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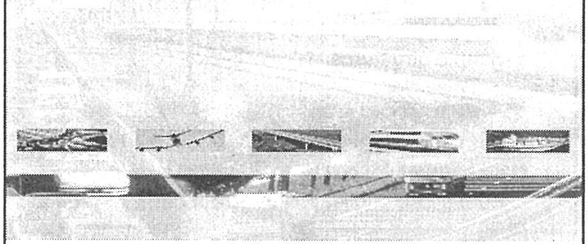
French two-girder composite bridges

Joël Raoul



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Summary

- 1. Market
- 2. Types of bridge
- 3. Materials
- 4. Calculations
- 5. Execution
- 6. Recent developments
- 7. Future developments

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French market

- Variable : 30 000 t to 40 000 t in average (but Millau bridge >30 000t)
- Type of road bridge (steel and composite)

	1996	1997	1998
composite twin girder	27	35	22
composite multiple girder	1	2	1
composite box girder	4	2	3

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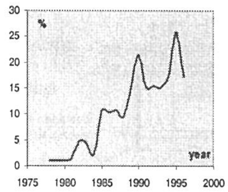
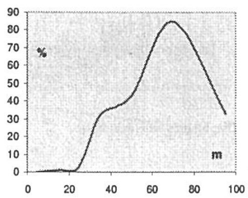
French market (road bridges)



Change in the market share of composite bridges as a percentage of total deck surface constructed



Market share of composite bridges depending on main span

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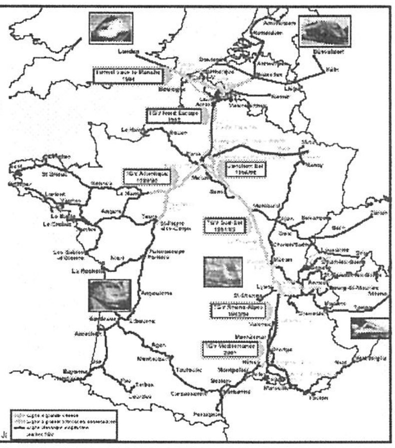
Rail bridges (high speed train : TGV)



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Rail bridges (high speed train : TGV)

- TGV south (up to Lyon) and west : no steel bridge
- TGV north : 13000 t (3600 m)
- TGV south of Lyon : 42000 t (9500 m)
- TGV east (in progress) : all the large bridges are composite 26000 t (5790 m)

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TGV east (in progress) : 13 two-girder bridges

type	Total length	Nb of spans	Max span	Total weight
2-girder	75	2	42	527
2-girder	415	8	53	1416
2-girder	452	8	60	1963
2-girder	100	3	40	300
2-girder	370	9	45	1105
2-girder	111	3	45	286
2-girder	86	3	34	227
2-girder	87	3	35	232

type	Total length	Nb of spans	Maximal span	Total weight
2-girder	602	12	52	2100
2-girder	309	11	41	1000
2-girder	90	3	35	235
2-girder	**1510**	**27**	**75**	**5500**
2-girder	92	5	22	300
2-lateral	163	5	42	1130
2-lateral	90	2	45	935
2-lateral	98	2	49	1039
2-lateral	287	6	63	1770
4-girder	191	3	**82**	1600
4-girder	181	4	52	1100
2-box section	478	8	74	3500

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How to improve competitiveness

- Fair tender with 2 solutions (composite and concrete)
- Simple structures
  - Two-girder
  - Reinforced concrete slab
- Simple calculations
- Userfriendly softwares
- Education, publication of guidance….

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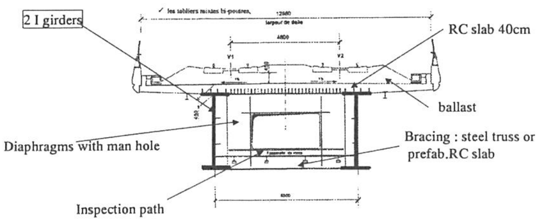
rail bridges : main features



	Span (m)	slenderness
Usual values	30 à 60	1/14ème
limits	80	1/18ème

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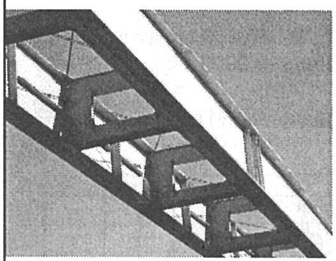
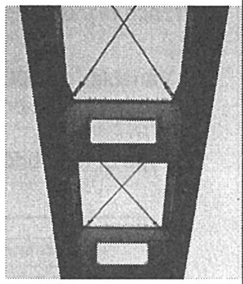
Two-girder railway bridge





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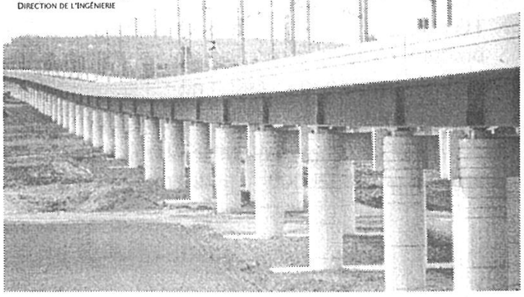
Haute-Colme (TGV north)

SNCF
DIRECTION DE L'INGÉNIERIE



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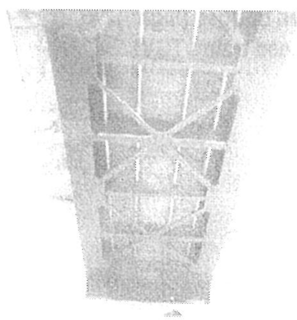
- Bracing : steel truss supporting an inspection path



