Rigid frame bridges

"Rigid frames are simplified arch bridges"
Christian Menn

"The art of building is an art; it is not and will never be a science"
Eugene Freyssinet

HISTORY OF FRAME BRIDGES
History and examples

- Abutment and piers design
  Perronet (1708–1794)
  The force path shows a high introduction of horizontal force
  \[ \rightarrow \text{Frame mode of operation} \]

- Transfer of horizontal forces
  Möllers (1840–1935)
  Use of earth loaded friction plate to transfer the horizontal force in the Abutment

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History and examples

- Risorgiment bridge Rom (IT), Hennebique (1911)

Photo: Lalupa, http://deu.archinform.net
History and examples

- Salginatobel bridge (CH), Maillard (1930)

- Arch section is adapted to the repartition of bending moments

- Simme bridge Garstatt (CH), Maillard (1940)
History and examples

- Marne bridges (FR), Freyssinet (1950)

Source: Association Freyssinet

OPERATING MODES AND ADVANTAGES
Operating mode

- Deck bridge
  - The superstructure is embedded in the column

- Two hinged frame bridge
  - Activation of the horizontal thrust → the corners discharge the field

Operating mode

- Horizontal thrust
  - The lower the frame, the higher the horizontal thrust

Remark: forces shown in the sketches are no vectors...

\[ H = \frac{3}{8} \cdot \frac{F \cdot l}{h \cdot (2 \cdot \frac{c}{2} \cdot h + 3)} \]
Operating mode

- Smaller deformations
- Redundant behavior
- Supports vertical and horizontal loads
- Reaction of constraints

Advantages

1. Frame corner attract the bending moment
   → greater slenderness
   → avoid piers
   → smaller construction costs

Tender design: 2 span girder

Erection of the middle pier
→ restriction of traffic

Executed design: frame bridge

Source:
SSF Ingenieure AG
Advantages

2. No joint and no bearings → smaller maintenance costs

“The only good joint is no joint”
Henry Derthick,
Tennessee Department of Transportation

Source: SSF Ingenieure AG

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Advantages

3. Reduction of buckling length

Allows slender structure and more design liberty

Photo: Unstruttalbrücke
By Marc Wenner

Photo: Pfle transmitter bridge
By Wolfgang Pehlemann

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STATICAL SYSTEMS

Isostatic frames

- System:

- Example:

Source: Association Eugène Freyssinet
Two hinged rigid-frame bridges

- System:

- Variations:

Two hinged rigid-frame bridges

- Examples:

Photo: Bridge Fernando Espinosa by Jorge M. Treviño
Two hinged rigid-frame bridges

- Examples:

Source: Structurae
Altonaer Straße Railroad Overpass

Source: photos.planete-tp-plus.com
Bridge over the Marne in Luzancy, Freyssinet, 1946
Restrained rigid-frame bridges

- System:

- Variations:

Hinges

- Hinges are rarely constructed as articulated bearings

- Most of the cases, the hinge is reached through the slender design of the piers

Source: TU Dresden

Photo: Viaduc de Martigues by Nicolas Janberg, Structurae
USUAL MATERIALS AND DIMENSIONS

Cross sections

<table>
<thead>
<tr>
<th>Cross section</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deck slab</td>
<td></td>
</tr>
<tr>
<td>T-beam</td>
<td>Reinforced concrete</td>
</tr>
<tr>
<td>Box girder</td>
<td>Prestressed concrete</td>
</tr>
<tr>
<td>Double webbed T-beam</td>
<td></td>
</tr>
<tr>
<td>Multiple webbed T-beam</td>
<td>Composite structure</td>
</tr>
</tbody>
</table>

Source:
Rahmentragwerke im Brückenbau; Braun et al., Beton- und Stahlbetonbau Vol. 101, No. 3
### Materials and usual slenderness

#### ROAD BRIDGES

<table>
<thead>
<tr>
<th>Material</th>
<th>Span</th>
<th>Slope “Corner”</th>
<th>Slope “Field”</th>
<th>Parallel girder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinforced concrete</td>
<td>&lt; 20m</td>
<td>12-18</td>
<td>20-25</td>
<td>18-21</td>
</tr>
<tr>
<td>Prestressed concrete</td>
<td>&gt; 20 m</td>
<td>15-19</td>
<td>24-30</td>
<td>20-25</td>
</tr>
<tr>
<td>Composite structure</td>
<td>&gt; 30 m</td>
<td>15-19</td>
<td>24-30</td>
<td>21-25</td>
</tr>
</tbody>
</table>

