Puentes 2023

Puentes Atirantados

INSTITUTO DE ESTRUCTURAS Y TRANSPORTE
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FACULTAD DE INGENIERIA

Dr. Ing. Fernando Sima
Setiembre 2023

Cable-supported bridges – Cable-Stayed Bridges: Overview

- Cable-Stayed Bridges can be classified by:

→ Span Arrangement:

  - Single Span
  - Two Span
  - Three Span (standard)
  - Multi Span

Lérez River Bridge in Pontevedra, Spain, 1995. Carlos Fernandez Casado, S.L.

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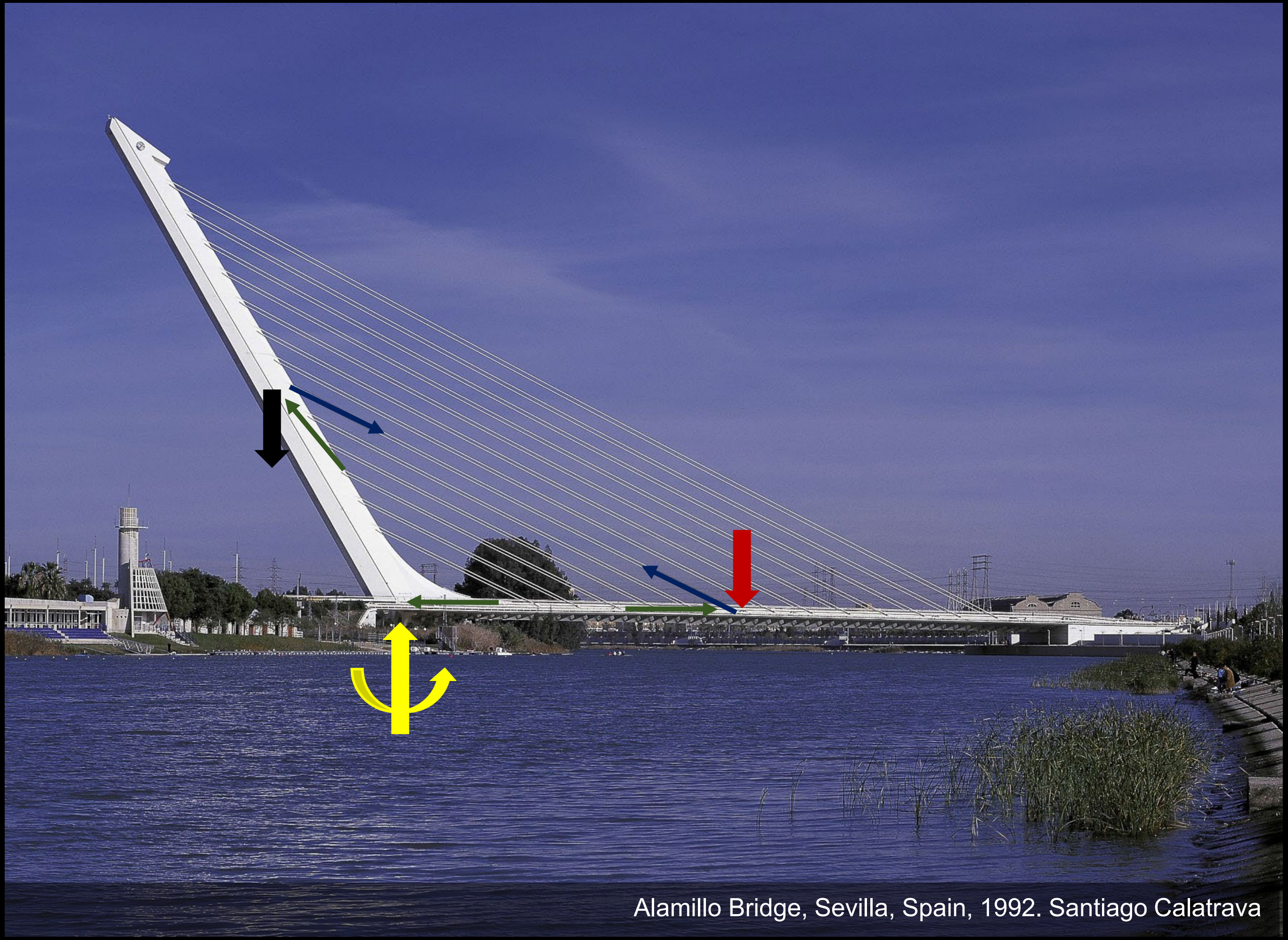

Alamillo Bridge, Sevilla, Spain, 1992. Santiago Calatrava

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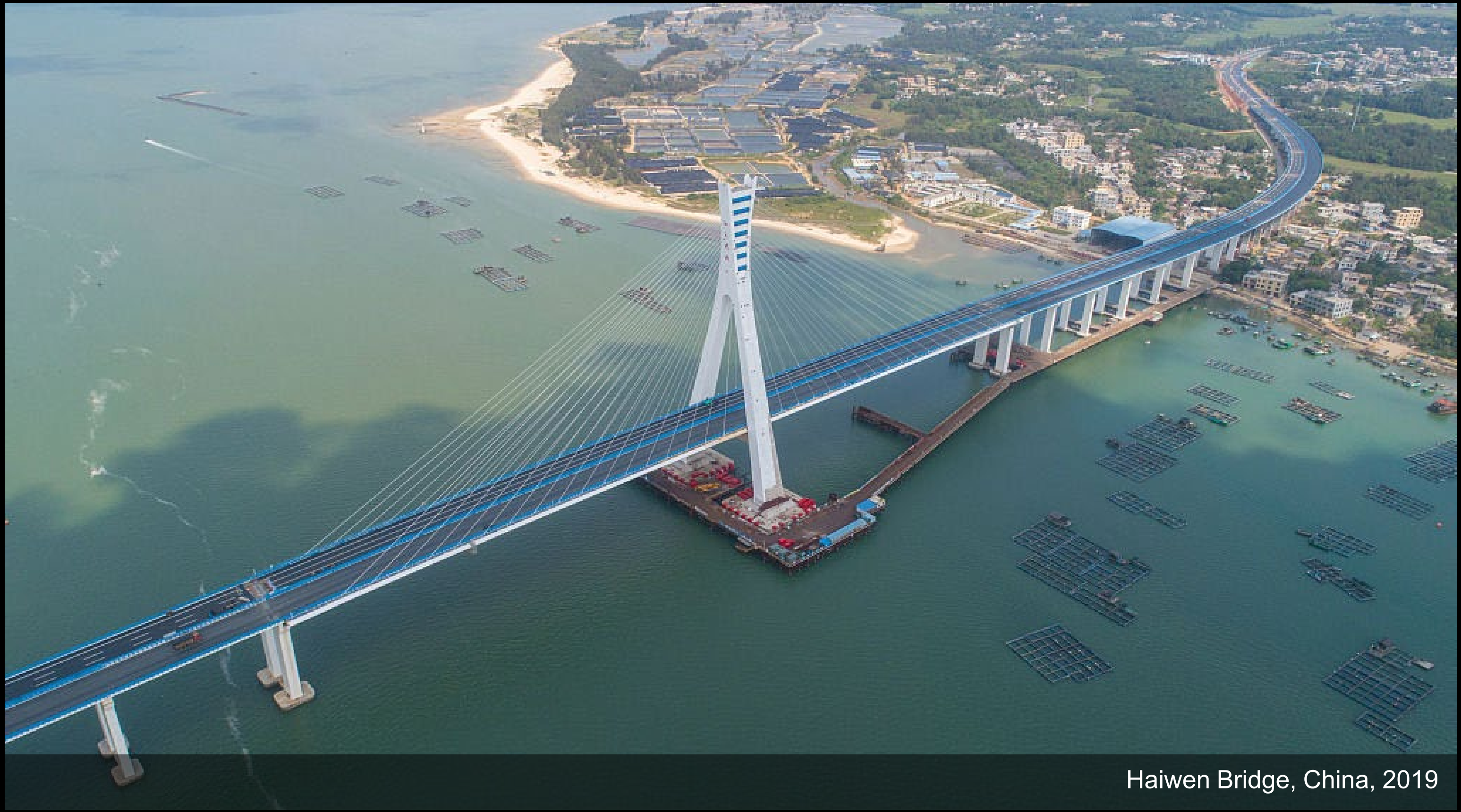

Haiwen Bridge, China, 2019

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Arthur Ravenel Jr. (Cooper River) Bridge, SC, USA, 2005. Parsons Brinkerhoff Quade & Douglas