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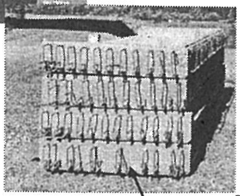

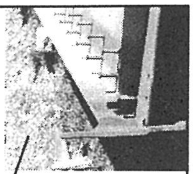

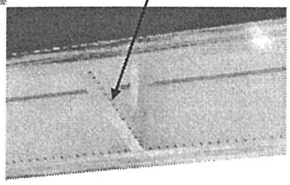

- Bracing : prefabricated RC slab supporting an inspection path

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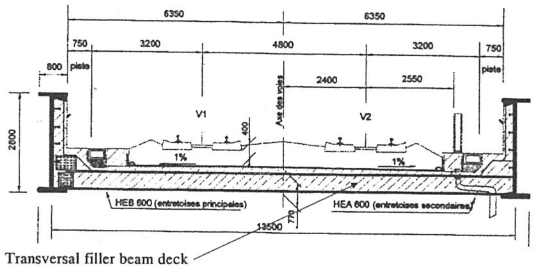
Rail bridges : two lateral girders



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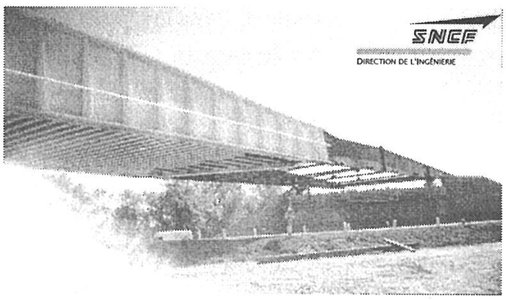
Rail bridges : two lateral girders



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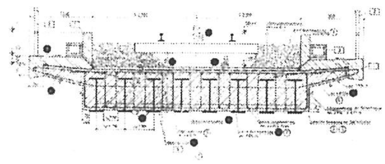
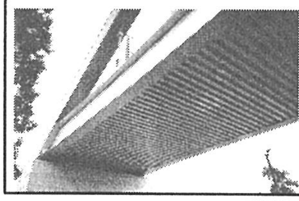
Rail bridges : filler beam decks

- longitudinal





- transversal

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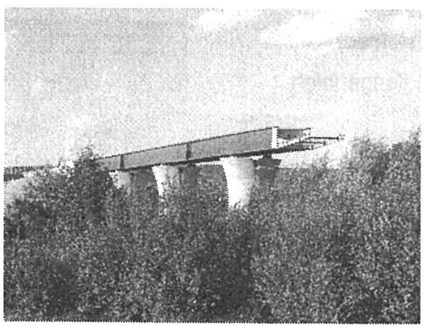
Twin girder rail bridges : launching



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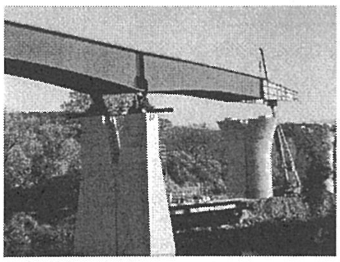
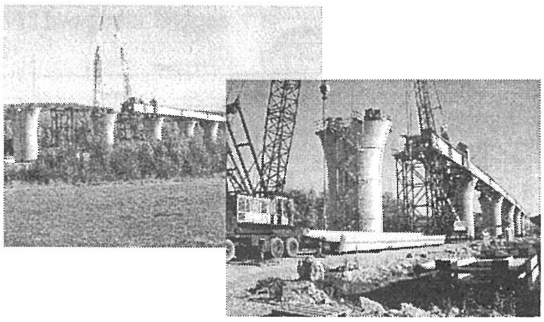
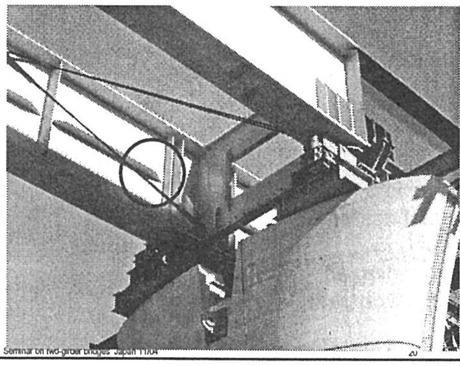
Twin girder rail bridges : launching nose



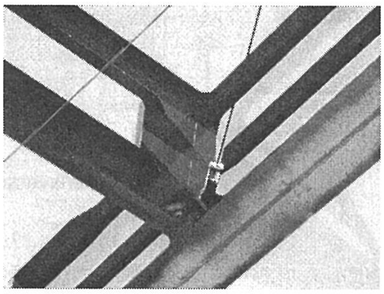
Twin girder rail bridges : erection using two cranes



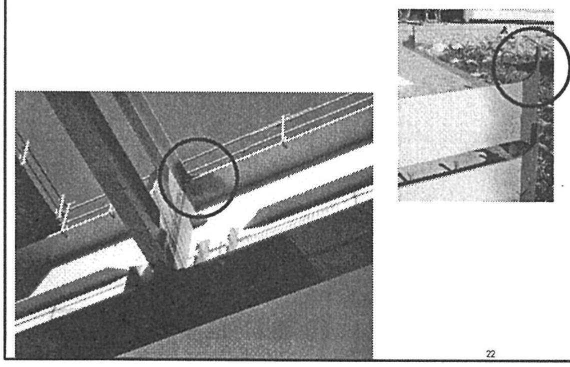
Twin girder rail bridges : launching rollers , stiffeners on support, discontinuous longitudinal stiffeners



