Why are tied arches important?

Typical span ranges for various long-span bridge types…

Ø Composite steel girders	< 500’
Ø Segmental concrete box	< 600’
Ø Steel through truss	300’ – 600’
Ø Steel tied arch	400’ – 1000’
Ø Cable stayed	600’ – 2000’
Ø Suspension	> 1500’

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Ø Suspension	> 1500’

There are other options in the tied-arch span range

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Ø Segmental concrete box	< 600’
Ø Steel through truss	300’ – 600’
Ø Steel tied arch	400’ – 1000’
Ø Cable stayed	600’ – 2000’
Ø Suspension	> 1500’

Only the tied arch is ideally suited to a single-span layout

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Ø Steel through truss	300’ – 600’
Ø Steel tied arch	400’ – 1000’
Ø Cable stayed	600’ – 2000’
Ø Suspension	> 1500’

Only the tied arch is ideally suited to a single-span layout

Many water crossings require only one long navigational span

Typical span ranges for various long-span bridge types…

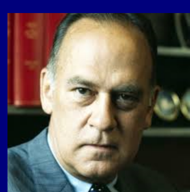
- Ø Composite steel girders < 500'
- Ø Segmental concrete box < 600'
- Ø Steel through truss 300' – 600'
- Ø Steel tied arch 400' – 1000'
- Ø Cable stayed 600' – 2000'
- Ø Suspension > 1500'

Only the tied arch is ideally suited to a single-span layout

A common river-crossing configuration:
- Ø One tied arch span of 500'-900'
- Ø Composite steel approach spans of 150'-250'

What is an arch?

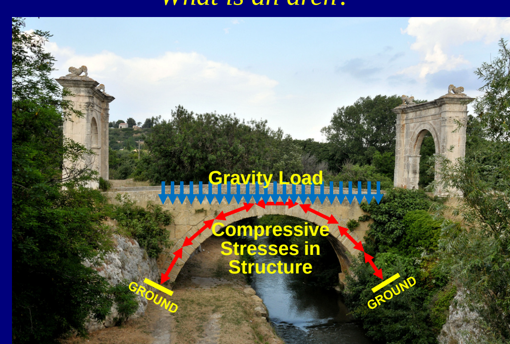
Justice Potter Stewart
Member of Supreme Court 1958-1981

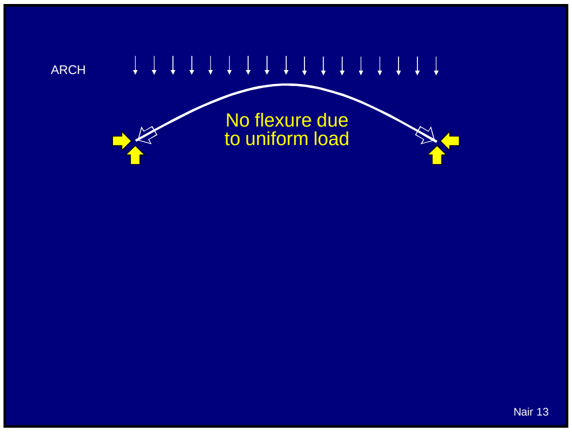


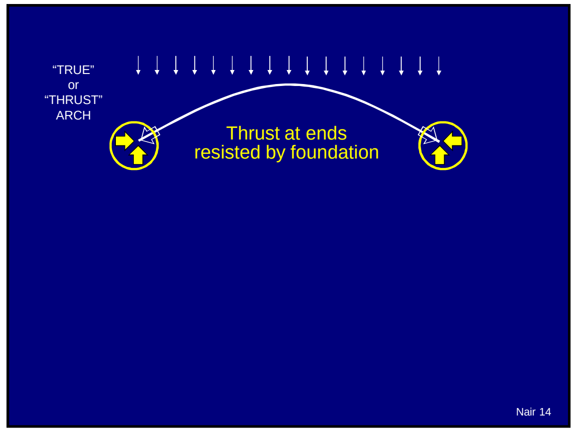
"I know it when I see it"

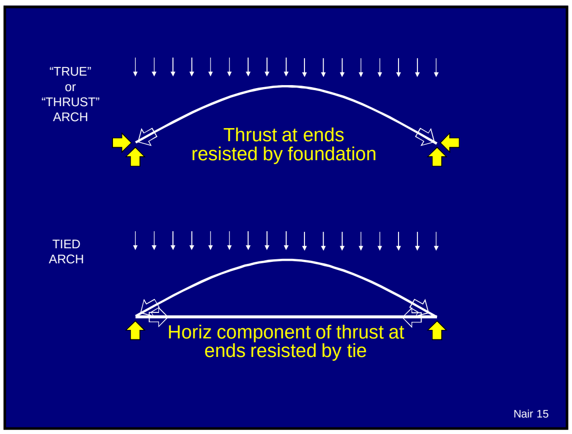
I know an arch when I see it

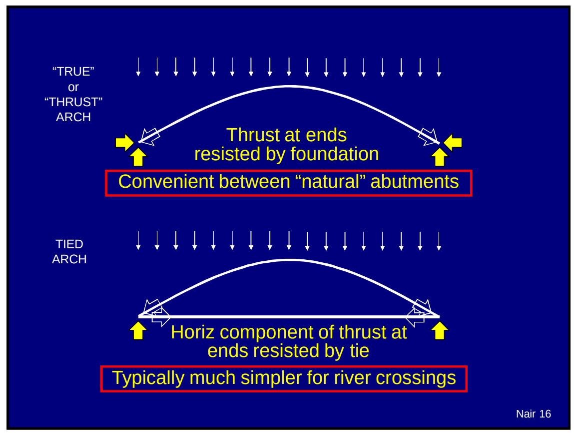
What is an arch?

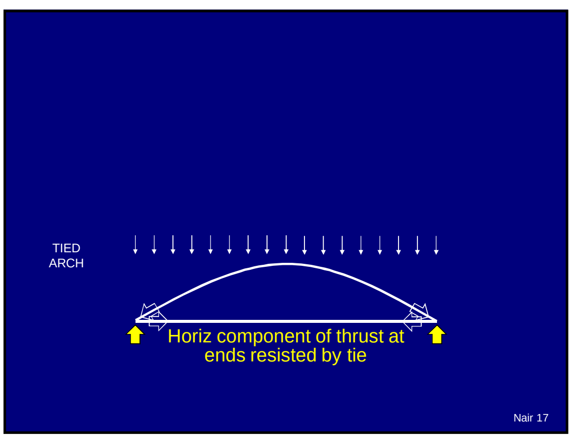


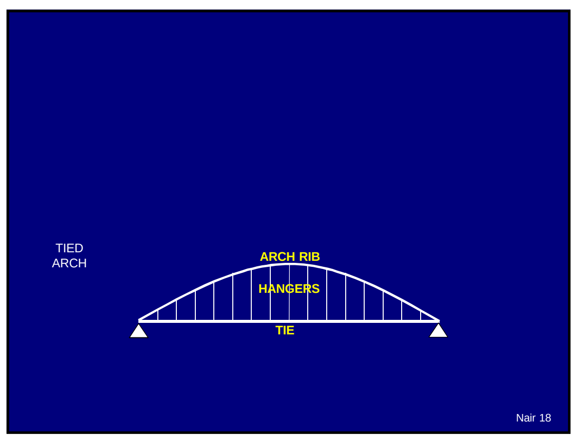

ARCH
No flexure due
to uniform load
Nair 13

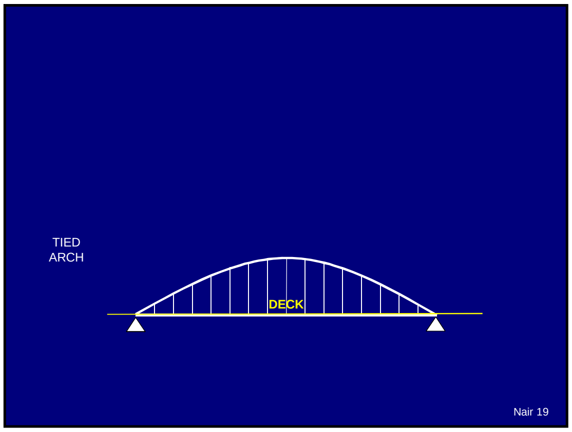

"TRUE"
or
"THRUST"
ARCH
Thrust at ends
resisted by foundation
Nair 14

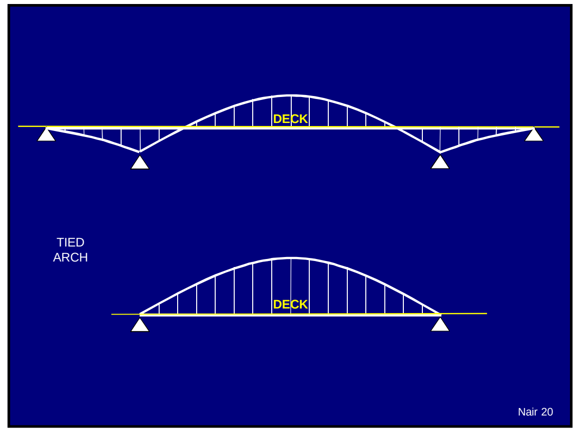

"TRUE"
or
"THRUST"
ARCH
Thrust at ends
resisted by foundation
TIED
ARCH
Horiz component of thrust at
ends resisted by tie
Nair 15