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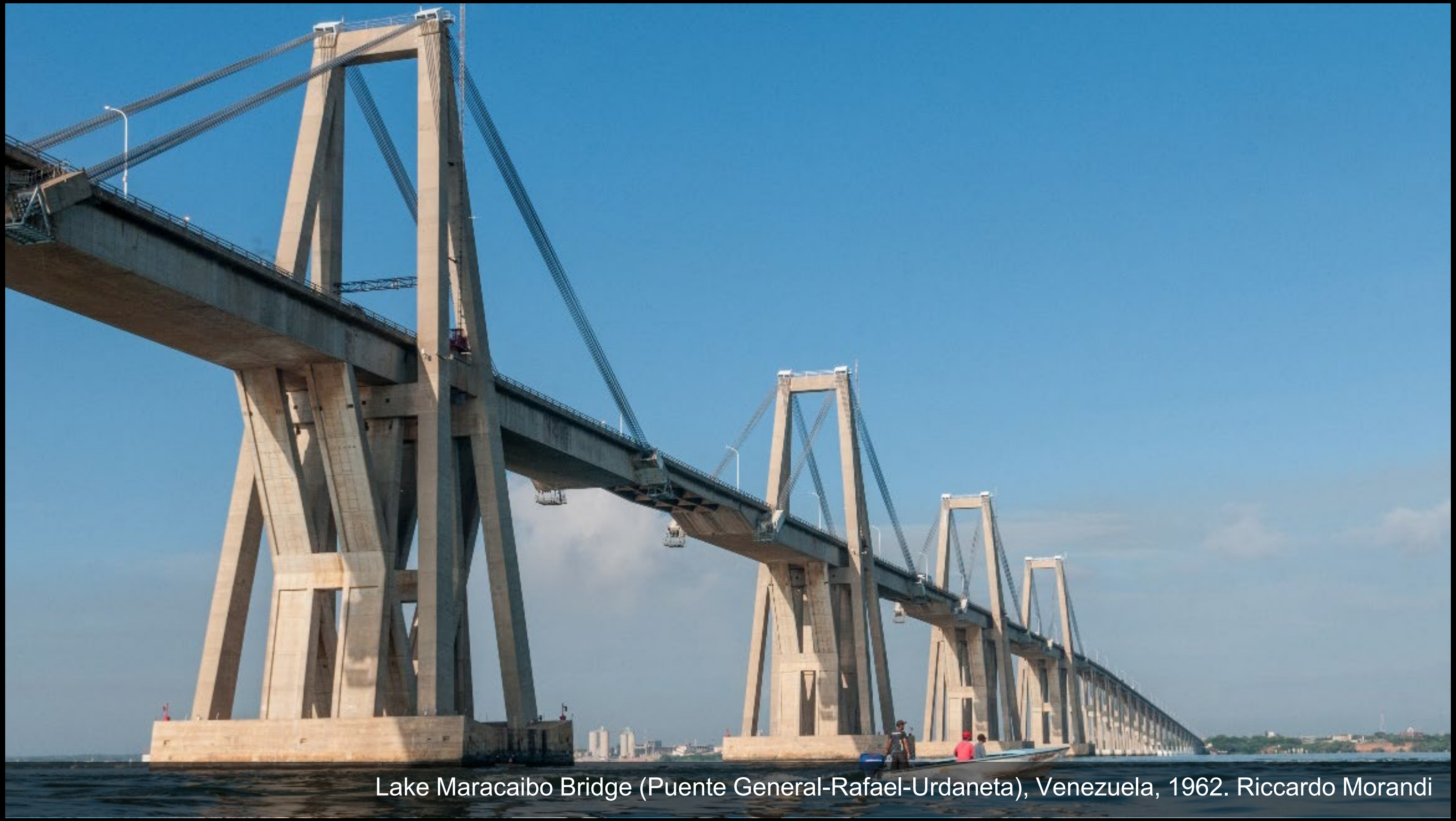

Lake Maracaibo Bridge (Puente General-Rafael-Urdaneta), Venezuela, 1962. Riccardo Morandi

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Rion Antirion (Charilaos Trikoupis) Bridge, Greece, 2004. Jacques Combault

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Ting Kau Bridge, Hong Kong, 1997. Sclaich Bergermann Partner

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Queensferry Crossing, Queensferry, UK, 2017. Jacobs / Arup

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Mersey Gateway Bridge, Cheshire, UK, 2017. COWI / FHECOR

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→ Stay Cable Arrangement:

  - Fan
  - Harp
  - Hybrid (Semi-Fan)

Ed Hendler Bridge, Pasco/Kennewick, WA, USA, 1978. Arvid Grant & Associates / Leonhardt & Andrä

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Øresund Bridge, Copenhagen, Denmark, 2000. COWI

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Brotonne Bridge, Normandy, France, 1977. Jean Muller

Cable-supported bridges – Cable-Stayed Bridges: Overview

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→ Stay Cable Planes:

  - Single Plane
  - Two Vertical Planes
  - Two Inclined Planes
  - Multiple Vertical Planes
  - Multiple Inclined Planes

Puente Centerario (Panama Canal Second Crossing), Panama, 2004. TYLI / LAP

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Sidney Lanier Bridge, Brunswick, GA, USA, 2003. TYLI

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Tatara Bridge, Hiroshima, Japan, 1999. Honshu-Shikoku Bridge Authority

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Pitt River Bridge, Vancouver, BC, Canada, 2009. IBT

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Port Mann Bridge, Vancouver, BC, Canada, 2012. TYLI / IBT

Cable-supported bridges – Cable-Stayed Bridges: Overview

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→ Tower Configuration:

- Single Tower
- “H” Tower
- “A” Tower
- Diamond Tower
- Double Diamond Tower
- Inverted “Y” Tower

Sunshine Skyway Bridge, Tampa, FL, USA, 1987. Figg & Muller

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Sidney Lanier Bridge, Brunswick, GA, USA, 2003. TYLI


JJ Audubon Bridge, LA, USA, 2011. Buckland & Taylor, Ltd.

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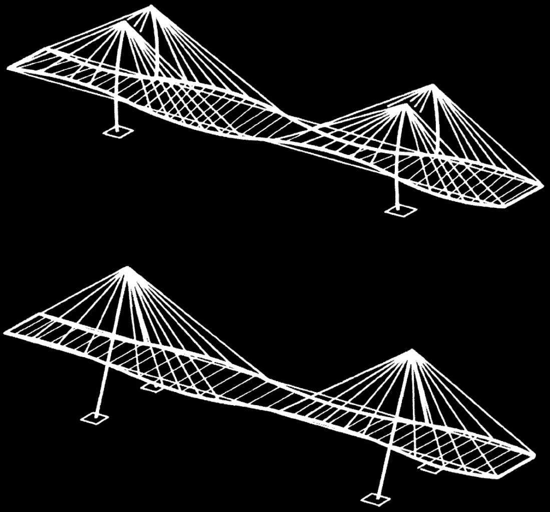

Second Meiko Nishi Bridge, Nagoya, Japan, 1997

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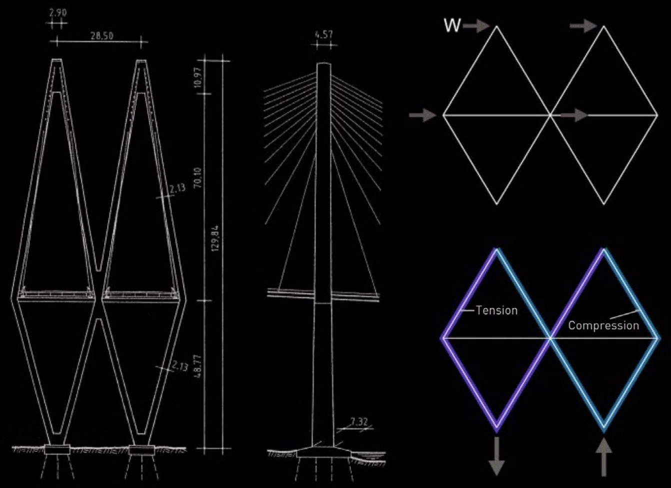


Fred Hartman Bridge, Baytown, TX, USA, 1995. LAP / URS

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Pont de Normandie, France, 1995. Michel Virlogeux

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- Flexible
  - Concrete Edge Girder
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  - Hybrid: Concrete Edge Girder + Steel Floor Beams
- Stiff
  - Concrete Box
  - Steel Box (Orthotropic)
  - Truss

Sidney Lanier Bridge, Brunswick, GA, USA, 2003. TYLI

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Port Mann Bridge, Vancouver, BC, Canada, 2012. TYLI / IBT

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East Huntington Bridge, WV, USA, 1985. Arvid Grant / LAP

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Stonecutters Bridge, Hong Kong, 2009. Arup / COWI

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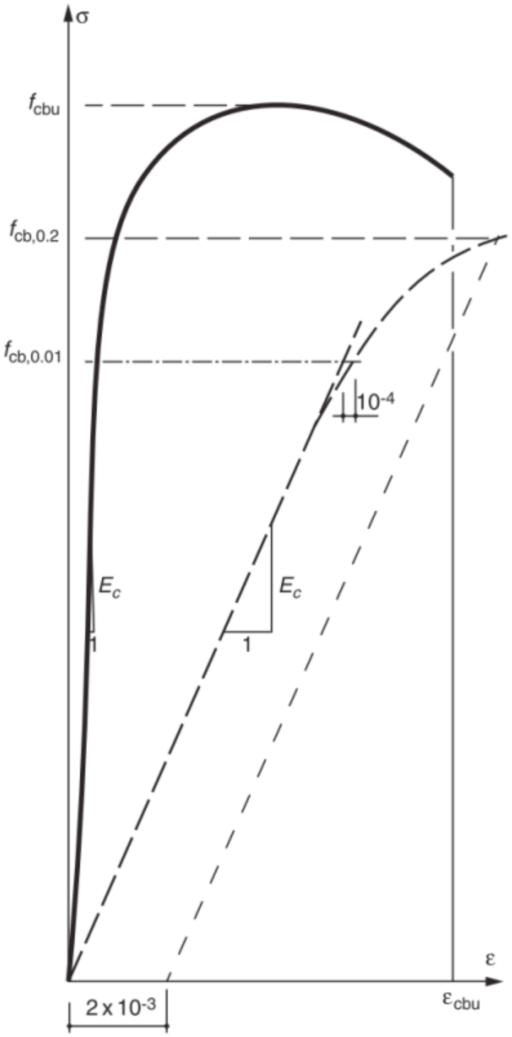
Øresund Bridge, Copenhagen, Denmark, 2000. COWI