#### RAILWAY BRIDGES

<table>
<thead>
<tr>
<th>Material</th>
<th>Span</th>
<th>Slope “Corner”</th>
<th>Slope “Field”</th>
<th>Parallel girder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinforced concrete</td>
<td>&lt; 20m</td>
<td>10-15</td>
<td>20-25</td>
<td>16-18</td>
</tr>
<tr>
<td>Prestressed concrete</td>
<td>not usual (necessity of full prestressed section)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composite structure</td>
<td>&gt; 20 m</td>
<td>15-18</td>
<td>25-30</td>
<td>18-21</td>
</tr>
</tbody>
</table>

Source: Rahmentragwerke im Brückenbau; Braun et al., Beton- und Stahlbetonbau Vol. 101, No. 3

### SOIL-BRIDGE INTERACTION

![Image of soil-bridge interaction](Picture: Lemnitzer et al.; Lateral Performance of Full-Scale Bridge Abutment Wall with Granular Backfill. Journal of geotechnical and geoenvironmental engineering, Vol. 135, No. 4)
Problem statement

- Abutment is part of the structure

![Diagram of Abutment and Foundation Interaction]

Foundation – Deep foundation

2 concepts:
- High vertical resistance and low bending stiffness → simple corner construction
- High vertical resistance and high bending stiffness → slender structure

Source:
Design Guide INTAB
Foundation – flat footing

By good soil conditions

Design criteria:
1. Hold admissible soil pressure under foundation
2. Hold friction resistance (with additional safety)
3. Hold the resulting axial force in the kern

Modeling interaction foundation – soil

Deep foundation

Flat footing

Sources:
(top) Vorgespannte integrale Brücken – Erfahrungen aus der Praxis, Fuchs, Danzl et al.; 2007
(bottom) Design Guide INTAB

Source:
Mahlo et al.; Bauingenieur Vol. 83, No. 11
Interaction structure – backfill

- For spans until 50m → Frame columns are directly back-filled

- Interaction due to abutment movements has to be considered

\[ s_{h, \text{max}, T N} = \alpha_{\text{eff}} \cdot \Delta T_{N} \cdot \text{pos} \cdot L_{\text{eff}} \]

Source:
Besonderheiten bei Entwurf und Bemessung integraler Betonbrücken, Berger et al. Beton- und Stahlbetonbau vol. 99, No. 4

Damages due to inadmissible deformations

"Blow-ups" – Cracks

Source:
Integral and semi-integral bridges, Martin P Burke Jr; Wiley Blackwell (2009)
Consideration of the interaction in the calculation

- Soil behind abutment represented by a loading

<table>
<thead>
<tr>
<th>ACTIVE</th>
<th>REST</th>
<th>Mobilized PASSIVE</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="Q1.png" alt="Diagram" /></td>
<td><img src="Q2.png" alt="Diagram" /></td>
<td><img src="Q3.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>

- Load case "min earth pressure"
- Load case "rest"
- Load case "max earth pressure"

- Load case combined with load case -ΔT (winter situation)
- Permanent load case
- Load case combined with load case +ΔT (summer situation)

Source:
Design Guide INTAB
Economic and Durable Design of Composite Bridges with Integral Abutments

Univ.-Prof. Dr.-Ing. Steffen Marx

Structural solutions

<table>
<thead>
<tr>
<th>Span</th>
<th>Transition</th>
<th>Photo</th>
</tr>
</thead>
<tbody>
<tr>
<td>L &lt; 30 m</td>
<td><img src="Q4.png" alt="Diagram" /></td>
<td><img src="Q5.png" alt="Photo" /></td>
</tr>
<tr>
<td>30 &lt; L &lt; 50 m</td>
<td><img src="Q6.png" alt="Diagram" /></td>
<td><img src="Q7.png" alt="Photo" /></td>
</tr>
<tr>
<td>50 &lt; L &lt; 90 m</td>
<td><img src="Q8.png" alt="Diagram" /></td>
<td><img src="Q9.png" alt="Photo" /></td>
</tr>
</tbody>
</table>

Source:
Besonderheiten bei Entwurf und Bemessung integraler Betonbrücken, Berger et.al. Beton- und Stahlbetonbau vol. 99, No. 4
Approach slab

- 1st Way: distribute differential deformations over entire length

- 2nd Way: realize a joint: example Airport Frankfurt am Main

Recommendations in construction phase

- In the calculation, the abutments are part of the structure → abutments are often not self-supporting