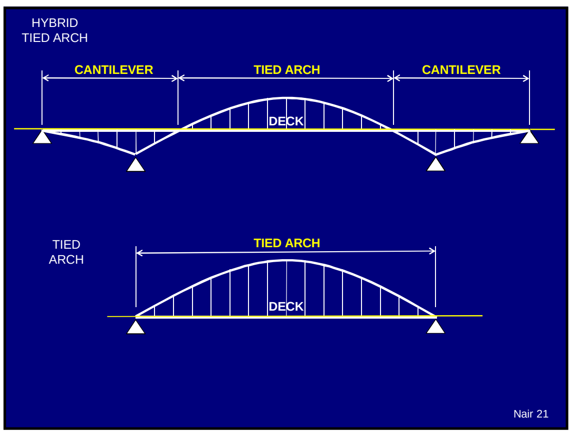

"TRUE"
or
"THRUST"
ARCH
Thrust at ends
resisted by foundation
Convenient between "natural" abutments
TIED
ARCH
Horiz component of thrust at
ends resisted by tie
Typically much simpler for river crossings
Nair 16


TIED
ARCH
Horiz component of thrust at
ends resisted by tie
Nair 17

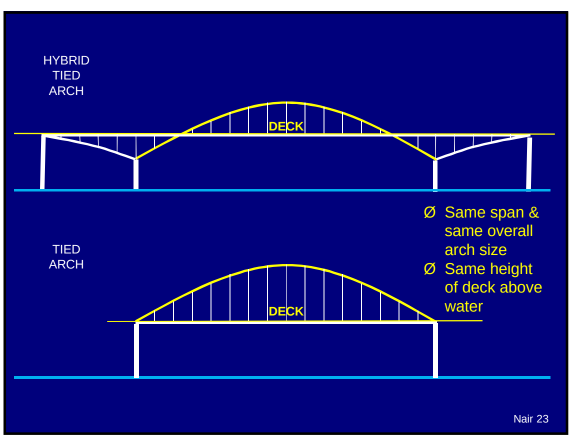

TIED
ARCH
ARCH RIB
HANGERS
TIE
Nair 18

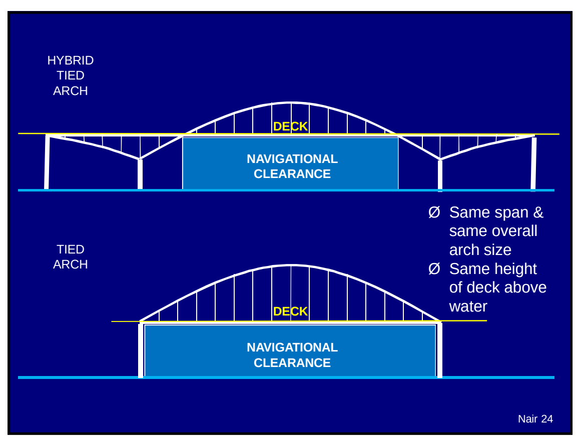

TIED
ARCH
DECK
Nair 19

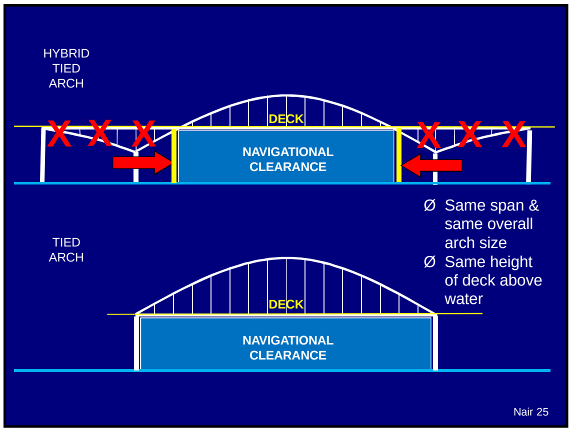

DECK
TIED
ARCH
DECK
Nair 20

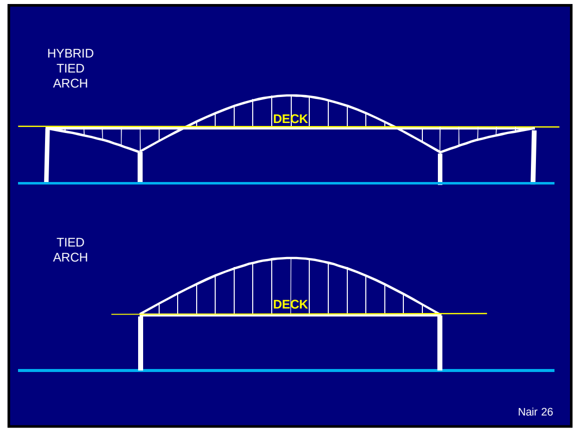

HYBRID
TIED ARCH
CANTILEVER
TIED ARCH
CANTILEVER
DECK
TIED
ARCH
TIED ARCH
DECK
Nair 21

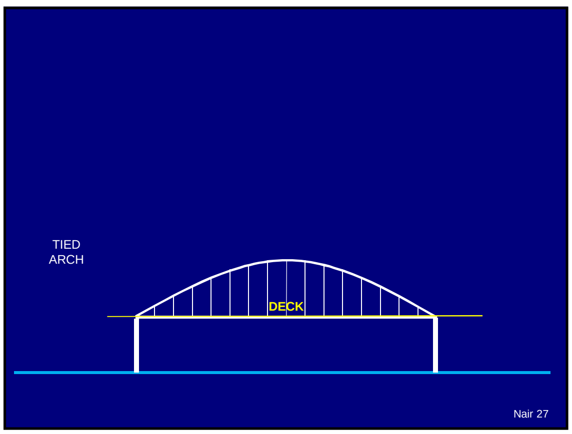

Nair 22

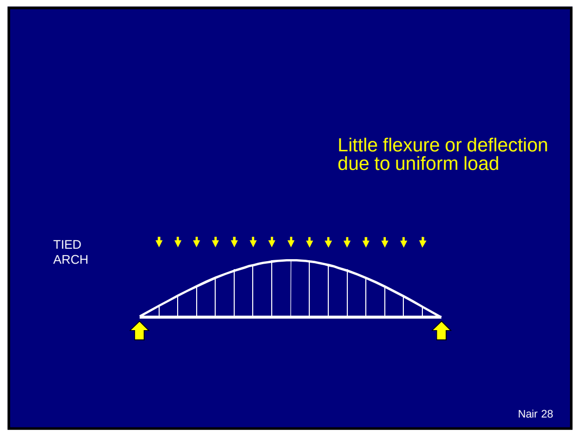

HYBRID
TIED
ARCH
DECK
Ø Same span & same overall arch size
Ø Same height of deck above water
TIED
ARCH
DECK
Nair 23

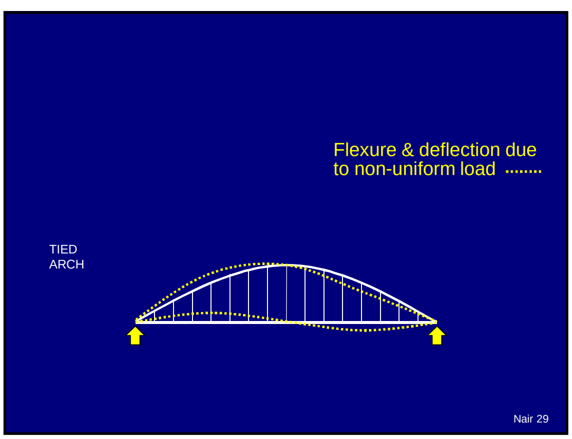

HYBRID
TIED
ARCH
DECK
NAVIGATIONAL
CLEARANCE
Ø Same span & same overall arch size
Ø Same height of deck above water
TIED
ARCH
DECK
NAVIGATIONAL
CLEARANCE
Nair 24

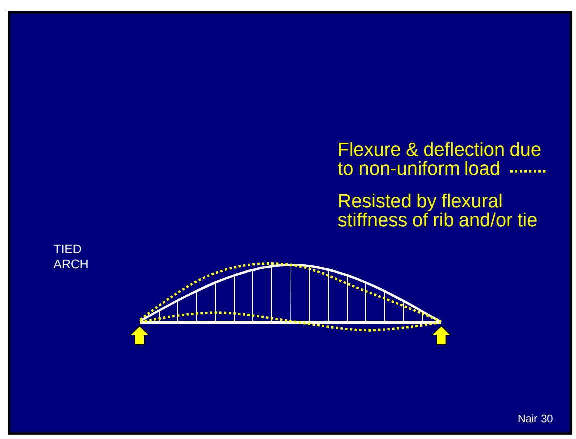

HYBRID
TIED
ARCH
DECK
NAVIGATIONAL
CLEARANCE
Ø Same span & same overall arch size
Ø Same height of deck above water
TIED
ARCH
DECK
NAVIGATIONAL
CLEARANCE
Nair 25