2. Cables

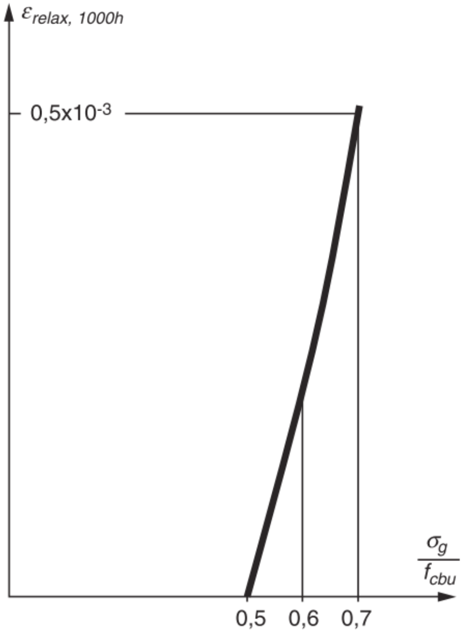
2.1. Tipos básicos de cables

		Conventional cable steel	Structural steel	
	Unity	(5 or 7 mm wires)	Mild	High strength
Yield stress (= 2% proof stress)	MPa	1180	240	690
Tensile strength	MPa	1570	370	790
Strain at breaking	%	4	24	
Modulus of elasticity	GPa	205	210	210
Typical chemical composition				
	C	0.80%	0.20%	0.15%
	Si	0.20%	0.30%	0.25%
	Mn	0.60%		0.80%
	Cu	0.05%	0.20%	0.30%
	Ni	0.05%		0.80%
	Cr	0.05%	0.30%	0.50%
	P	0.03%	0.04%	0.03%
	S	0.02%	0.04%	0.03%



the modulus of elasticity: E_c
the 0.2% proof stress: $f_{cb,0.2}$
the limit of proportionality (0.01% stress): $f_{cb,0.01}$
the ultimate tensile strength: f_{cbu}
the total elongation at rupture: ε_{cbu}

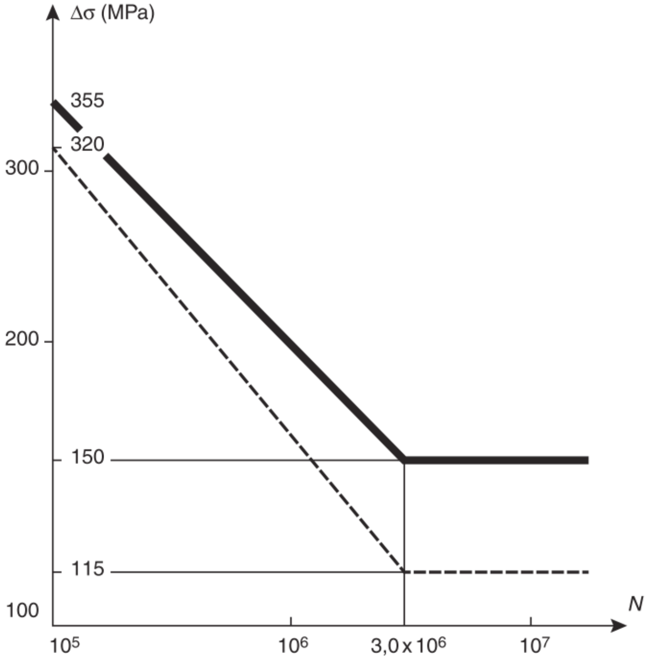
Relajación



Fatiga

Wöhler $\log \Delta\sigma = C_1 \log N + C_2$

	Allowable stress range $\Delta\sigma$ (MPa)	
Number N of cycles	Parallel-wire cable	Parallel-strand cable
$N < 3 \times 10^6$	$\log\Delta\sigma = -0.253 \log N + 3.815$	$\log\Delta\sigma = -0.301 \log N + 4.01$
$N \geq 3 \times 10^6$	$\Delta\sigma = 150$	$\Delta\sigma = 115$



2.1. Tipos básicos de cables

Cordón de 7 alambres (típico de pretensado)

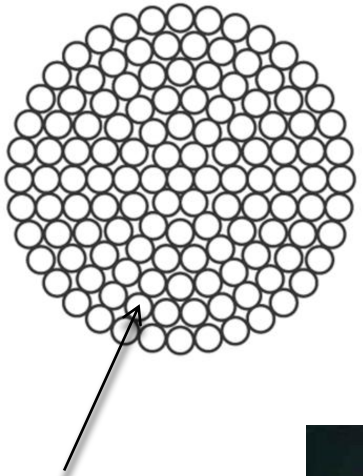
1770 MPa – 1860 Mpa
E=190 GPa

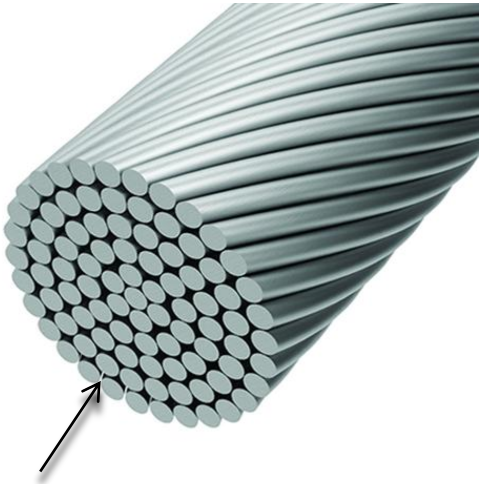
Alambre central recto y 6 alambres en espiral con un paso relativamente largo (módulo 6-8% menor al del acero)

2. Cables

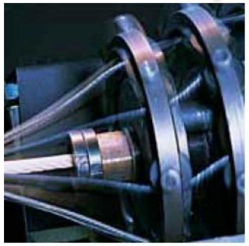
2.1. Tipos básicos de cables

Cordón en espiral abierto (Open Spiral strand – OSS)

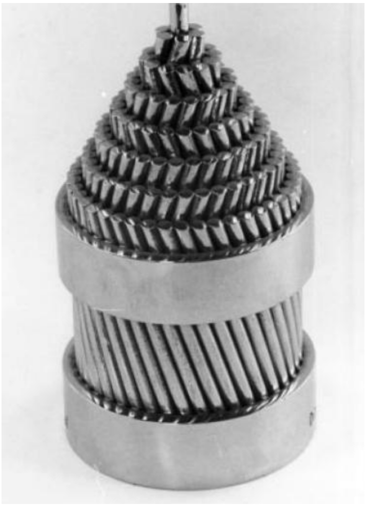




Varias capas de alambres helicoidales con dirección alternada y paso menor



Verseilung eines Seiles
Stranding of a cable

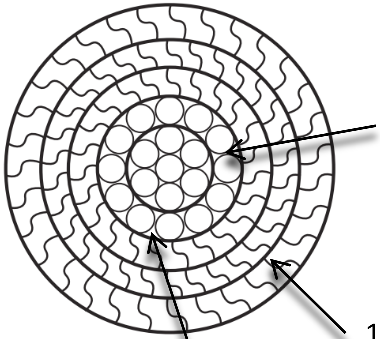


E=170 Gpa
Resistencia 0.9 fctb

Vorbereitung zum Vorrecken eines Seiles
Preparation of prestretching for a cable

Messung der Seildehnung
Measuring of cable elongation

Cable cerrado (Full locked cable – FLC)

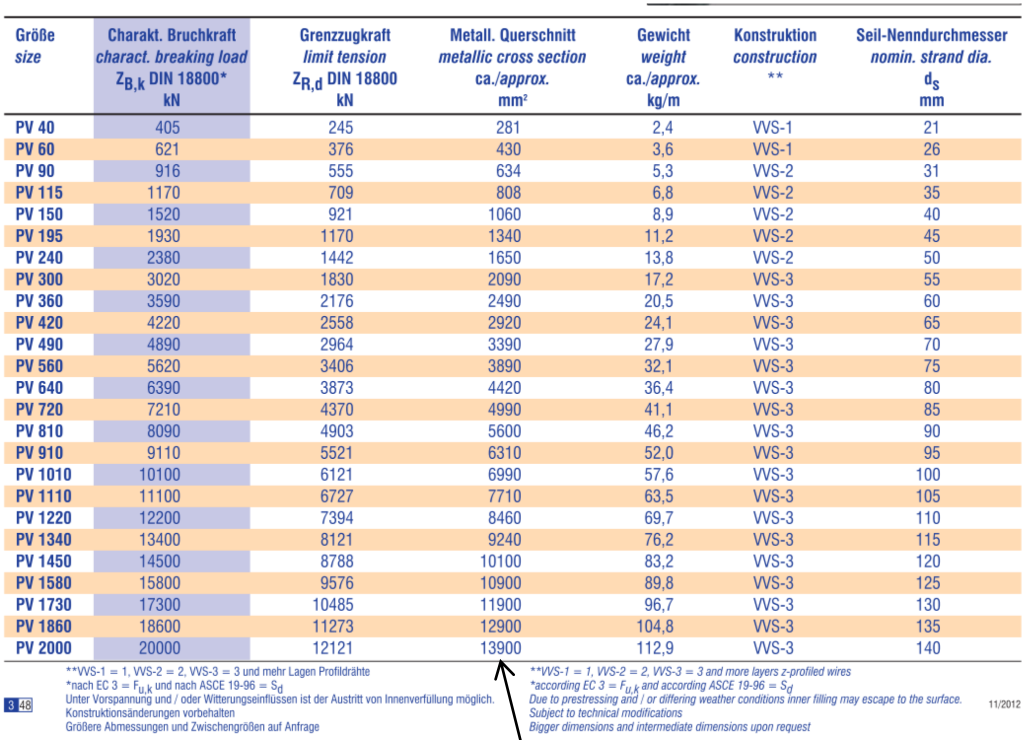


Alambres interiores circulares

1 a 3 capas de alambres en Z

Relleno interior

Cables Pfeifer



Größe *size*	Charakt. Bruchkraft *charact. breaking load* $Z_{B,k}$ DIN 18800* kN	Grenzzugkraft *limit tension* $Z_{R,d}$ DIN 18800 kN	Metall. Querschnitt *metallic cross section* ca./*approx.* mm²	Gewicht *weight* ca./*approx.* kg/m	Konstruktion *construction* **	Seil-Nenndurchmesser *nomin. strand dia.* d_s mm
PV 40	405	245	281	2,4	VVS-1	21
PV 60	621	376	430	3,6	VVS-1	26
PV 90	916	555	634	5,3	VVS-2	31
PV 115	1170	709	808	6,8	VVS-2	35
PV 150	1520	921	1060	8,9	VVS-2	40
PV 195	1930	1170	1340	11,2	VVS-2	45
PV 240	2380	1442	1650	13,8	VVS-2	50
PV 300	3020	1830	2090	17,2	VVS-3	55
PV 360	3590	2176	2490	20,5	VVS-3	60
PV 420	4220	2558	2920	24,1	VVS-3	65
PV 490	4890	2964	3390	27,9	VVS-3	70
PV 560	5620	3406	3890	32,1	VVS-3	75
PV 640	6390	3873	4420	36,4	VVS-3	80
PV 720	7210	4370	4990	41,1	VVS-3	85
PV 810	8090	4903	5600	46,2	VVS-3	90
PV 910	9110	5521	6310	52,0	VVS-3	95
PV 1010	10100	6121	6990	57,6	VVS-3	100
PV 1110	11100	6727	7710	63,5	VVS-3	105
PV 1220	12200	7394	8460	69,7	VVS-3	110
PV 1340	13400	8121	9240	76,2	VVS-3	115
PV 1450	14500	8788	10100	83,2	VVS-3	120
PV 1580	15800	9576	10900	89,8	VVS-3	125
PV 1730	17300	10485	11900	96,7	VVS-3	130
PV 1860	18600	11273	12900	104,8	VVS-3	135
PV 2000	20000	12121	13900	112,9	VVS-3	140