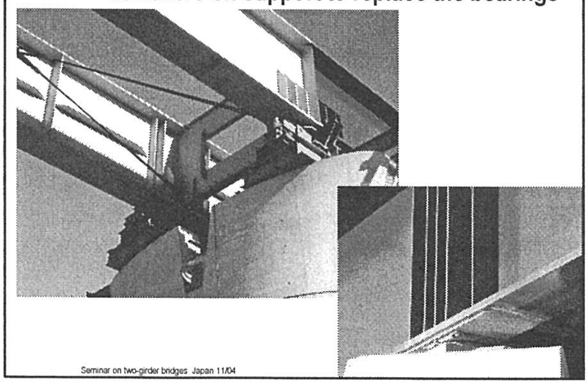
Twin girder rail bridges : detail of stiffened man hole, gussets, provisional bracing



Twin girder rail bridges : welding of diaphragms

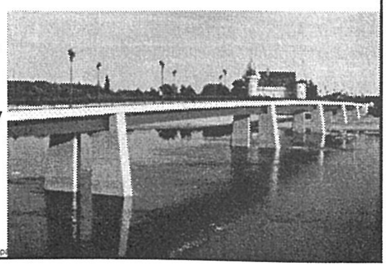


Twin girder rail bridges : secondary vertical stiffeners on support to replace the bearings



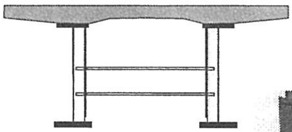
Road bridges : main features

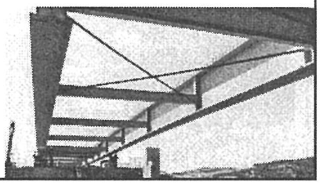
- Simple design (entirely welded)
- Unique flange (high quality steels)
- Limit state simple calculations
- Execution (quality plan)
- Aesthetic
- Reliability



Two main types of cross-sections

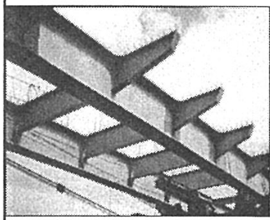
- Cross girders not connected

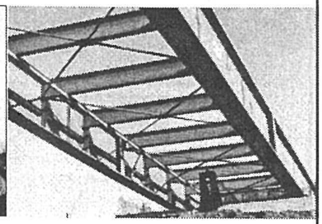




Two main types of cross-sections

- Cross girders connected
  - With or without overhanging parts

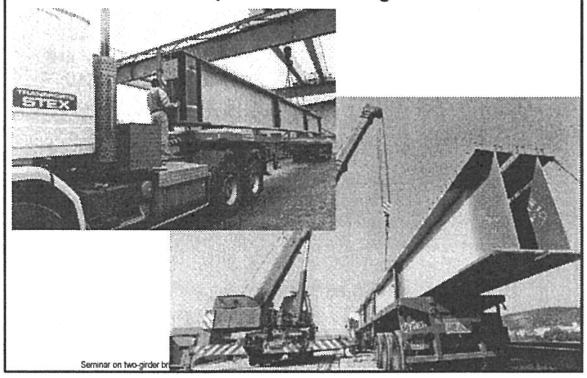




Twin girder road bridges

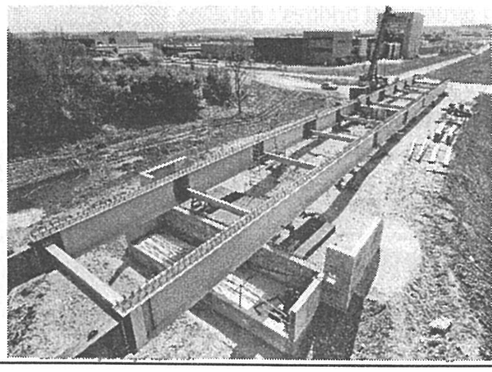
- Fabrication of large segments
- Transport
- Erection (launching)
- Casting of concrete
- Controls

Twin girder road bridges : transport of large prefabricated segments



Twin girder road bridges : control before welding of segments

Twin girder road bridges : welding of segments before launching



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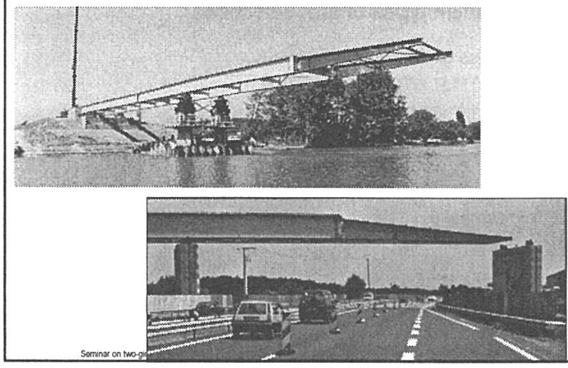
Twin girder road bridges : erection by launching



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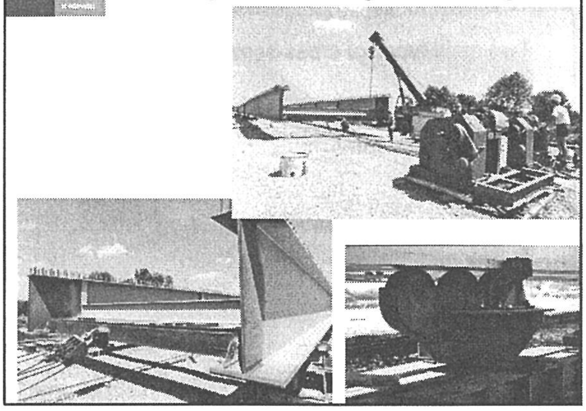
Twin girder road bridges : launching