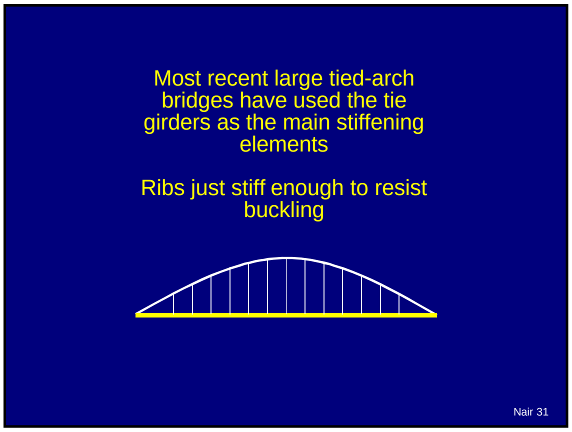

HYBRID
TIED
ARCH
DECK
TIED
ARCH
DECK
Nair 26


TIED
ARCH
DECK
Nair 27

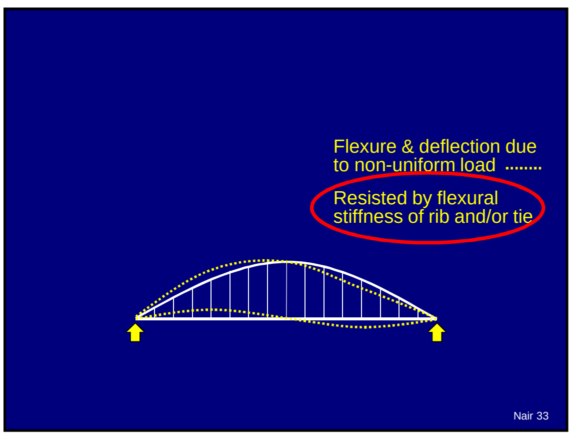

Little flexure or deflection due to uniform load
TIED
ARCH
Nair 28

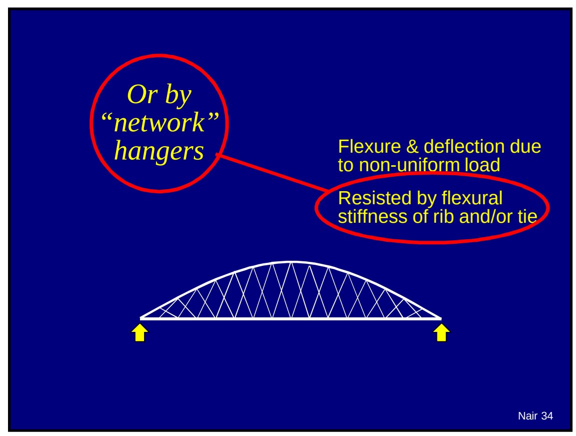

Flexure & deflection due to non-uniform load ....
TIED
ARCH
Nair 29

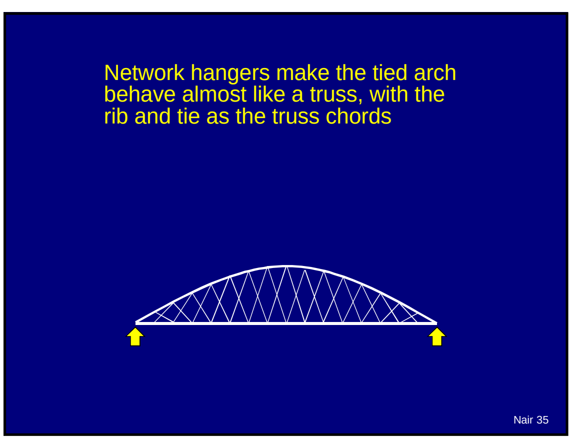

Flexure & deflection due to non-uniform load ....
Resisted by flexural stiffness of rib and/or tie
TIED
ARCH
Nair 30

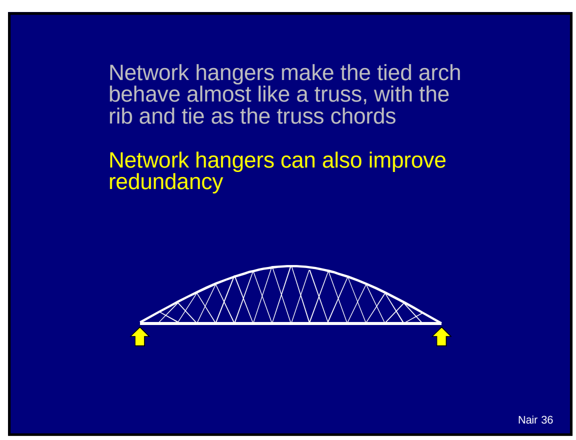

Most recent large tied-arch bridges have used the tie girders as the main stiffening elements
Ribs just stiff enough to resist buckling
Nair 31

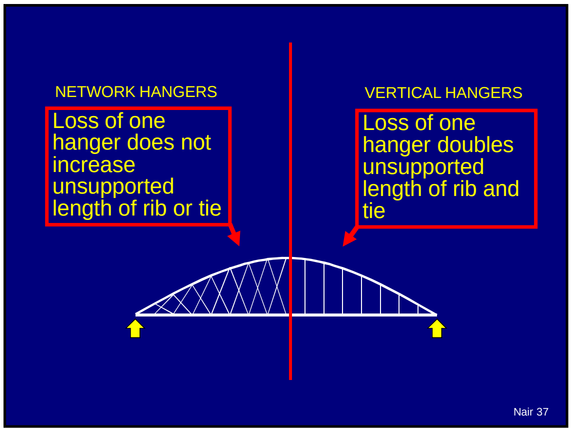

Nair 32

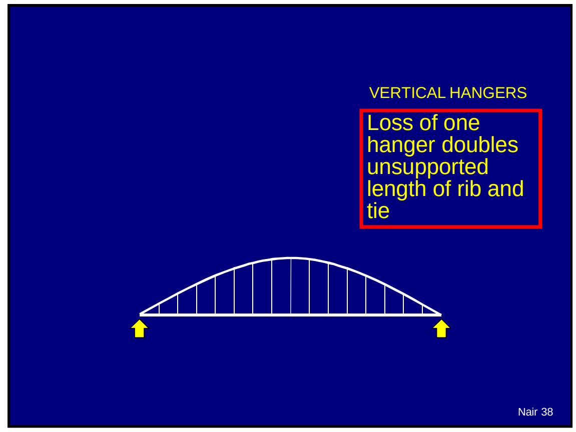

Flexure & deflection due to non-uniform load
Resisted by flexural stiffness of rib and/or tie
Nair 33

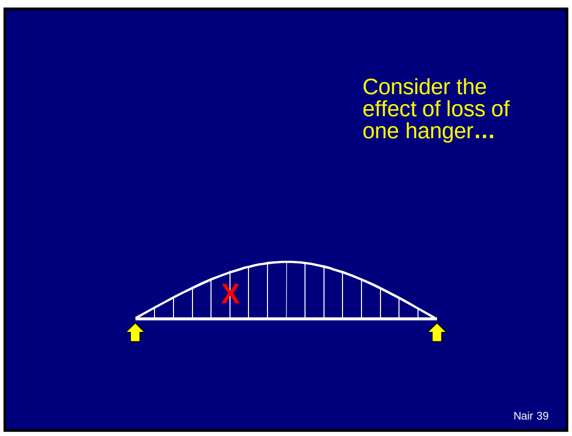

Or by "network" hangers
Flexure & deflection due to non-uniform load
Resisted by flexural stiffness of rib and/or tie
Nair 34


Network hangers make the tied arch behave almost like a truss, with the rib and tie as the truss chords
Nair 35

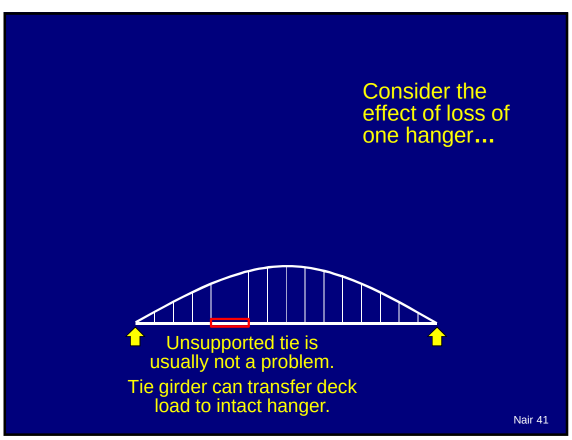

Network hangers make the tied arch behave almost like a truss, with the rib and tie as the truss chords
Network hangers can also improve redundancy
Nair 36

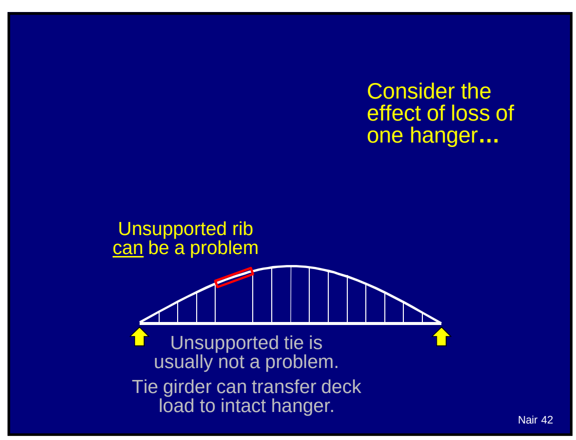

NETWORK HANGERS
Loss of one hanger does not increase unsupported length of rib or tie
VERTICAL HANGERS
Loss of one hanger doubles unsupported length of rib and tie
Nair 37

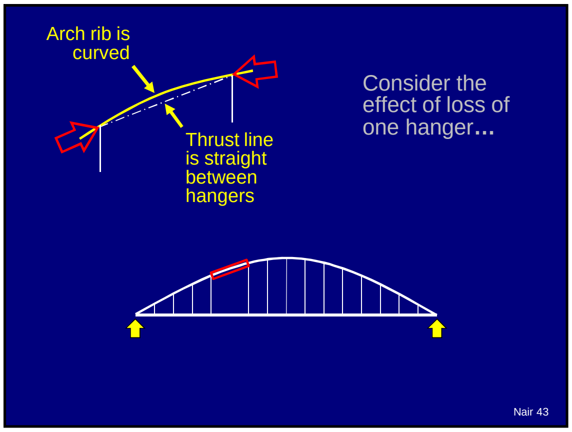

VERTICAL HANGERS
Loss of one hanger doubles unsupported length of rib and tie
Nair 38