**VVS-1 = 1, VVS-2 = 2, VVS-3 = 3 und mehr Lagen Profildrähte
*nach EC 3 = $F_{u,k}$ und nach ASCE 19-96 = S_d
Unter Vorspannung und / oder Witterungseinflüssen ist der Austritt von Innenverfüllung möglich.
Konstruktionsänderungen vorbehalten
Größere Abmessungen und Zwischengrößen auf Anfrage

***VVS-1 = 1, VVS-2 = 2, VVS-3 = 3 and more layers z-profiled wires*
**according EC 3 = $F_{u,k}$ and according ASCE 19-96 = S_d*
Due to prestressing and / or differing weather conditions inner filling may escape to the surface.
Subject to technical modifications
Bigger dimensions and intermediate dimensions upon request

3 48

11/2012

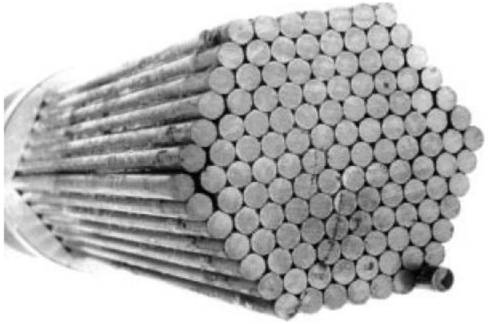
$1 - 13900/(\pi \cdot 70^2) = 10\ \%$

Alambres 1370-1570 MPa
E=160 +/- 10 GPa

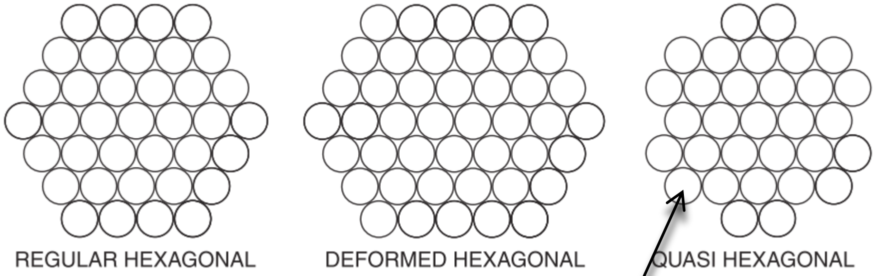
Menor relación de vacíos que cualquier otro tipo de cable

Protección contra corrosión: galvanizado (GALFAN) y pintado
Densidad eq. 8.8 KN/m^3

Cable de alambres paralelos

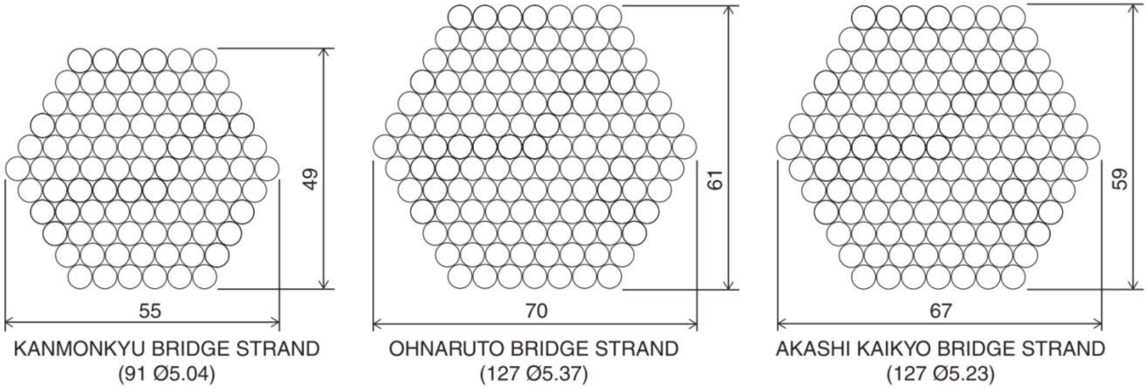


Parallel-wire strand with 127 nos. 5 mm wires (Bisan Seto Bridges)



Alambres 5-5.5 mm

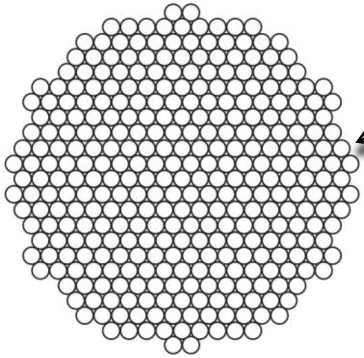
Problema de enrollarlo/desenrollarlo para transporte con diámetros razonables sin distorcionar la sección transversal durante mucho tiempo. Hoy habituales en los puentes japoneses.



Cable de alambres paralelos (PWS)– Puentes Atirantados

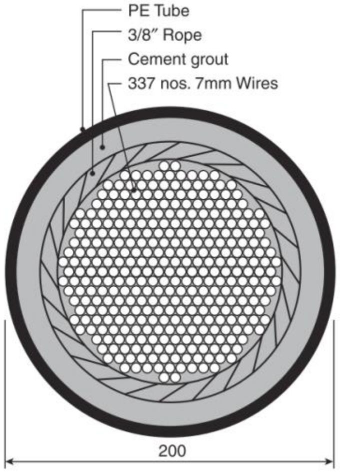
19 x 7 mm hasta 449 x 7 mm

Cables más grandes del puente Zárate-Brazo Largo - 337 x 7 mm



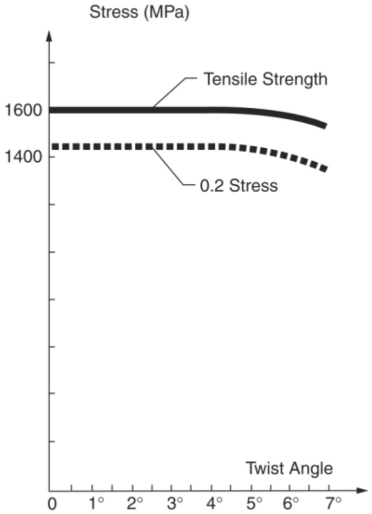
Antiguamente envuelto por un cable de acero para mantener el posición el manojo de cables , tubo de protección (PE o SS) e inhibidor de la corrosión llenando los huecos (grout)
Para un cable de diam 200 mm la sección metálica era de 14584 mm2

$$1 - 14584/(\pi \cdot 100^2) = 54\ \%$$



γ_{eq}	= 115-120 KN/m3	Grout
	85-90 KN/m3	Grasa

Sistema de protección del Puente Zarate-Brazo Largo. Fisuración del tubo de PE y grout



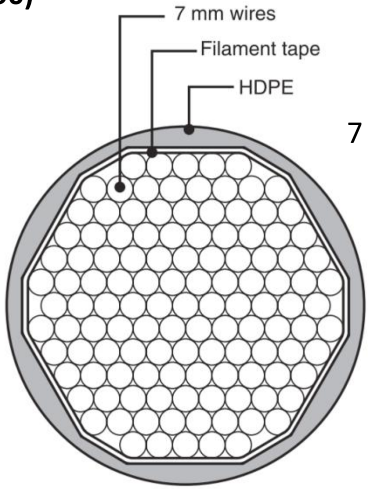
Nuevos Cables de alámbres paralelos PWS (desde los años 90)

Levemente torneado para facilitar el enrollado y desenrollado y la compactación del cable en tensión.