  1. The structural engineer must provide instructions for the placing sequence of the backfill

  2. The stability of the abutment while stripping
HOW TO CONTROL THE DISTRIBUTION OF INTERNAL FORCES?

Design criteria

- The slenderness in bridge middle is in the most crossing situations a limiting criteria in design

- Regulating the stiffness of frame corner → greater slenderness can be obtained:
Parameters to control the distribution of internal forces

1. Stiffness and length relation betw. superstructure and abutment

2. Abutment as framework

---

**Changes**

<table>
<thead>
<tr>
<th></th>
<th>Reference</th>
<th>h=10.5m</th>
<th>h=5.0m</th>
<th>h=2.5...1.0 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\text{corner}}$ [kNm]</td>
<td>-16.160</td>
<td>-15.945</td>
<td>-16.675</td>
<td>-21.095</td>
</tr>
<tr>
<td>$M_{\text{field}}$ [kNm]</td>
<td>9.151</td>
<td>9.370</td>
<td>8.637</td>
<td>4.218</td>
</tr>
<tr>
<td>$\Delta M_{\text{field}}$</td>
<td>+2.4 %</td>
<td>-5.6 %</td>
<td>-53.9 %</td>
<td></td>
</tr>
</tbody>
</table>

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**Slender columns**

→ High fixing moment + allows superstructure contraction (useful by prestressing)
Parameters to control the distribution of internal forces

3. Structure on "tiptoes"

Release of the field + minimize horizontal thrust

![Diagram showing forces](image)

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Parameters to control the distribution of internal forces

4. Use the righting bending moment of the backfill

Examples: Mosel bridge in Metz (FR)
Risölfjärd bridge in Rom (IT)

Useful by low rigid-frame bridges

The high horizontal thrust can't be properly taken through the dam

Source: Jiri Straski, www.shp.eu
Parameters to control the distribution of internal forces

4. Use the righting bending moment of the backfill

4. Use of jacks

- Activate the passive earth pressure (especially by poor conditions)
- Compensate elastic and plastic contraction of superstructure (due to P, C, S, especially by low rigid-frame bridges)
- Control the bending moment in the field

Examples:
- Rosenstein bridge Stuttgart, 1952 (DE)
- Marne bridges, Freyssinet, 1946 (FR)

No usual method!
Why does it make sense to prestress rigid-frames?

- Rigid frames → Aim = relieve field to get higher slenderness
- Long spans → Hold serviceability
**Effect of prestressing on the frame**

<table>
<thead>
<tr>
<th>Load case</th>
<th>Deformation and supporting reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead loads</td>
<td></td>
</tr>
<tr>
<td>Prestressing</td>
<td>deviation forces, horizontal forces</td>
</tr>
<tr>
<td>Traffic load</td>
<td></td>
</tr>
<tr>
<td>Dead loads + Prestressing</td>
<td></td>
</tr>
<tr>
<td>Dead loads + Prestressing + Traffic loads</td>
<td></td>
</tr>
</tbody>
</table>

Prestressing → horizontal supporting reaction due to dead loads decrease

Source: Spannbeton für die Praxis, Fritz Leonhardt

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**Tendon layout in the frame corner**

**Long spans or stiff columns**

**Flexible columns**

By flexible columns:
- Negative bending moments ↓
- Favorable prestressing effect
- Axial force in columns

→ Prestressing of columns and superstructure
- High biaxial stress state
- Complex tendon geometry

→ Prestressing of columns not necessary
→ Reinforcement
Tendon layout in the superstructure

- Continuous tendons over the entire length → get a full compressed cross section in the field
- The deviation forces should be affine to the dead load

Tendon layout – Example
Calculate internal forces

- On isostatic systems
  \[ M_p = M_{p,\text{dir}} = -P \cdot e \]
  \[ N_p = N_{p,\text{dir}} = -P \]

- On hyperstatic systems: \( \rightarrow \) deviation forces method

The tendon is replaced by its statical effect:

1. Anchor forces
2. Deviation forces
   \[ M_p = M_{p,\text{dir}} + M_{p,\text{ind}} \]
   \[ N_p = N_{p,\text{dir}} + N_{p,\text{ind}} \]
3. Friction forces
4. Support reactions

Deviation forces method

1. Statical effect

2. Calculation of anchor and deviation forces

3. Calculation of support reactions (software)

4. Calculation of internal forces

5. Calculation of isostatic and hyperstatic internal forces
   \[ M_{p,\text{ind}} = M_p - M_{p,\text{dir}} \]
   \[ N_{p,\text{ind}} = N_p - N_{p,\text{dir}} \]
   primary prestressing forces
   secondary prestressing forces
Influence of frame stiffness by prestressing

- Stiff columns

Prestressing force is completely introduced into the abutments → Prestressing is useless

Only the deviation forces are effective

The stiffer the column, the lower the degree of efficiency

Source: Bemessung im konstruktiven Betonbau, Zilch, Zehetmaier, Springer Verlag

Solution if the loss is to important: allow the elastic (P) and plastic (c+s) superstructure contraction.