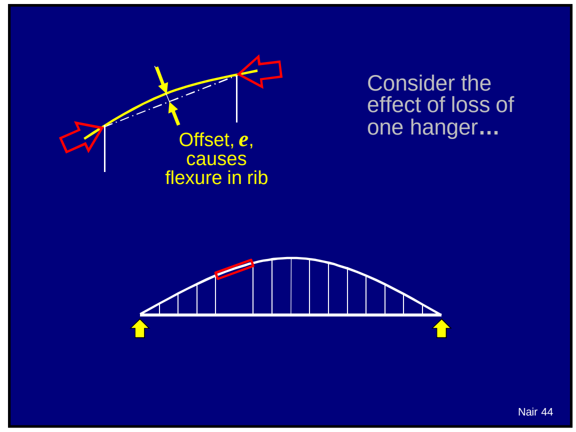

Consider the effect of loss of one hanger…
X
Nair 39

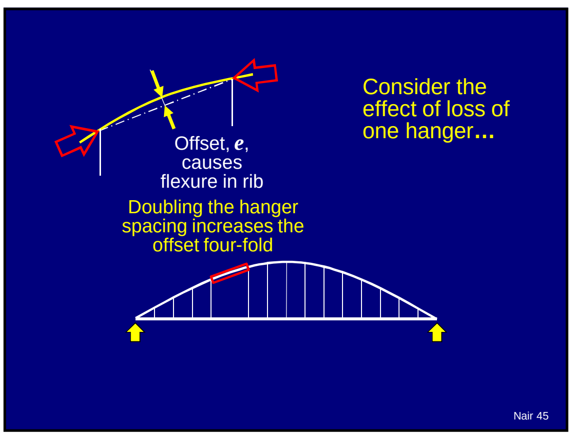

Consider the effect of loss of one hanger…
Unsupported tie is usually not a problem.
Nair 40

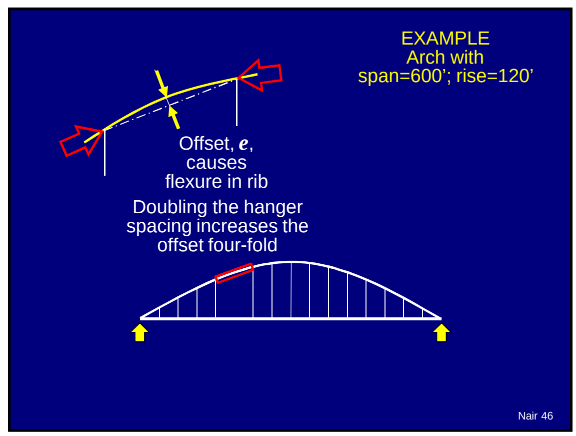

Consider the effect of loss of one hanger…
Unsupported tie is usually not a problem.
Tie girder can transfer deck load to intact hanger.
Nair 41

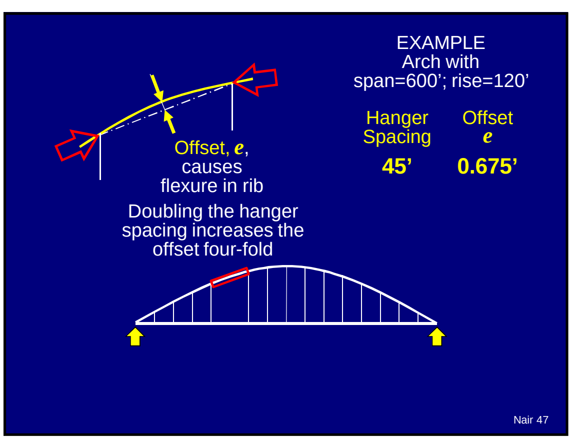

Consider the effect of loss of one hanger…
Unsupported rib can be a problem
Unsupported tie is usually not a problem.
Tie girder can transfer deck load to intact hanger.
Nair 42

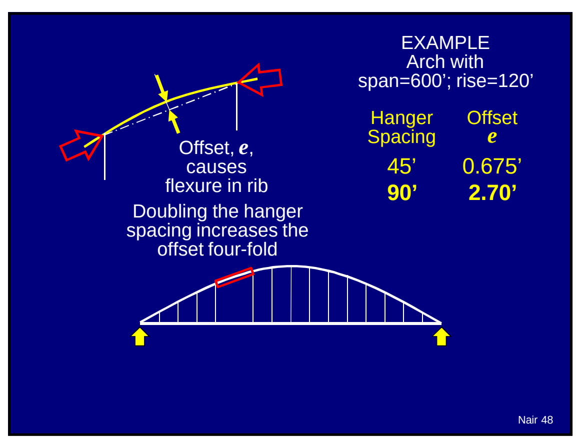

Arch rib is curved
Thrust line is straight between hangers
Consider the effect of loss of one hanger…
Nair 43

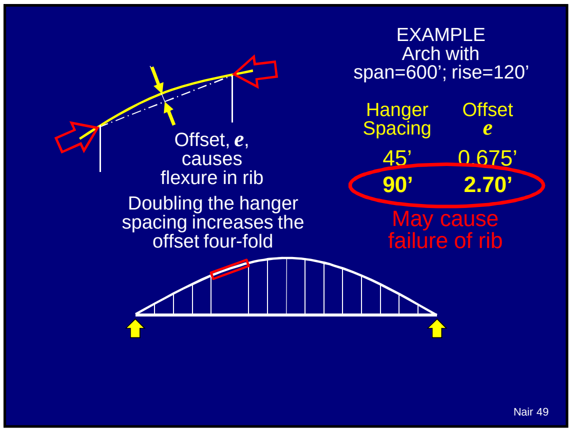

Offset, e, causes flexure in rib
Consider the effect of loss of one hanger…
Nair 44

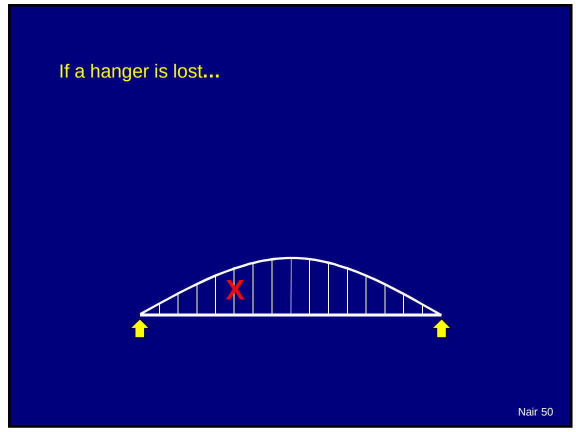

Offset, e, causes flexure in rib
Doubling the hanger spacing increases the offset four-fold
Consider the effect of loss of one hanger…
Nair 45

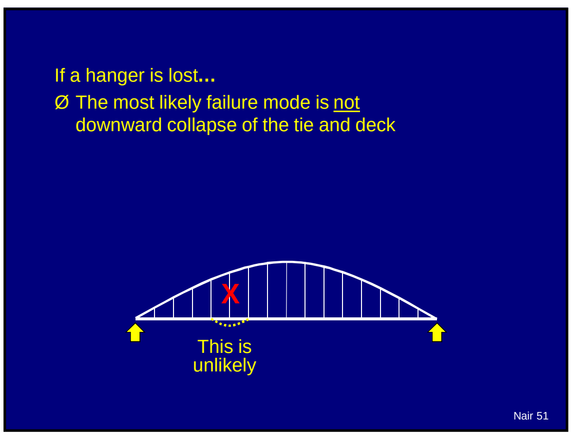

EXAMPLE
Arch with span=600'; rise=120'
Offset, e, causes flexure in rib
Doubling the hanger spacing increases the offset four-fold
Nair 46

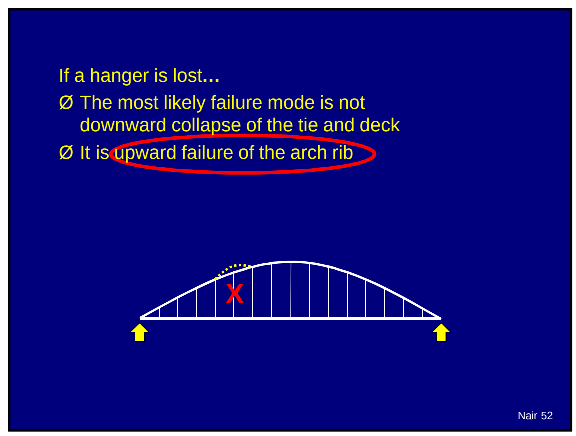

EXAMPLE
Arch with span=600'; rise=120'
Hanger Spacing
Offset e
45'
0.675'
Offset, e, causes flexure in rib
Doubling the hanger spacing increases the offset four-fold
Nair 47