Para un cable de diam 175 mm la sección metálica era de 16202 mm2

$$1 - 16202/(\pi \cdot 175^2) = 33\ \%$$

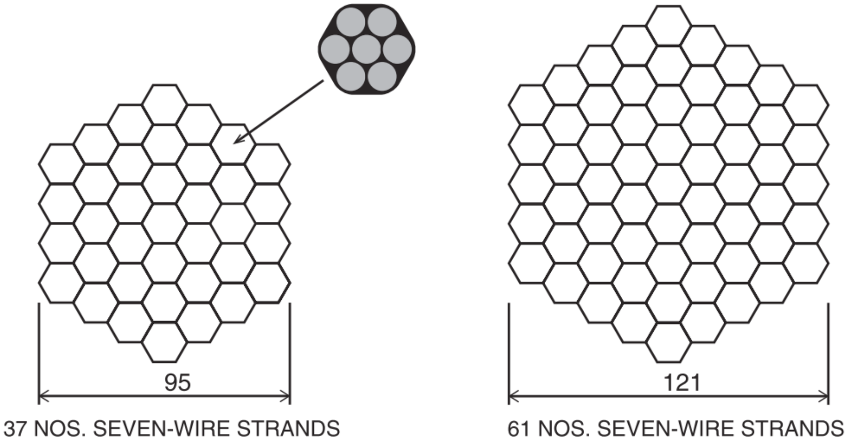
γ_{eq} = 82 KN/m3

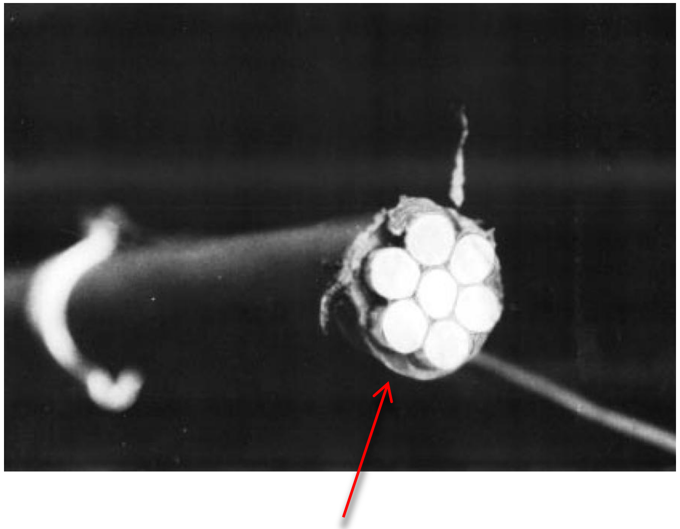


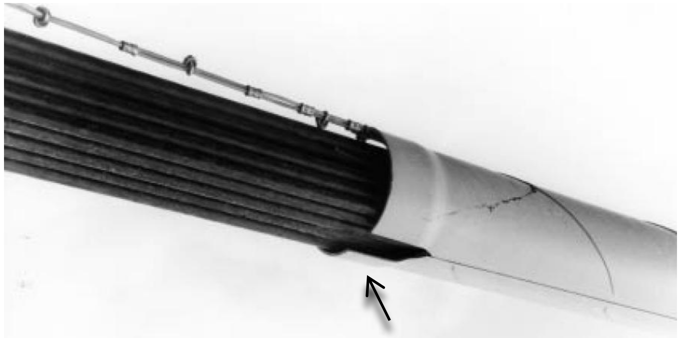
7 x 7 mm hasta 421 x 7 mm

Cable de cordones paralelos – Puentes Atirantados

Se sustituyen los alambres de 7 mm por cordones de 7 alambres (hasta 127)







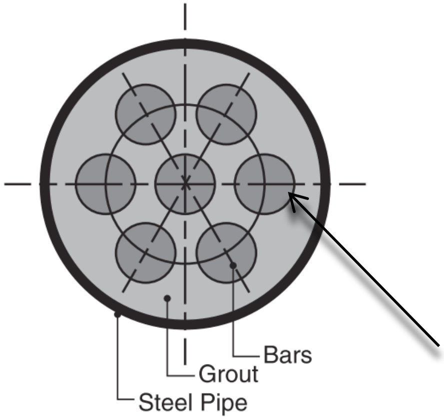
Tubo exterior de PE (Puente Normandia) eventualmente (si no se utiliza recubrimiento individual de HDPE) relleno inhibidor de corrosión

Relación de vacíos alta!
Para un cable de 109 x 0.6’ la sección metálica es de 109x140=15260 mm2 y un diam. de 315 mm

$$1 - 15260/(\pi \cdot 157.5^2) = 80.4\ \%$$

Grandes puentes – se elimina el recubrimiento individual y se utiliza un sistema de deshumidificación.

Cable de Barras de acero (Puentes atirantados)



Sistema utilizado en algunos de los primeros puentes atirantados (ya no se utiliza)

7-10 barras diam 26.5, 32 o 36 mm
fyk= 1080 Mpa / 1230 Mpa (rotura)

Relación de vacíos alta!
Para un cable de 10 x 36 mm la sección metálica es de 10x1018=10180 mm2 y un diam. de 241 mm

$$1 - 110180/(\pi \cdot 120^2) = 78\ \%$$

γ_{eq} = 125 KN/m3

2. Cables

2.1. Tipos básicos de cables

Cable multi-cordón

Formado por varios cordones espiral

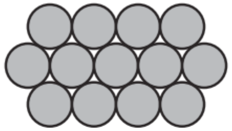
Strömsund Bridge(F. Dischinger, 1955)

Askøy Bridge (AAS Jacobsen, 1992)

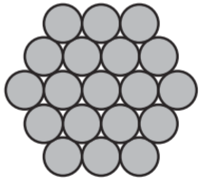
2. Cables

2.1. Tipos básicos de cables

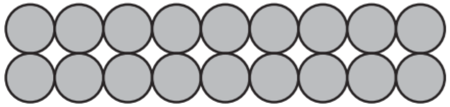
Cable multi-cordón



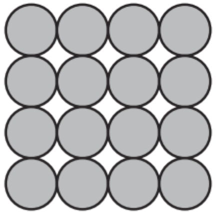
THEODOR HEUSS BRIDGE: 13 Ø73



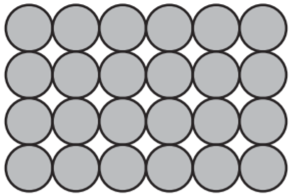
LEVERKUSEN BRIDGE: 19 Ø59,5



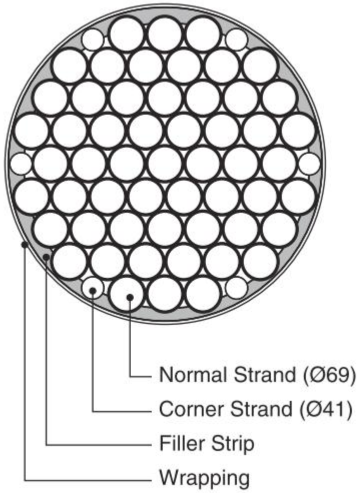
MAXAU BRIDGE: 18 Ø82



SEVERINS BRIDGE: 16 Ø84



ERSKINE BRIDGE: 24 Ø76

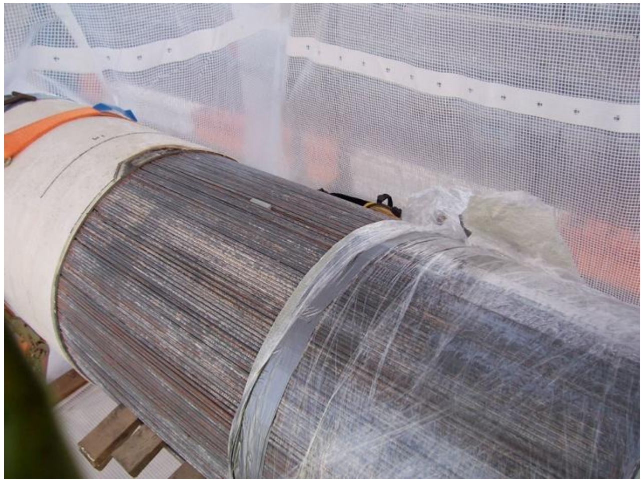


Lillebæl Bridge(Jonson-Ostenfeld, 1970)

Cable de alambres paralelos – Cable principal puentes colgantes

Air-Spinning: Metodo más utilizado durante 100 años para la ejecución del cable principal.Hasta 30000 x 5mm alambres instalados uno a uno, de extremo a estremo, luego compactados y envueltos (wrapping) por un alambre galvanizado de acero con tratamiento de recocido blando

Cable principal del Puente de San Francisco - 27572 Alambres

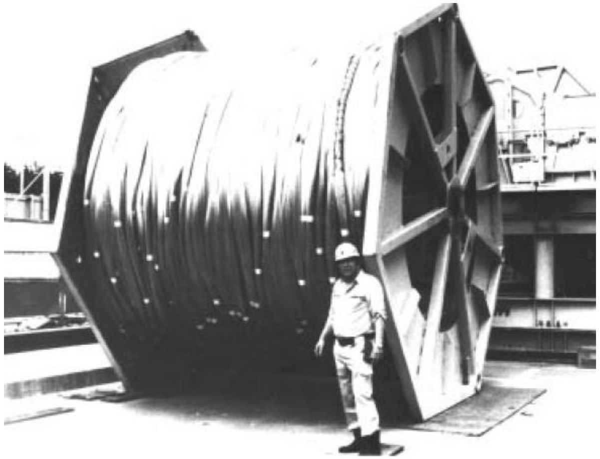


Cable principal del Puente Severn - 8322 Alambres galvanizados

“wrapping” bajo tensión para conseguir fricción entre los alambres (i.e. aumento notable de rigidez a flexión del cable)

Cable de alambres paralelos – Cable principal puentes colgantes

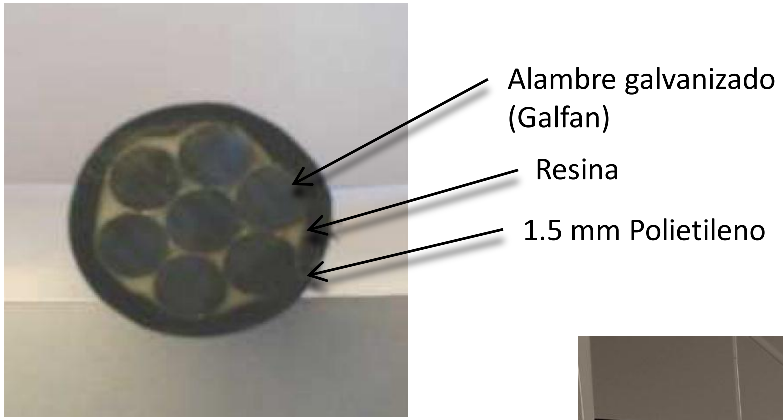
Cable de cordones de alambres paralelos prefabricados (PPWS)



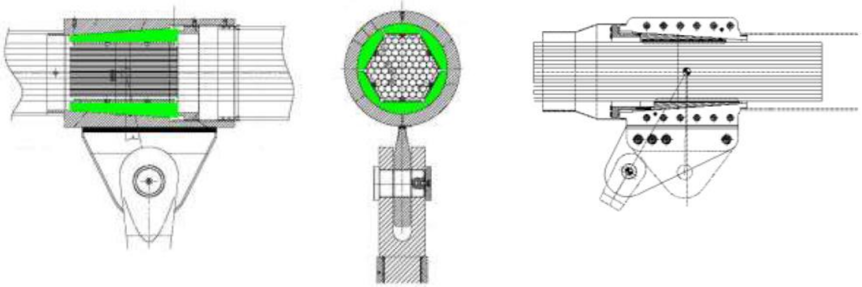
Cordones prefabricados de alambres paralelos (4000 m) Puente Akashi Kaikyo