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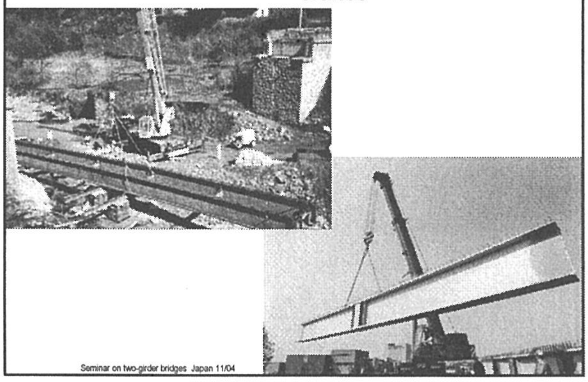
Twin girder road bridges : erection using cranes



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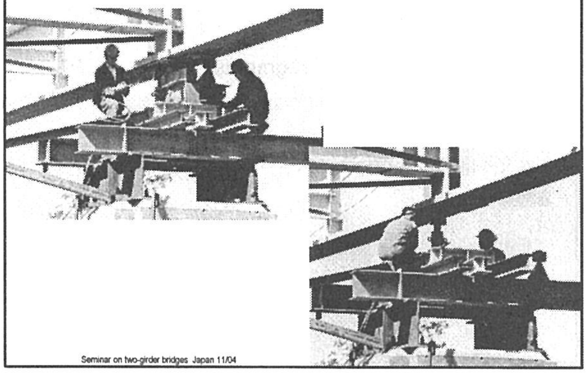
Twin girder road bridges : jacking down on supports



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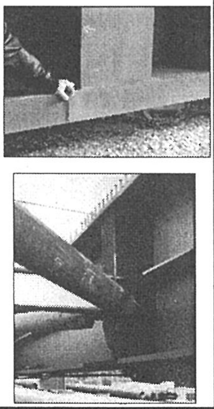
Twin girder road bridges : detailing

- Unique thick flange (150mm)
- T-type stiffeners flange not welded to the lower flange
- Entirely welded
- Discontinuous long. Stiffeners
- Provisional bracing



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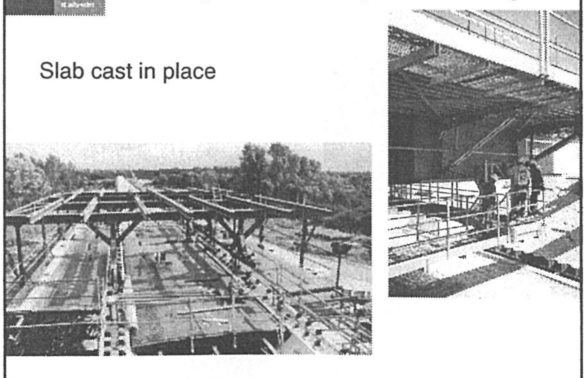
Twin girder road bridges : concreting

Slab cast in place



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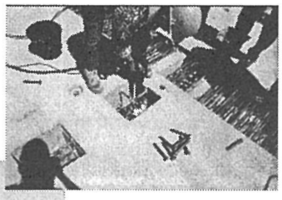
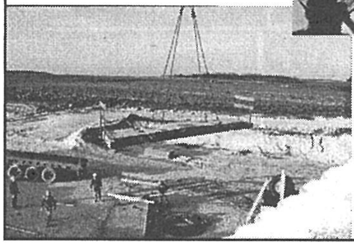
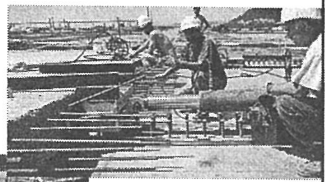
Twin girder road bridges : concreting

Prefabricated elements

Twin girder road bridges : concreting

Launched slab




Twin girder road bridges : controls



Materials

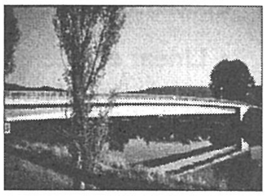
1. Unique thick flanges (EN1993-1-10)
   - **S355K2**
     for t ≤ 30mm (40J at -20° C)
   - **S355N** (or S355M)
     for t ≤ 80mm (40J at -20° C)
   - **S355NL** (or S355ML)
     for **150** ≥ t ≥ 80 (27J at -50° C)

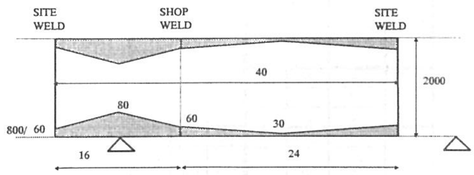
2. Longitudinally profiled plates

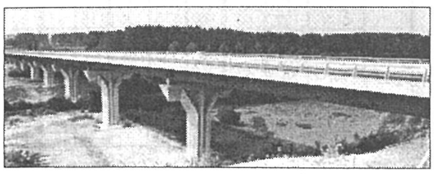
3. Thermomechanical steels
   - Plates
     S460M (≤120 mm) as weldable as S355N
   - Rolled sections
     S460M (QST) h≈1000mm

Longitudinally profiled plates

type	maximum variation in thickness (in mm)	maximum slope (in mm per metre)
	55	8
	55	8
	55	8