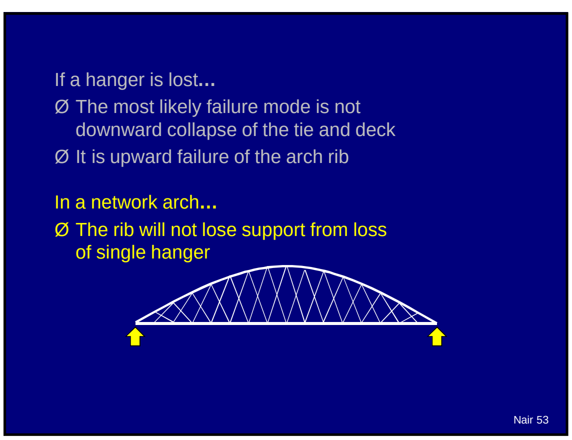

EXAMPLE
Arch with span=600'; rise=120'
Hanger Spacing
Offset e
45'
0.675'
90'
2.70'
Offset, e, causes flexure in rib
Doubling the hanger spacing increases the offset four-fold
Nair 48

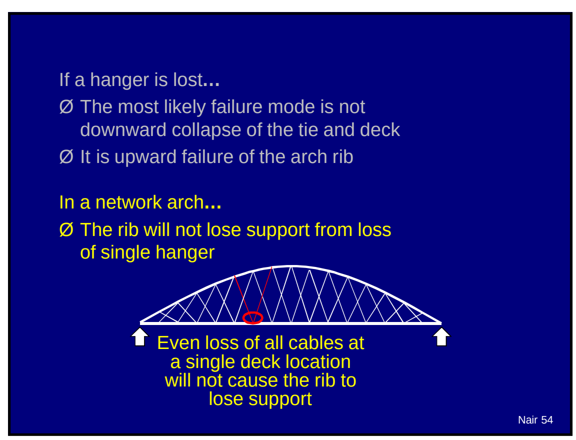

EXAMPLE
Arch with
span=600'; rise=120'
Offset, e, causes flexure in rib
Doubling the hanger spacing increases the offset four-fold
Hanger Spacing
Offset e
45'
0.675'
90'
2.70'
May cause failure of rib
Nair 49

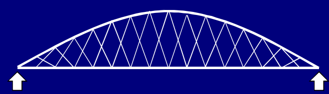

If a hanger is lost…
X
Nair 50


If a hanger is lost…
Ø The most likely failure mode is not downward collapse of the tie and deck
X
This is unlikely
Nair 51

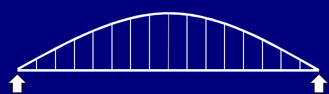

If a hanger is lost…
Ø The most likely failure mode is not downward collapse of the tie and deck
Ø It is upward failure of the arch rib
X
Nair 52


If a hanger is lost…
Ø The most likely failure mode is not downward collapse of the tie and deck
Ø It is upward failure of the arch rib
In a network arch…
Ø The rib will not lose support from loss of single hanger
Nair 53

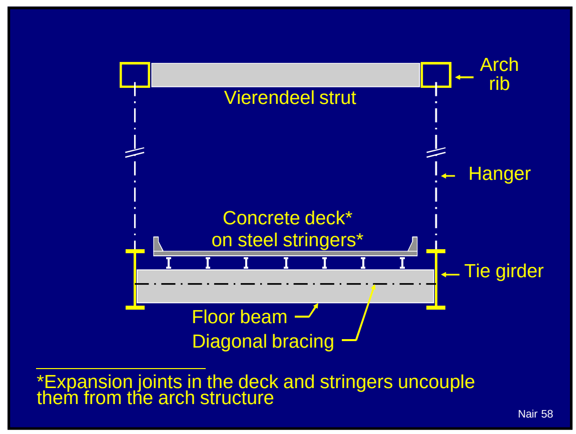

If a hanger is lost…
Ø The most likely failure mode is not downward collapse of the tie and deck
Ø It is upward failure of the arch rib
In a network arch…
Ø The rib will not lose support from loss of single hanger
Even loss of all cables at a single deck location will not cause the rib to lose support
Nair 54

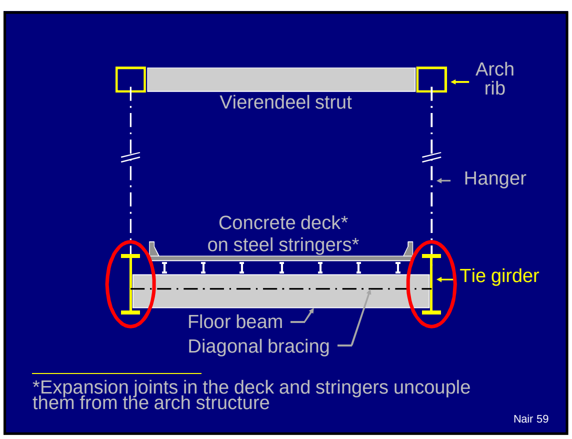


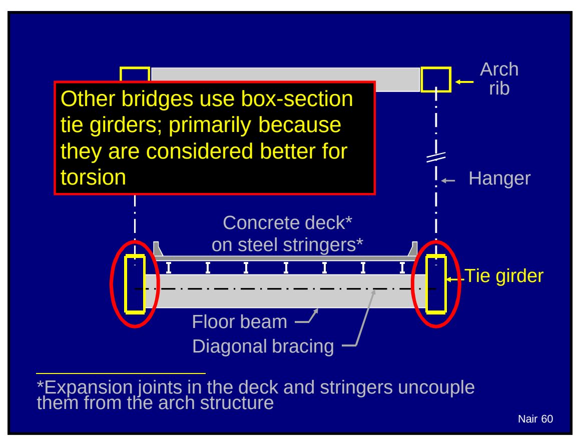
There are genuine benefits to the network arch concept, but vertical hangers remain the default solution

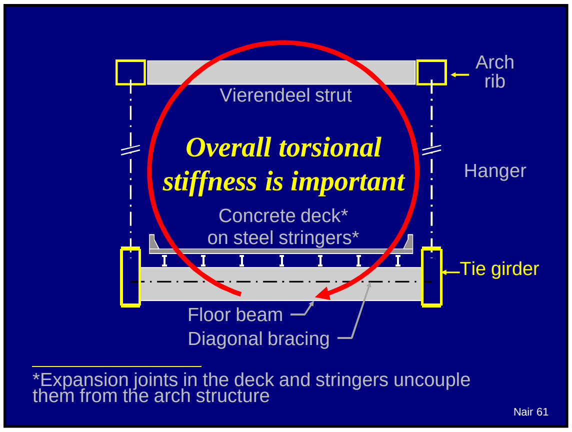


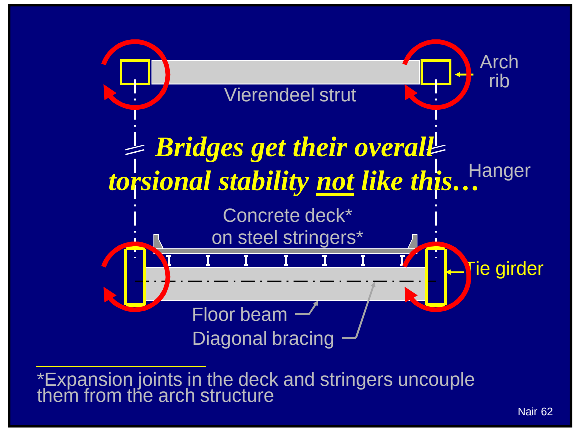
Now let's focus on two real bridges…

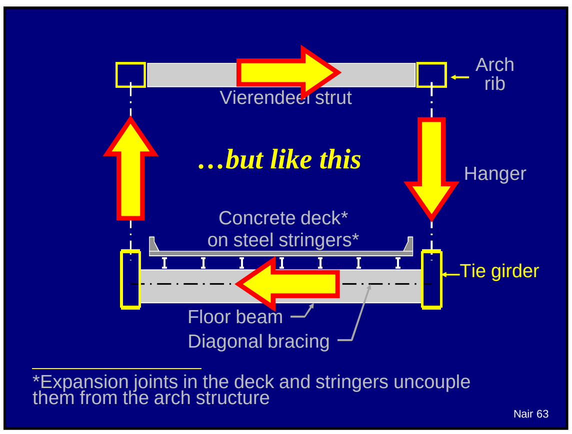


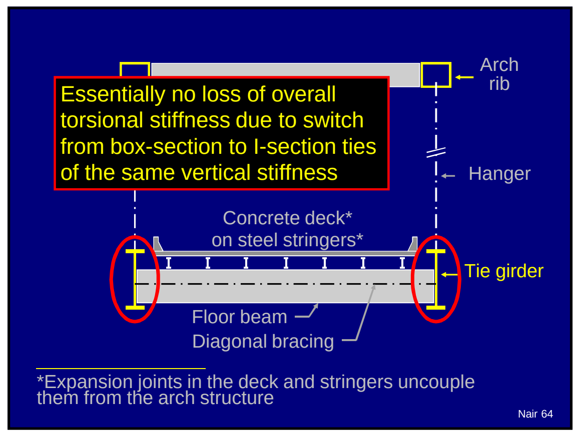


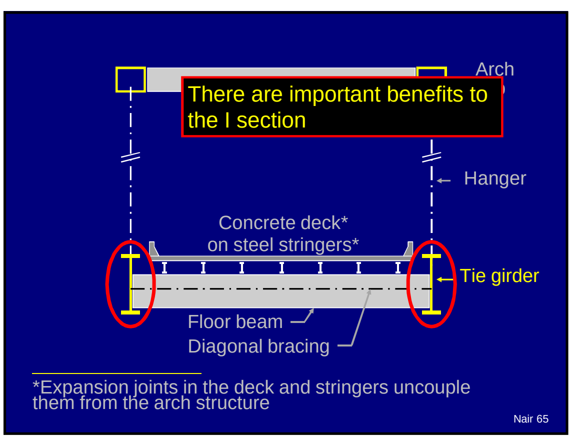


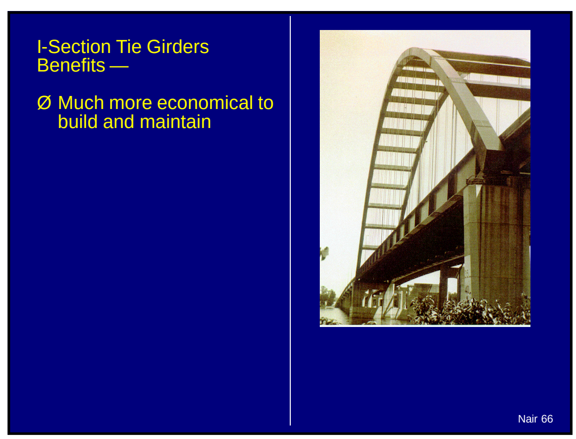

Arch
rib
Vierendeel strut
Overall torsional
stiffness is important
Hanger
Concrete deck*
on steel stringers*
Tie girder
Floor beam
Diagonal bracing
*Expansion joints in the deck and stringers uncouple them from the arch structure
Nair 61