Cable principal del Akashi Kaikyo – 36830 alambres (127 x 290 x 5,23 mm)

Nuevos desarrollos: Cable de cordones paralelos autoprotegidos – Cable principal puentes colgantes



Típico cordón de 7 alambres con protección individual (Cohestrand® - Freysinet)



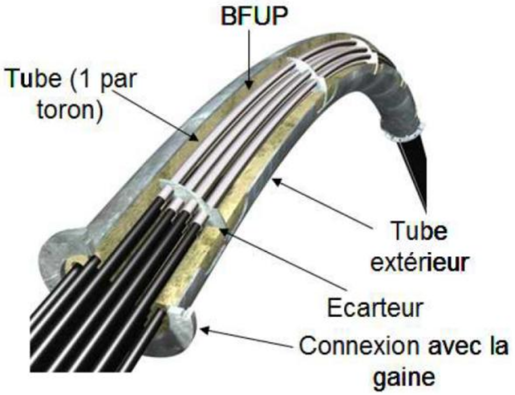


Figura 3: sección de un collar con 75 cordones empleado para el puente de Kanne en Bélgica (2004)

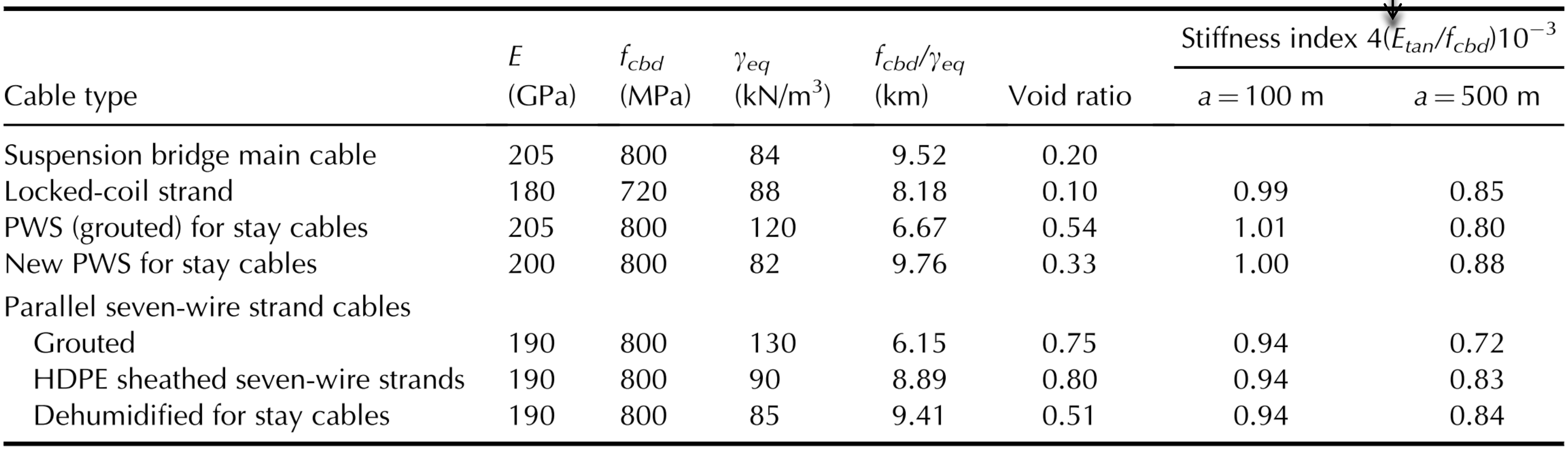
Puente Verdun Sur Garonne (2012)

2. Cables

2.1. Tipos básicos de cables

Comparativa

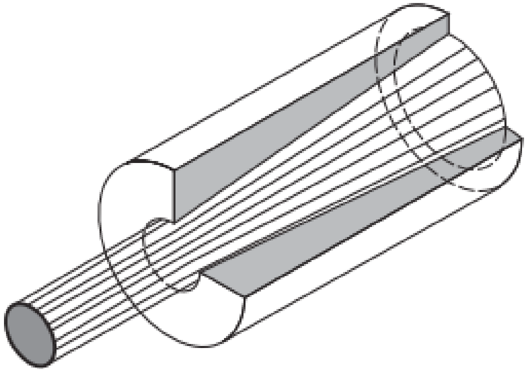
Eficiencia del sistema a través de la rigidez AE_{eq}

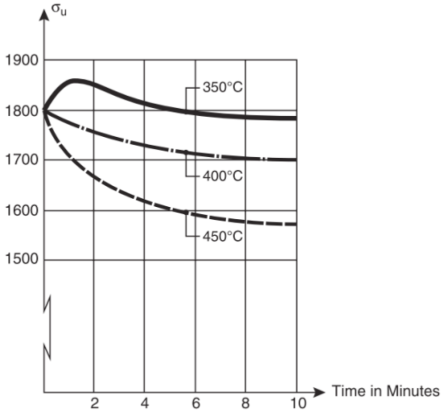


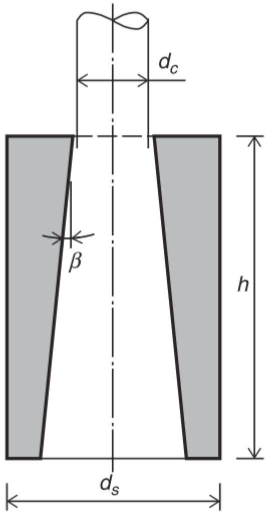
Cable type	E (GPa)	f_{cbd} (MPa)	γ_{eq} (kN/m^3)	f_{cbd}/γ_{eq} (km)	Void ratio	Stiffness index $4(E_{tan}/f_{cbd})10^{-3}$	
						$a = 100$ m	$a = 500$ m
Suspension bridge main cable	205	800	84	9.52	0.20		
Locked-coil strand	180	720	88	8.18	0.10	0.99	0.85
PWS (grouted) for stay cables	205	800	120	6.67	0.54	1.01	0.80
New PWS for stay cables	200	800	82	9.76	0.33	1.00	0.88
Parallel seven-wire strand cables							
Grouted	190	800	130	6.15	0.75	0.94	0.72
HDPE sheathed seven-wire strands	190	800	90	8.89	0.80	0.94	0.83
Dehumidified for stay cables	190	800	85	9.41	0.51	0.94	0.84