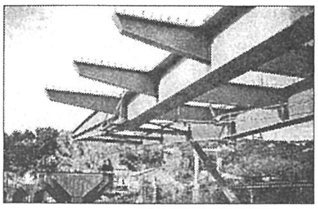




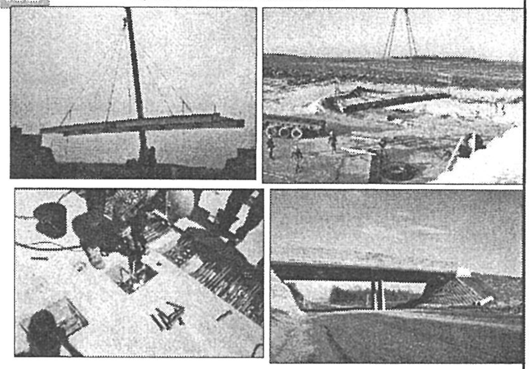


Thermomechanical steels

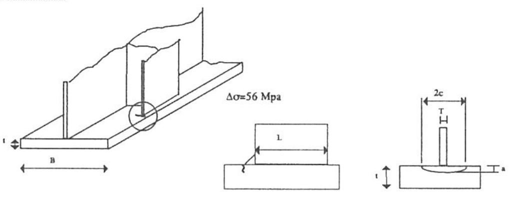
- Weldability
- S460M has the same CEV as S355N
- Better toughness
- Savings (preheating…)



Q.S.T. rolled sections



Toughness requirement to EN 1993-1-10



Initial defect $a/c=0.4$ et $a_0 = 0.5 \ln t$ (si t=80mm a_0=2.2mm $2c_0$=11mm)

Damage $D_{max}=1$

Paris law : $da/dN = C\,\Delta K^m$ with m=3 and C=1.83 10^{-13}

$\Delta K = \Delta\sigma\,(\pi a_c)^{0.5}\,Y\,M_k$ with $Y=f(a,c,B,t)$ and $M_k=f(T,L,B,\theta,a,t)$

Final critical defect given by : $K_I=K_{IC}$

Toughness requirement to EN 1993-1-10

Nuance	Qualité	Energie Charpy K_V at T [°C]	J_{min}	Temperature de référence T_{Ed} [°C]																				
				σ_{Ed} = 0,75 $f_y(t)$							σ_{Ed} = 0.50 $f_y(t)$							σ_{Ed} = 0.25 $f_y(t)$						
				10	0	-10	-20	-30	-40	-50	10	0	-10	-20	-30	-40	-50	10	0	-10	-20	-30	-40	-50
S235	JR	20	27	60	50	40	35	30	25	20	90	75	65	55	45	40	35	135	115	100	85	75	65	60
	J0	0	27	90	75	60	50	40	35	30	125	105	90	75	65	55	45	175	155	135	115	100	85	75
	J2	-20	27	125	105	90	75	60	50	40	170	145	125	105	90	75	65	200	200	175	155	135	115	100
S275	JR	20	27	55	45	35	30	25	20	15	80	70	55	50	40	35	30	125	110	95	80	70	60	55
	J0	0	27	75	65	55	45	35	30	25	115	95	80	70	55	50	40	165	145	125	110	95	80	70
	J2	-20	27	110	95	75	65	55	45	35	155	130	115	95	80	70	55	200	190	165	145	125	110	95
	M,N	-20	40	135	110	95	75	65	55	45	180	155	130	115	95	80	70	200	200	190	165	145	125	110
	ML,NL	-50	27	185	160	135	110	95	75	65	200	200	180	155	130	115	95	230	200	200	200	190	165	145
S355	JR	20	27	40	35	25	20	15	15	10	65	55	45	40	30	25	25	110	95	80	70	60	55	45
	J0	0	27	60	50	40	35	25	20	15	95	80	65	55	45	40	30	150	130	110	95	80	70	60
	J2	-20	27	90	75	60	50	40	35	25	135	110	95	80	65	55	45	200	175	150	130	110	95	80
	K2,M,N	-20	40	110	90	75	60	50	40	35	155	135	110	95	80	65	55	200	200	175	150	130	110	95
	ML,NL	-50	27	155	130	110	90	75	60	50	200	180	155	135	110	95	80	210	200	200	200	175	150	130
S420	M,N	-20	40	95	80	65	55	45	35	30	140	120	100	85	70	60	50	200	185	160	140	120	100	85
	ML,NL	-50	27	135	115	95	80	65	55	45	190	165	140	120	100	85	70	200	200	200	185	160	140	120
S460	Q	-20	30	70	60	50	40	30	25	20	110	95	75	65	55	45	35	175	155	130	115	95	80	70
	M,N	-20	40	90	70	60	50	40	30	25	130	110	95	75	65	55	45	200	175	155	130	115	95	80
	QL	-40	30	105	90	70	60	50	40	30	155	130	110	95	75	65	55	200	200	175	155	130	115	95
	ML,NL	-50	27	125	105	90	70	60	50	40	180	155	130	110	95	75	65	200	200	200	175	155	130	115
	QL1	-60	30	150	125	105	90	70	60	50	200	180	155	130	110	95	75	215	200	200	200	175	155	130
S690	Q	0	40	40	30	25	20	15	10	10	65	55	45	35	30	20	20	120	100	85	75	60	50	45
	Q	-20	30	50	40	30	25	20	15	10	80	65	55	45	35	30	20	140	120	100	85	75	60	50
	QL	-20	40	60	50	40	30	25	20	15	95	80	65	55	45	35	30	165	140	120	100	85	75	60
	QL	-40	30	75	60	50	40	30	25	20	115	95	80	65	55	45	35	190	165	140	120	100	85	75
	QL1	-40	40	90	75	60	50	40	30	25	135	115	95	80	65	55	45	200	190	165	140	120	100	85
	QL1	-60	30	110	90	75	60	50	40	30	160	135	115	95	80	65	55	200	200	190	165	140	120	100