Arch
rib
Vierendeel strut
Bridges get their overall
torsional stability not like this…
Hanger
Concrete deck*
on steel stringers*
Tie girder
Floor beam
Diagonal bracing
*Expansion joints in the deck and stringers uncouple them from the arch structure
Nair 62


Arch
rib
Vierendeel strut
…but like this
Hanger
Concrete deck*
on steel stringers*
Tie girder
Floor beam
Diagonal bracing
*Expansion joints in the deck and stringers uncouple them from the arch structure
Nair 63

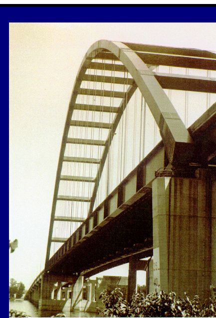

Arch
rib
Essentially no loss of overall torsional stiffness due to switch from box-section to I-section ties of the same vertical stiffness
Hanger
Concrete deck*
on steel stringers*
Tie girder
Floor beam
Diagonal bracing
*Expansion joints in the deck and stringers uncouple them from the arch structure
Nair 64


Arch
There are important benefits to the I section
Hanger
Concrete deck*
on steel stringers*
Tie girder
Floor beam
Diagonal bracing
*Expansion joints in the deck and stringers uncouple them from the arch structure
Nair 65


I-Section Tie Girders
Benefits —
Ø Much more economical to build and maintain
Nair 66

I-Section Tie Girders Benefits —

- Much more economical to build and maintain
  - Slightly less steel
  - Much lower fabrication cost
  - Simpler connections
  - Much easier inspection



I-Section Tie Girders Benefits —

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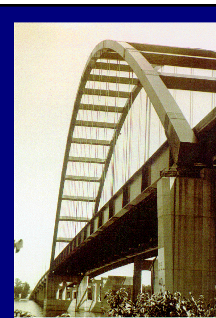
- Avoids secondary stress issues at floor beam connections



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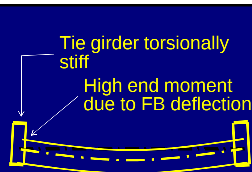

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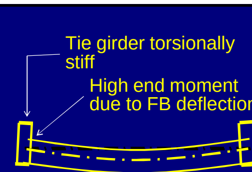
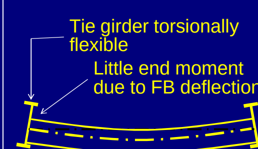
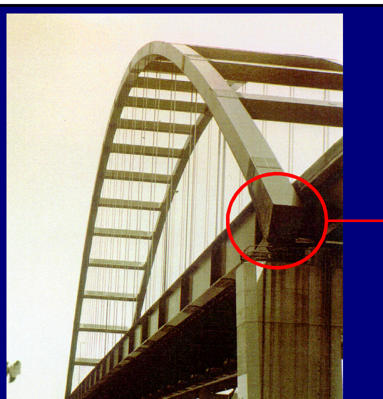
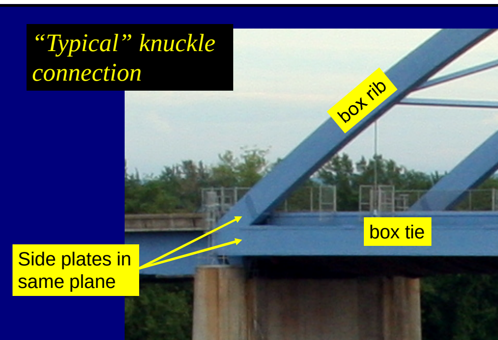


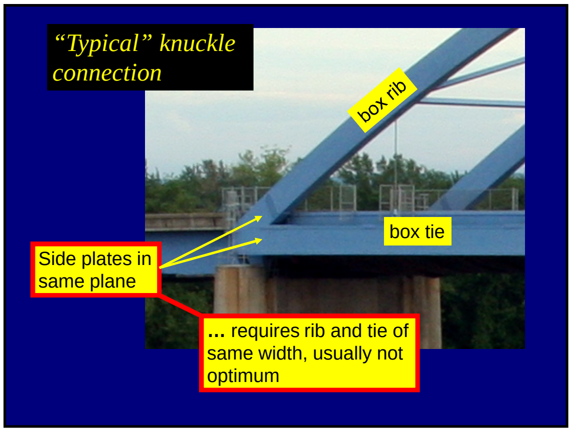


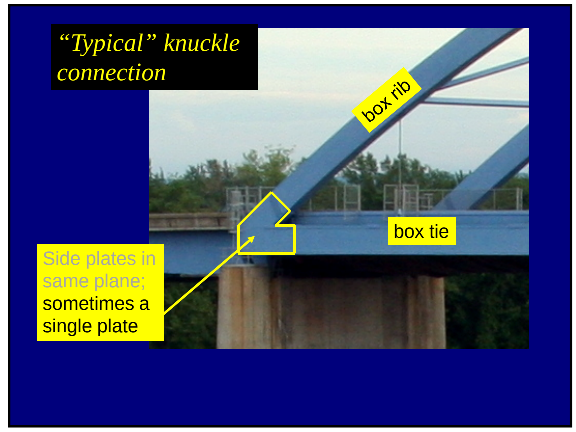


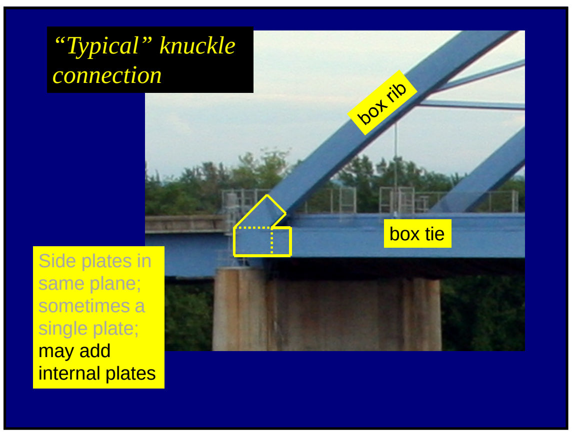
Rib-Tie “Knuckle”

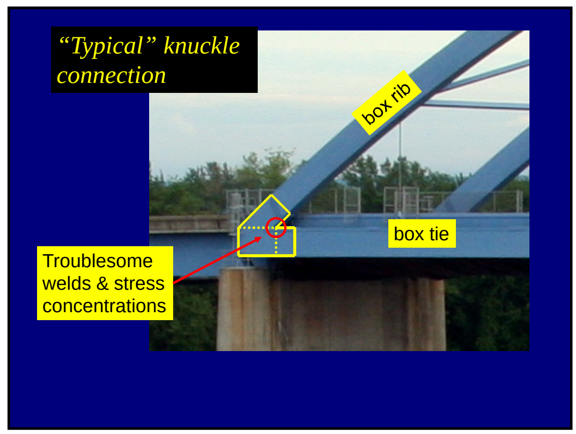
“Typical” knuckle connection

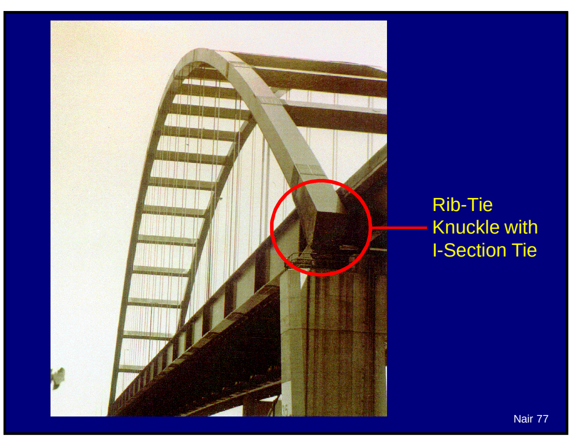


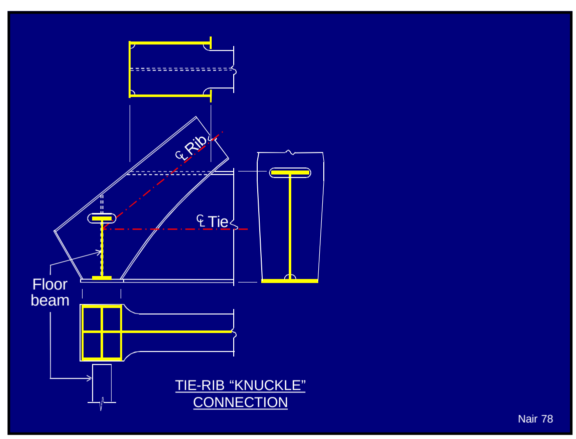

"Typical" knuckle connection
box rib
box tie
Side plates in same plane
… requires rib and tie of same width, usually not optimum