E_{tan} tal que $\sigma = 0.75 f_{cbd}$

6.1 Aspectos básicos



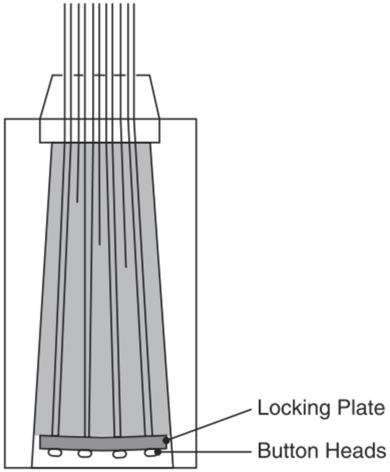


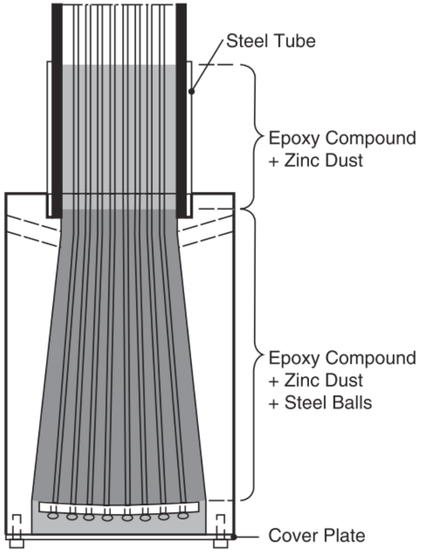


$h = 4d_c\text{-}5d_c$

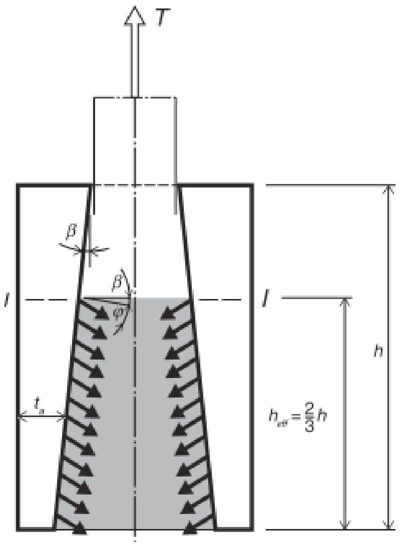
$ds = 2.5d_c\text{-}3d_c$

$\tan\beta = \frac{1}{8}\text{-}\frac{1}{12}$



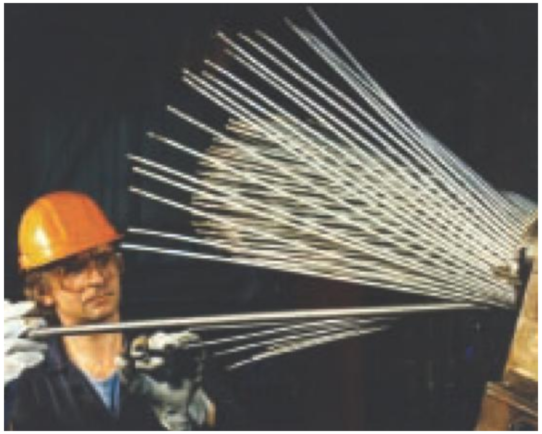


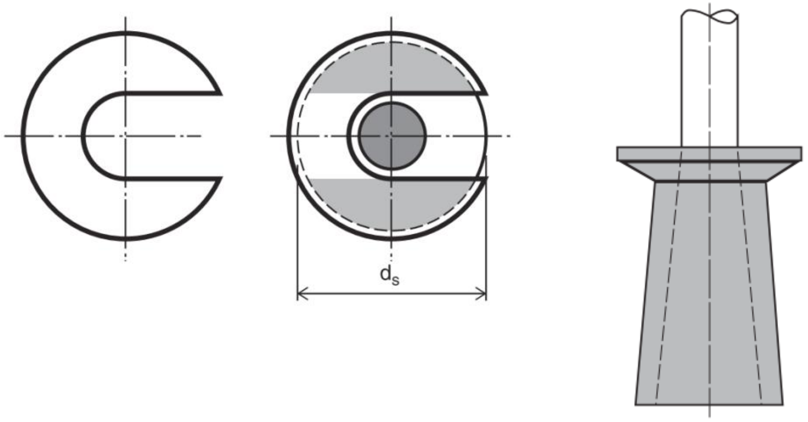
6.1 Aspectos básicos



$$P_r = \frac{T}{2\pi \tan(\phi + \beta)}$$

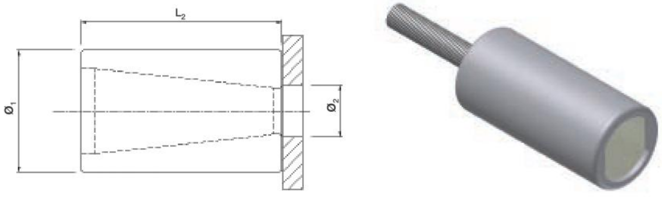
$$\sigma = \frac{3}{2}\frac{P_t}{h t_a} = \frac{3}{4\pi}\frac{T}{\tan(\phi + \beta)}$$