1. Design slender columns
   (but result also in a greater field bending moment)
2. Decouple column and abutment wings while prestressing
3. Design column as framework
4. Horizontal movable hinge
   (not usual)

Source: Spannbeton für die Praxis, Fritz Leonhardt
Influence of horizontal "settlements"

- Rigid-frame bridges produces important horizontal forces
- Due to settlements, horizontal forces decrease → redistribution of internal forces (like shrinkage)
- Frames with framework columns or structure "on tiptoes" are less sensitive to settlements

Influence of time-delayed concrete deformations

- Material: Creep and shrinkage (+relaxation)
- Structure: Time-delayed deformations
- Effects: Influence on hyperstatical reactions → redistribution of forces
- Influence on $N_{p,ind}$ and $M_{p,ind}$
- Decrease of prestressing force
- Influence on $N_p$ and $M_p$
Influence on hyperstatical reactions

Creep: hyperstatical reactions appears irrespective from elasticity modulus

→ No hyperstatical reaction forces due to pretensioning or dead loads are created

Conditions:
→ support conditions remain unchanged
→ creep law is the same over the structure

Remark:
→ the effect of sudden deformations is nearly completely eliminated by concrete creeping
Influence on hyperstatical reactions

**Shrinkage:** Shrinkage = continuously deformation

If shrinkage contraction is restrained
→ hyperstatical reaction forces \((N_S, M_S, V_S)\)

\(N_S, M_S, V_S\) are continuously reduced by concrete creeping

Decrease of pretensioning force

Deformation and contraction of the structure
→ the tendon strain decreases
→ the pretensioning force decrease

\[
\Delta P_{c+e}(t) = A_p \cdot \left( e_{cs} \cdot E_p + 0.8 \cdot \Delta \sigma_p + \frac{E_p}{E_{cm}} \varphi(t, t_0) \cdot \sigma_{e,dp} \right) \\
1 + \frac{E_p}{E_{cm}} \frac{A_p}{A_e} \left( 1 + \frac{A}{I_e} \cdot z_{cp} \cdot z_{sp} \right) \left[ 1 + 0.8 \cdot \varphi(t, t_0) \right] \\
\text{(EN 1992-1-1)}
\]

\[
\widetilde{z}_{cp} = \frac{M_{p,dc} + M_{p,ind}}{P}
\]

Takes the effect of hyperstatical reactions into account
Calculation of the necessary prestressing force

Geometry
- Internal forces due to external load cases
- Tendon layout
- Internal forces due to prestressing
- Influence of time-delayed effects

Aim:
- By $t = \infty$
- In the frame field
- Under dead loads + prestressing forces
- $\rightarrow$ Axial compression state

$\sigma_{t, \infty} \cdot (G + P)$

Design and construction of the frame corners

- Negative bending moment

Truss model:

Structural solution:

"Backpack" $\rightarrow$ easier construction

Source: SSF Ingenieure AG
Design and construction of the frame corners

- Positive bending moment

Truss model:

Comparison of solution:

Source:
Konstruieren im Stahlbetonbau, Schlaich, Schäfer, Betonkalender 1993, Teil II, Ernst & Sohn

Accomplished example 1

Foot bridges for the city Augsburg
Source:
SSF Ingeniure AG
Accomplished example 1

Foot bridges for the city Augsburg
Source: SSF Ingenieure AG
Accomplished example 1

Foot bridges for the city Augsburg
Source: SSS Ingenieure AG

Foot bridges for the city Augsburg
Source: SSS Ingenieure AG
Accomplished example 2

Seitenhafenbrücke in Wien
Source:
Die Seitenhafenbrücke in Wien, Kral et al. Beton- und Stahlbetonbau Vol. 107 No. 3

Accomplished example 2

Seitenhafenbrücke in Wien
Source:
Die Seitenhafenbrücke in Wien, Kral et al. Beton- und Stahlbetonbau Vol. 107 No. 3
THANK YOU FOR YOUR ATTENTION