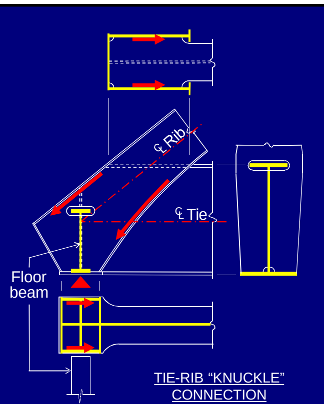

"Typical" knuckle connection
box rib
box tie
Side plates in same plane; sometimes a single plate


"Typical" knuckle connection
box rib
box tie
Side plates in same plane; sometimes a single plate; may add internal plates


"Typical" knuckle connection
box rib
box tie
Troublesome welds & stress concentrations

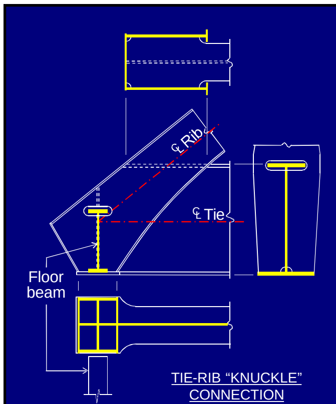

Rib-Tie Knuckle with I-Section Tie
Nair 77


℄ Rib
℄ Tie
Floor beam
TIE-RIB "KNUCKLE" CONNECTION
Nair 78

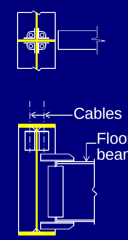


TIE-RIB "KNUCKLE" CONNECTION

All forces between rib and tie are transferred by in-plane loading of plates through fillet welds



TIE-RIB "KNUCKLE" CONNECTION



TYPICAL FLOOR BEAM AND HANGER CONNECTIONS TO TIE

Stability Design of Tied-Arch Bridges —

Textbooks and AASHTO stated at the time (1980) that tied arches were not susceptible to in-plane instability.

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The reason given was that 2nd-order effects in the rib and tie counteracted each other.

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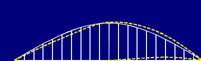

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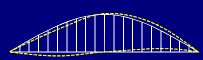

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The disturbing effect of rib displacement is balanced by the restoring effect of tie displacement.

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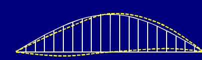

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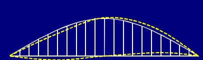

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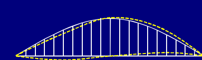

?

And therefore, in-plane instability is not an issue.

Disproved in two papers:

- "Buckling and Vibration of Arches and Tied Arches" by R.S. Nair, *Journal of Structural Engineering*, ASCE, June 1986
- "Practical Application of Energy Methods to Stability Problems" by R.S. Nair, *Engineering Journal*, AISC, 4^{th} Qtr. 1997

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Lateral stability of the arch ribs was recognized as an issue, but 2^{nd}-order analysis to account for it was considered to be beyond the level of technology available to bridge engineers.

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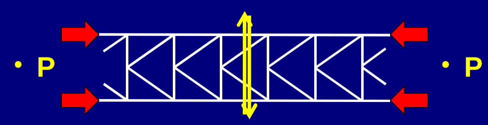
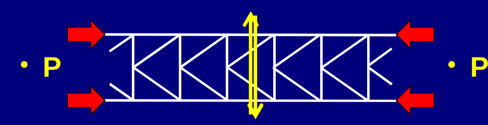
The "two-percent rule" was often used for the design of bridge bracing, including bracing between arch ribs.

The "two-percent rule" —



Design for shear of 2% of • P across every panel of bracing

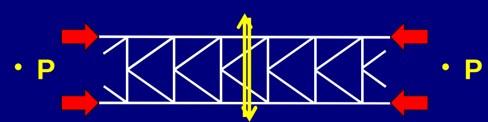
The "two-percent rule" —



Design for shear of 2% of • P across every panel of bracing

This is broadly similar to the "relative bracing" (2010) or "panel bracing" (2016) provisions of AISC 360

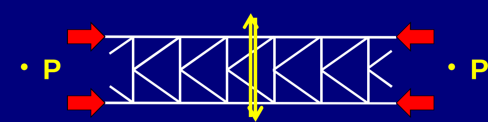
The "two-percent rule" —



Design for shear of 2% of • P across every panel of bracing

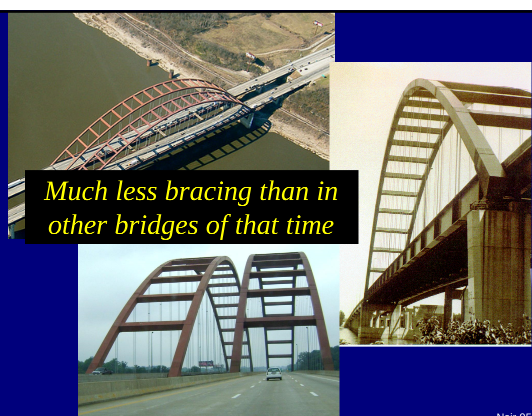
This approach was not used for the JB Bridge

The "two-percent rule" —

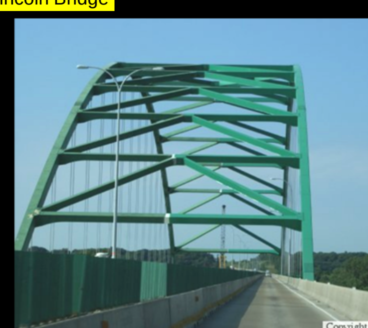


Design for shear of 2% of • P across every panel of bracing

Instead, used 2nd-order analysis and a primitive form of today's Direct Analysis Method



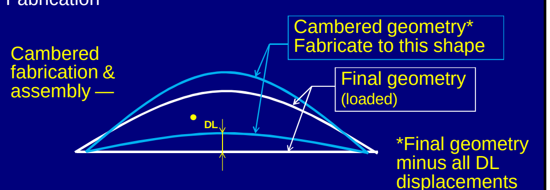
Abraham Lincoln Bridge



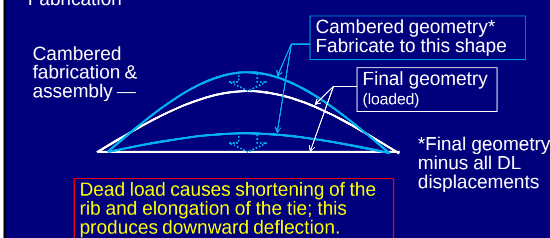
FABRICATION

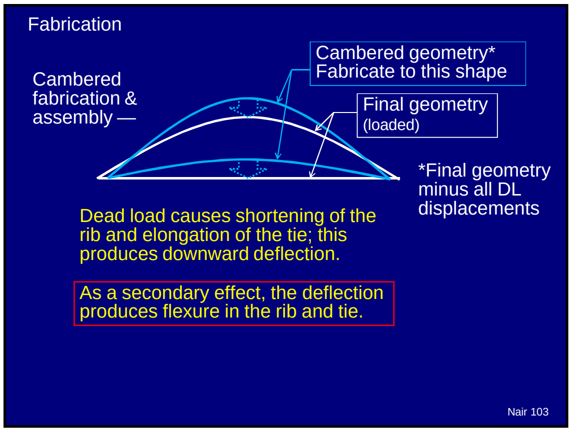
A special technique was used to reduce flexure in the ribs and ties