Toughness requirement to EN 1993-1-10

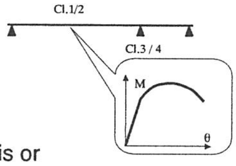
Nuance	Qualité	Energie Charpy K_V at T [°C]	J_{min}	Temperature de référence T_{Ed} [°C]						
				σ_{Ed} = 0.50 $f_y(t)$						
				10	0	-10	-20	-30	-40	-50
S235	JR	20	27	90	75	65	55	45	40	35
	J0	0	27	125	105	90	75	65	55	45
	J2	-20	27	170	145	125	105	90	75	65
S275	JR	20	27	80	70	55	50	40	35	30
	J0	0	27	115	95	80	70	55	50	40
	J2	-20	27	155	130	115	95	80	70	55
	M,N	-20	40	180	155	130	115	95	80	70
	ML,NL	-50	27	200	200	180	155	130	115	95
S355	JR	20	27	65	55	45	40	30	25	25
	J0	0	27	95	80	65	55	45	40	30
	J2	-20	27	135	110	95	80	65	55	45
	K2,M,N	-20	40	155	135	110	95	80	65	55
	ML,NL	-50	27	200	180	155	135	110	95	80

Structural analysis

- **Linear elastic analysis**
- *Non-linear global analysis (materials as in EC2-2 and EC3-2)*

Linear elastic analysis

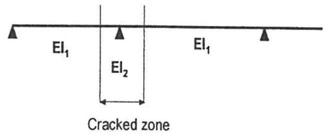
- Redistribution due to plastification at mid-span is neglected except if :
  - Class 1 or 2 at mid-span (if $M_{Ed} > M_{el,Rd}$)
  - Class 3 or 4 on support
  - $L_{min}/L_{max} < 0.6$



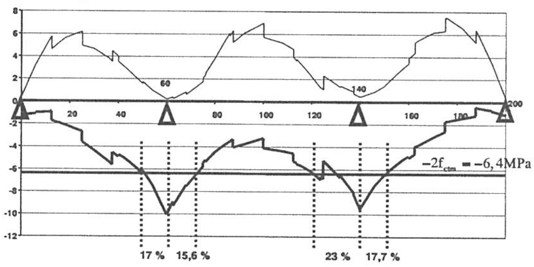
- Non-linear elastic analysis or
- Linear elastic analysis with $\mathbf{M_{Ed} < 0.9\ M_{pl,Rd}}$ in sagging moment regions

Linear elastic analysis

If under characteristic combination $2f_{ctm} \leq \sigma_c \Rightarrow$ cracked global analysis

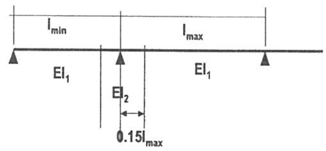


Example of cracked zones in a composite bridge 60-80-60



Linear elastic analysis

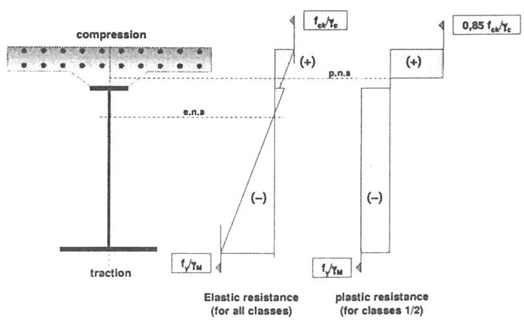
- Alternative if
  - No prestressing
  - $L_{min}/l_{max}>0.6$



Longitudinal shear

- uncracked global analysis
- Particular rules where $M_{el,Rd} < M_{Ed} < M_{pl,Rd}$

Cross-section verification at ULS (M>0)



Modular ratio

$$n_L = n_0 \cdot (1+\psi_L \phi_t)$$

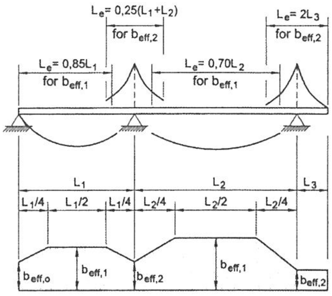
$n_0 = \frac{E_a}{E_{cm}}$ and $\phi_t = \phi(t-t_0)$ creep coefficient given by EC2 :

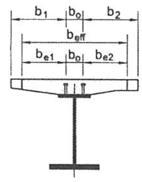
Value of t_0 :
- t_0 = 1 day for shrinkage
- t_0 = a mean value in case of concrete cast in several stages

ψ_L is given by :

Permanent loads	1,1
shrinkage	0,55
Imposed deformations	1,5

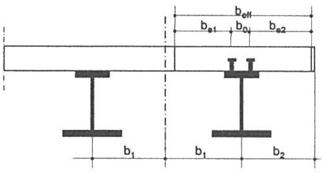
Equivalent spans for effective width



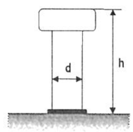


Effective width

$$b_{eff} = b_0 + \sum \beta_i b_{ei} \quad \text{with} \quad \begin{cases} b_{ei} = \min(\frac{L_e}{8}; b_i) \\ \beta_i = 0{,}55 + 0{,}025\frac{L_e}{b_{ei}} \le 1 \quad \text{end supports} \\ \beta_i = 1 \quad \text{elsewhere} \end{cases}$$



Studs

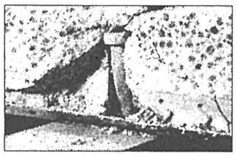


$$P_{Rk} = \min(P^1_{Rk}; P^2_{Rk})$$

$$P^1_{Rk} = 0{,}8\ f_u \pi \frac{d^2}{4} \quad \text{and} \quad P^2_{Rk} = 0{,}29 \alpha d^2 \sqrt{f_{ck} E_{cm}}$$

$$\alpha = 0{,}2.\left(\frac{h}{d}+1\right) \quad \text{if} \quad 3 \le \frac{h}{d} \le 4$$

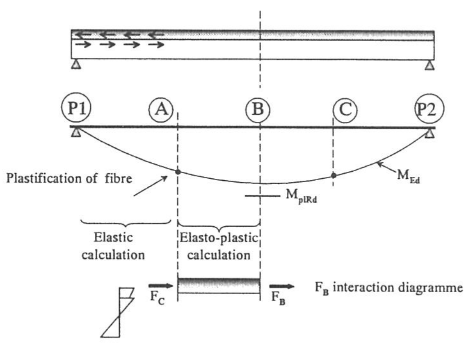
If not $\alpha = 1$



At S.L.S. $P_{Rd} = 0.6 P_{Rk}$

At U.L.S. $P_{Rd} = \frac{P_{Rk}}{1.25}$

Verification at ULS



Verification at SLS

- Limitation of stresses
  - Mainly f_y in the steel part
- Limitation of crack widths
  - In general 0.3 mm (tension stiffening is taken into account : simplified method available)
- Very restrictive requirements for rail bridges to insure :
  - Comfort of passengers
  - Contact wheel-rail

Simplified method

- Minimum reinforcement (to put in general in all the sections)

$$A_s.\sigma_s = k_s.k_c.k.f_{ct,eff}.A_{ct}$$

k_s=0.9 ; k=0.8 ; $f_{ct,eff}=f_{ctm}$; k_c depends on the stress distribution, in general k_c=1

σ_s may be given by a table to limit the crack width

Steel stress σ_s (N/mm²)	Maximum bar diameter ϕ^* (mm) for design crack width w_k		
	w_k=0.4mm	w_k=0.3mm	w_k=0.2mm
160	40	32	25
200	32	25	16
240	20	16	12
280	16	12	8
320	12	10	6

That leads to about 1% of reinforcement

Simplified method

- Control of cracking (in all the sections subjected to direct loading)
  - Maximum bar diameter
  - Or maximum spacing

depending on $\sigma_s = \sigma_{s,0} + \Delta\sigma_s$ with :

$$\Delta\sigma_s = \frac{0{,}4 f_{ctm}}{\alpha_{st}\rho_s}$$

For a medium span bridge $\sigma_s \cong$ 100 MPa

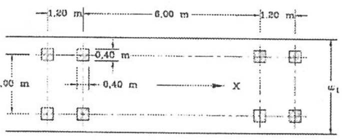
$$\alpha_{st} = \frac{A \cdot I}{A_a \cdot I_a}$$

Steel stress σ_s (N/mm²)	Maximum bar diameter ϕ^* (mm) for design crack width w_k		
	w_k=0.4mm	w_k=0.3mm	w_k=0.2mm
160	40	32	25
200	32	25	16
240	20	16	12
280	16	12	8
320	12	10	6

Steel stress σ_s (N/mm²)	Maximum bar spacing (mm) for design crack width w_k		
	w_k=0.4mm	w_k=0.3mm	w_k=0.2mm
160	300	300	200
200	300	250	150
240	250	200	100
280	200	150	50
320	150	100	-
360	100	50	-

Fatigue verification in EC3

- Calculation of $\Delta\sigma_{E,2}$ under a fatigue loading



P = 480kN

- Influence of the type of influence line
- Influence of the type of traffic
- Influence of the type of the number of lanes

Fatigue verification in EC3

partial factor for loading= 1,0

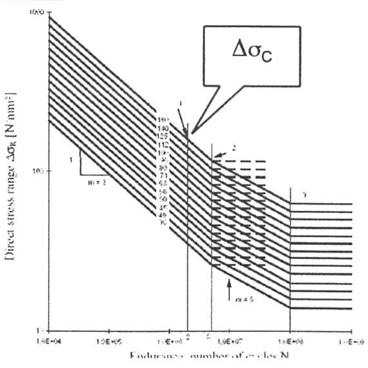
- verification

$$\frac{\gamma_{Ff}\ \Delta\sigma_{E.2}}{\Delta\sigma_C / \gamma_{Mf}} \le 1{,}0$$

Category of detail

Assessment method	Consequence of failure	
	Low consequence	High consequence
Damage tolerant	1,00	1,15
Safe life	1,15	1,35

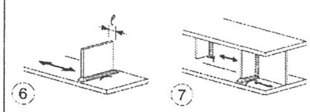
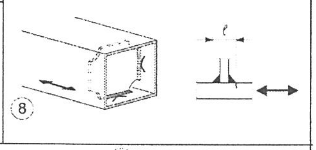
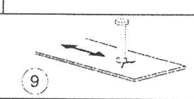
Fatigue curves in EC3



$$\frac{\gamma_{Ff}\ \Delta\sigma_{E.2}}{\Delta\sigma_C / \gamma_{Mf}} \le 1{,}0$$

1 Detail category $\Delta\sigma_C$
2 Constant amplitude fatigue limit $\Delta\sigma_D$
3 Cut-off limit $\Delta\sigma_L$

$\Delta\sigma_C$ for each detail

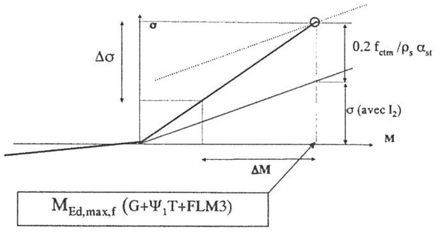
80	t≤50mm	
71	50<t≤80mm	
80		

Fatigue EC4

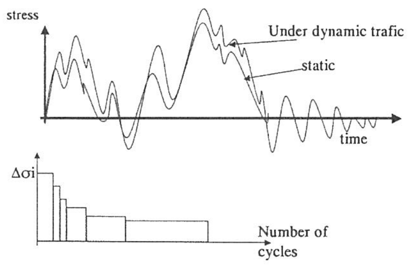
1- $\Delta\sigma$ is calculated using :