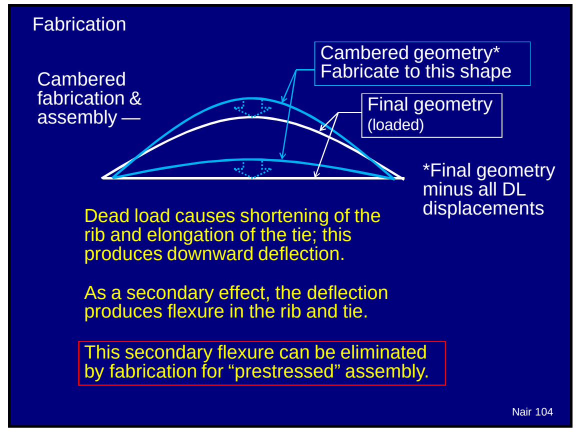
Fabrication

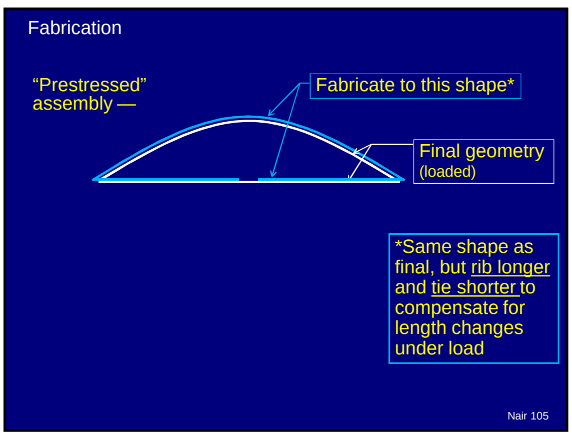


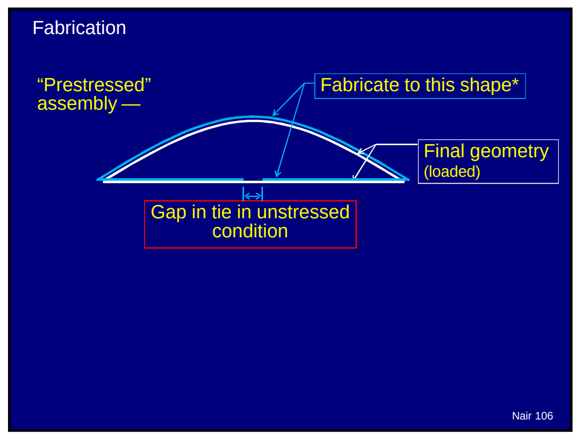
Fabrication

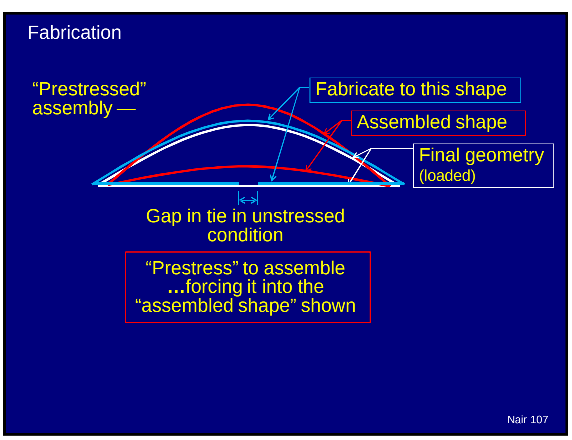


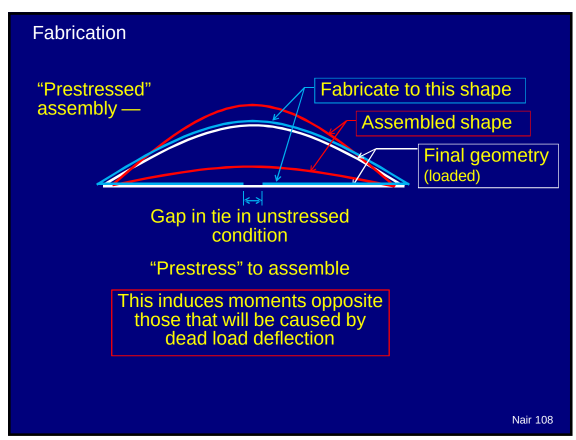

Fabrication
Cambered fabrication & assembly —
Cambered geometry* Fabricate to this shape
Final geometry (loaded)
*Final geometry minus all DL displacements
Dead load causes shortening of the rib and elongation of the tie; this produces downward deflection.
As a secondary effect, the deflection produces flexure in the rib and tie.
Nair 103


Fabrication
Cambered fabrication & assembly —
Cambered geometry* Fabricate to this shape
Final geometry (loaded)
*Final geometry minus all DL displacements
Dead load causes shortening of the rib and elongation of the tie; this produces downward deflection.
As a secondary effect, the deflection produces flexure in the rib and tie.
This secondary flexure can be eliminated by fabrication for “prestressed” assembly.
Nair 104

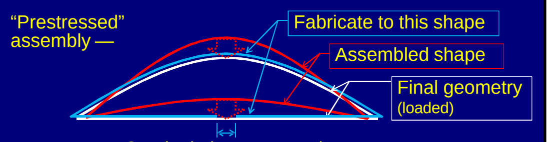

Fabrication
“Prestressed” assembly —
Fabricate to this shape*
Final geometry (loaded)
*Same shape as final, but rib longer and tie shorter to compensate for length changes under load
Nair 105


Fabrication
“Prestressed” assembly —
Fabricate to this shape*
Final geometry (loaded)
Gap in tie in unstressed condition
Nair 106


Fabrication
“Prestressed” assembly —
Fabricate to this shape
Assembled shape
Final geometry (loaded)
Gap in tie in unstressed condition
“Prestress” to assemble …forcing it into the “assembled shape” shown
Nair 107


Fabrication
“Prestressed” assembly —
Fabricate to this shape
Assembled shape
Final geometry (loaded)
Gap in tie in unstressed condition
“Prestress” to assemble
This induces moments opposite those that will be caused by dead load deflection
Nair 108

Fabrication

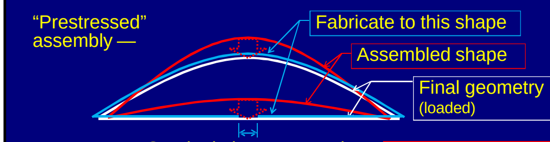


"Prestress" to assemble

This induces moments opposite those that will be caused by dead load deflection

DL deflection relieves those induced moments

Fabrication



"Prestress" to assemble

This induces moments opposite those that will be caused by dead load deflection

DL deflection relieves those induced moments

This procedure, the fabrication dimensions and the forces at each stage were indicated in the drawings

The innovations discussed…
- Ø I-section tie girders
- Ø Simple rib-tie knuckle connection
- Ø DAM for economy and to reduce bracing
- Ø Fabrication for prestressed erection

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- Ø I-section tie girders
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Are all incorporated and refined in the design of
- Ø IL-104 Bridge over Illinois River in Meredosia
  - … now in late stages of construction

The innovations discussed…
- Ø I-section tie girders
- Ø Simple rib-tie knuckle connection
- Ø DAM for economy and to reduce bracing
- Ø Fabrication for prestressed erection

Are all incorporated and refined in the design of
- Ø IL-104 Bridge over Illinois River in Meredosia
  - … now in late stages of construction

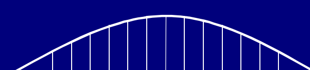
Modern DAM allowed fewer struts that in JB Bridge; no struts at hanger locations

IL-104 Bridge on 8/22/2017

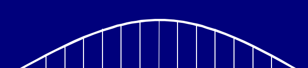
IL-104 Bridge on 8/22/2017

Most recent large tied-arch bridges have used tie girders as the main stiffening elements

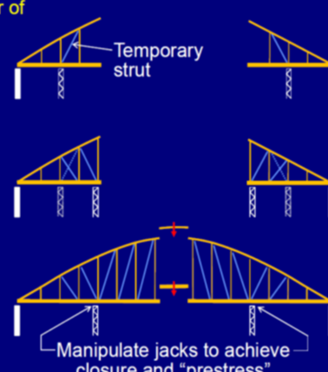
Ribs just stiff enough to resist buckling



The stiff tie approach was adopted at Jefferson Barracks partly to ease construction…

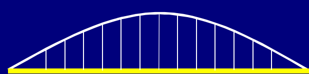


Erection — Keeping center of channel open



The stiff tie approach was adopted at Jefferson Barracks partly to ease construction…

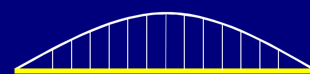
Same stiff tie approach was adopted for IL-104 at Meredosia



The stiff tie approach was adopted at Jefferson Barracks partly to ease construction…

Same stiff tie approach was adopted for IL-104 at Meredosia

But IL-104 was erected from above using erection towers

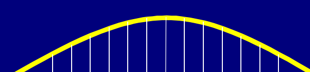


The stiff tie approach was adopted at Jefferson Barracks partly to ease construction…

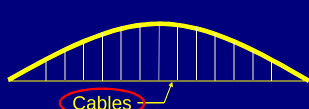
Same stiff tie approach was used for Beardstown (US-67) and Meredosia (IL-104)

But IL-104 was erected from above using erection towers

… which would have permitted a big-rib, small-tie design

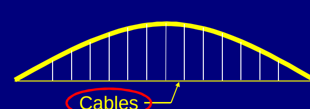


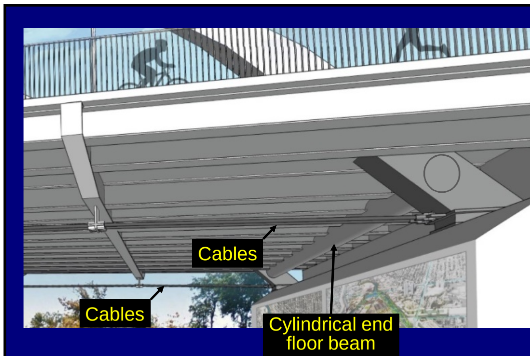
The ultimate big-rib, small-tie design is a cable tie

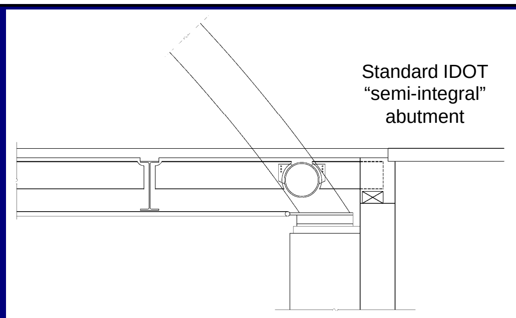


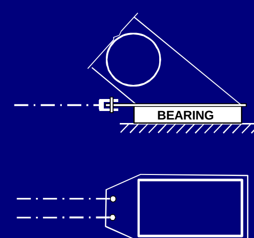
The ultimate big-rib, small-tie design is a cable tie

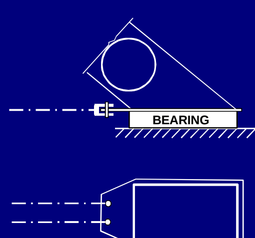
… as in EXP's proposal for Division Street











Simple, economical, redundant,
not fracture-critical

exp.

Questions?

Questions?

shankar.nair@exp.com