- I_2 where concrete is in tension
- I_1 where concrete is in compression

2- Tension stiffening is used only for reinforcement



Fatigue of rail bridges more complexe

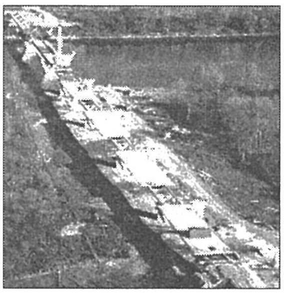


$D(v{=}0) = \Sigma ni/Ni = C\times\Sigma ni.(\Delta\sigma i)^m = D(v{=}0)\times(1+0{,}5\phi)^m$

SNCF DIRECTION DE L'INGÉNIERIE

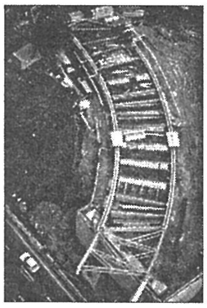
Execution

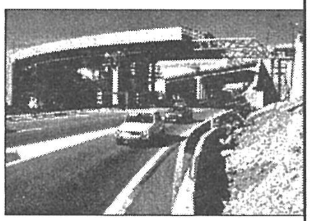
- Concrete to avoid early age and thermal shrinkage
- Concreting by segment
- Resistance and time before removing formworks
- Special requirement for waterproofing layer



Recent developments

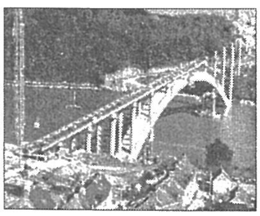
Bridges launched with the slab (or a part of it)

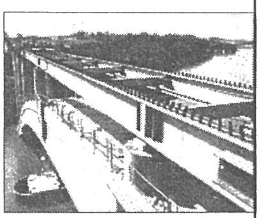




Recent developments

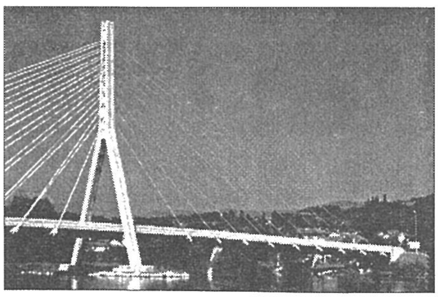
Hybrid bridges (two-girder + concrete arch)





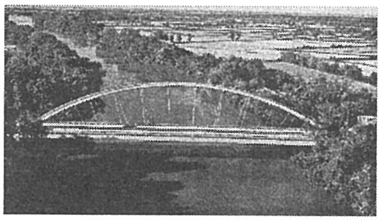
Recent developments

Hybrid bridges (two-girder + stays)



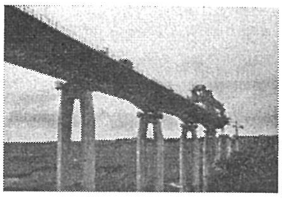
Recent developments

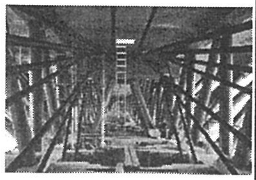
- Bowstring arch with a composite tie



Recent developments

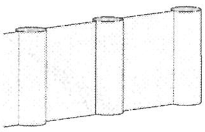
Concrete bridges with steel webs

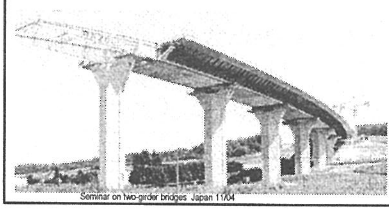




Recent developments

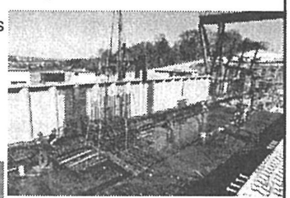
Concrete bridges with steel webs and prestressing by tendons

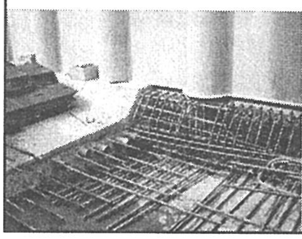




Recent developments

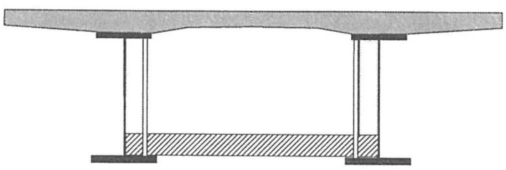
Concrete bridges with steel webs and prestressing by tendons





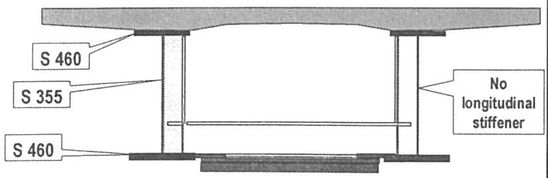
Futur developments

Double composite action



Futur developments

- Hybrid girders (S355 web and S460M flanges)
- Web stiffening according to Eurocode
- Temporary wind bracing left in place and designed for redundancy (smaller safety factor for fatigue)



Futur developments

- Twin box section
- Longitudinally unstiffened
- No cross girders

Seminar on two-girder bridges Japan 11/04 79