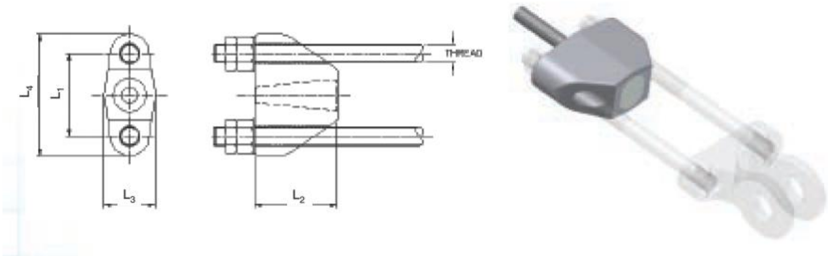


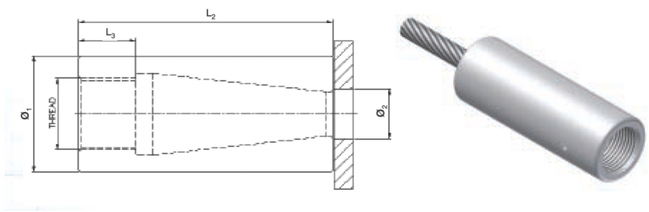


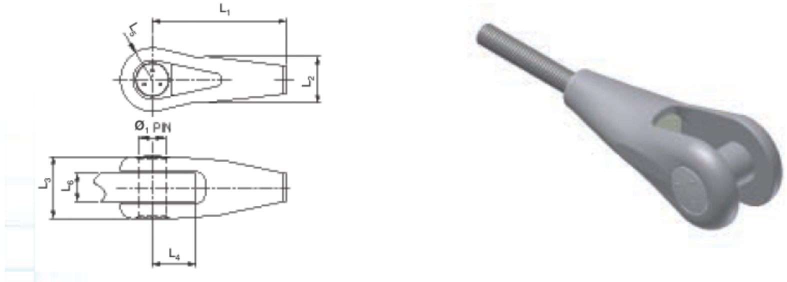
6. Anclajes y conexiones

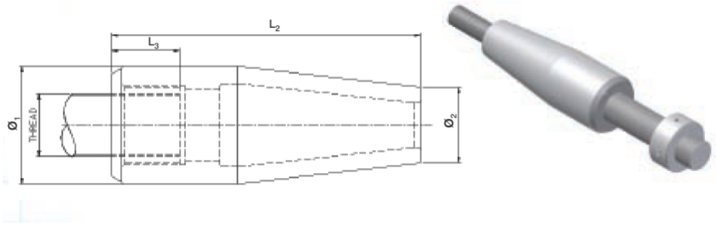
6.1 Aspectos básicos

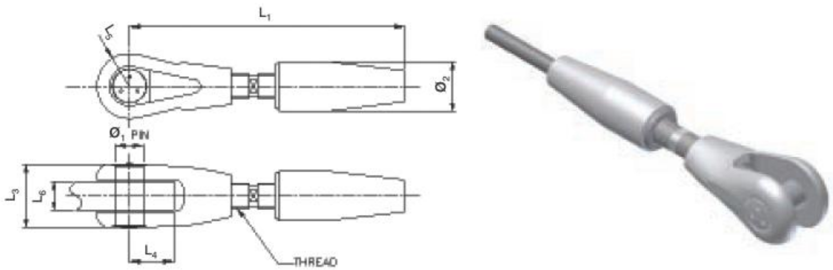






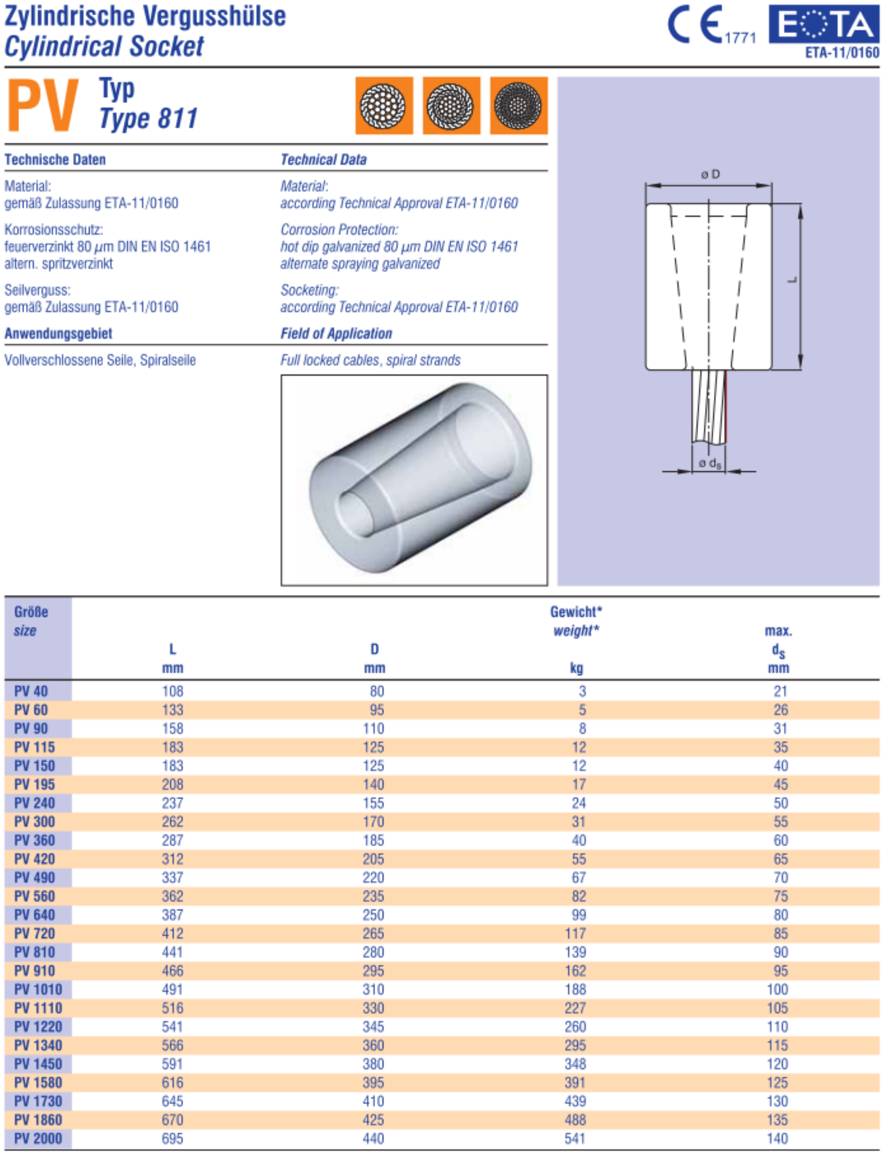






6. Anclajes y conexiones

6.1 Aspectos básicos



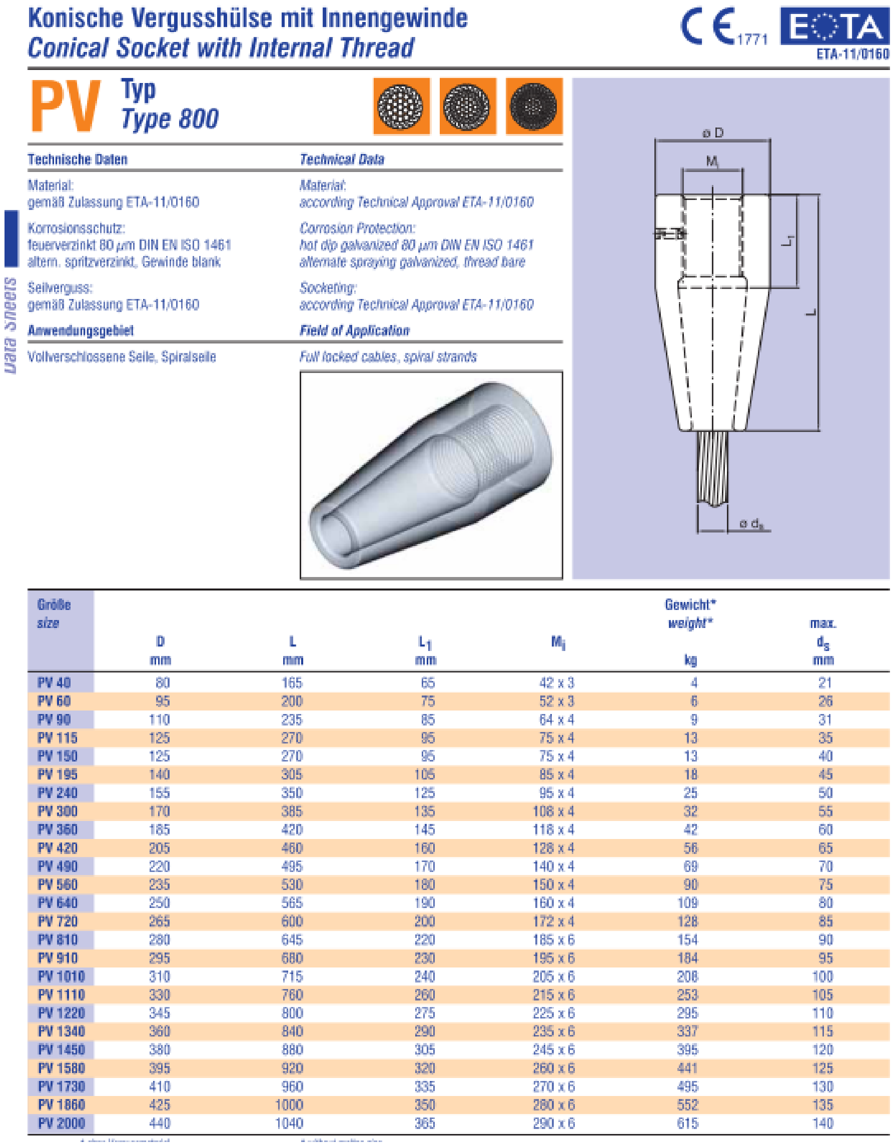
Zylindrische Vergusshülse
Cylindrical Socket

PV **Typ**
Type 811

Technische Daten	***Technical Data***
Material: gemäß Zulassung ETA-11/0160	*Material:* *according Technical Approval ETA-11/0160*
Korrosionsschutz: feuerverzinkt 80 µm DIN EN ISO 1461 altern. spritzverzinkt	*Corrosion Protection:* *hot dip galvanized 80 µm DIN EN ISO 1461* *alternate spraying galvanized*
Seilverguss: gemäß Zulassung ETA-11/0160	*Socketing:* *according Technical Approval ETA-11/0160*
Anwendungsgebiet	***Field of Application***
Vollverschlossene Seile, Spiralseile	*Full locked cables, spiral strands*

Größe ***size***	**L** **mm**	**D** **mm**	**Gewicht*** ***weight**** **kg**	**max.** **d_S** **mm**
PV 40	108	80	3	21
PV 60	133	95	5	26
PV 90	158	110	8	31
PV 115	183	125	12	35
PV 150	183	125	12	40
PV 195	208	140	17	45
PV 240	237	155	24	50
PV 300	262	170	31	55
PV 360	287	185	40	60
PV 420	312	205	55	65
PV 490	337	220	67	70
PV 560	362	235	82	75
PV 640	387	250	99	80
PV 720	412	265	117	85
PV 810	441	280	139	90
PV 910	466	295	162	95
PV 1010	491	310	188	100
PV 1110	516	330	227	105
PV 1220	541	345	260	110
PV 1340	566	360	295	115
PV 1450	591	380	348	120
PV 1580	616	395	391	125
PV 1730	645	410	439	130
PV 1860	670	425	488	135
PV 2000	695	440	541	140

6.1 Aspectos básicos



Konische Vergusshülse mit Innengewinde
Conical Socket with Internal Thread

CE 1771 EOTA ETA-11/0160

PV **Typ** ***Type 800***

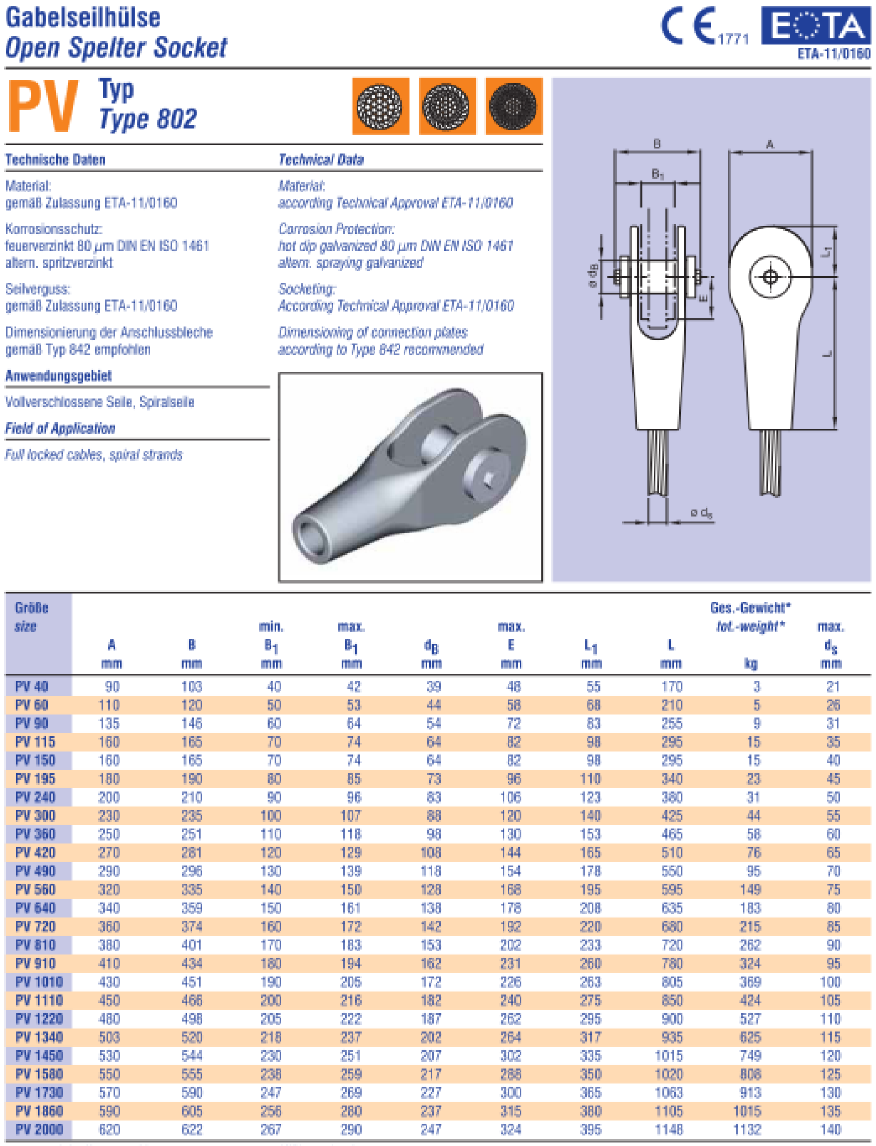
Data sheets

Technische Daten	***Technical Data***
Material: gemäß Zulassung ETA-11/0160	*Material:* *according Technical Approval ETA-11/0160*
Korrosionsschutz: feuerverzinkt 80 µm DIN EN ISO 1461 altern. spritzverzinkt, Gewinde blank	*Corrosion Protection:* *hot dip galvanized 80 µm DIN EN ISO 1461* *alternate spraying galvanized, thread bare*
Seilverguss: gemäß Zulassung ETA-11/0160	*Socketing:* *according Technical Approval ETA-11/0160*
Anwendungsgebiet	***Field of Application***
Vollverschlossene Seile, Spiralseile	*Full locked cables, spiral strands*

Größe ***size***	D mm	L mm	L_1 mm	M_i	Gewicht* *weight* kg	max. d_s mm
PV 40	80	165	65	42 x 3	4	21
PV 60	95	200	75	52 x 3	6	26
PV 90	110	235	85	64 x 4	9	31
PV 115	125	270	95	75 x 4	13	35
PV 150	125	270	95	75 x 4	13	40
PV 195	140	305	105	85 x 4	18	45
PV 240	155	350	125	95 x 4	25	50
PV 300	170	385	135	108 x 4	32	55
PV 360	185	420	145	118 x 4	42	60
PV 420	205	460	160	128 x 4	56	65
PV 490	220	495	170	140 x 4	69	70
PV 560	235	530	180	150 x 4	90	75
PV 640	250	565	190	160 x 4	109	80
PV 720	265	600	200	172 x 4	128	85
PV 810	280	645	220	185 x 6	154	90
PV 910	295	680	230	195 x 6	184	95
PV 1010	310	715	240	205 x 6	208	100
PV 1110	330	760	260	215 x 6	253	105
PV 1220	345	800	275	225 x 6	295	110
PV 1340	360	840	290	235 x 6	337	115
PV 1450	380	880	305	245 x 6	395	120
PV 1580	395	920	320	260 x 6	441	125
PV 1730	410	960	335	270 x 6	495	130
PV 1860	425	1000	350	280 x 6	552	135
PV 2000	440	1040	365	290 x 6	615	140

6. Anclajes y conexiones

6.1 Aspectos básicos



Gabelseilhülse
Open Spelter Socket

PV **Typ**
Type 802

Technische Daten	*Technical Data*
Material: gemäß Zulassung ETA-11/0160	*Material:* *according Technical Approval ETA-11/0160*
Korrosionsschutz: feuerverzinkt 80 µm DIN EN ISO 1461 altern. spritzverzinkt	*Corrosion Protection:* *hot dip galvanized 80 µm DIN EN ISO 1461* *altern. spraying galvanized*
Seilverguss: gemäß Zulassung ETA-11/0160	*Socketing:* *According Technical Approval ETA-11/0160*
Dimensionierung der Anschlussbleche gemäß Typ 842 empfohlen	*Dimensioning of connection plates* *according to Type 842 recommended*

Anwendungsgebiet

Vollverschlossene Seile, Spiralseile

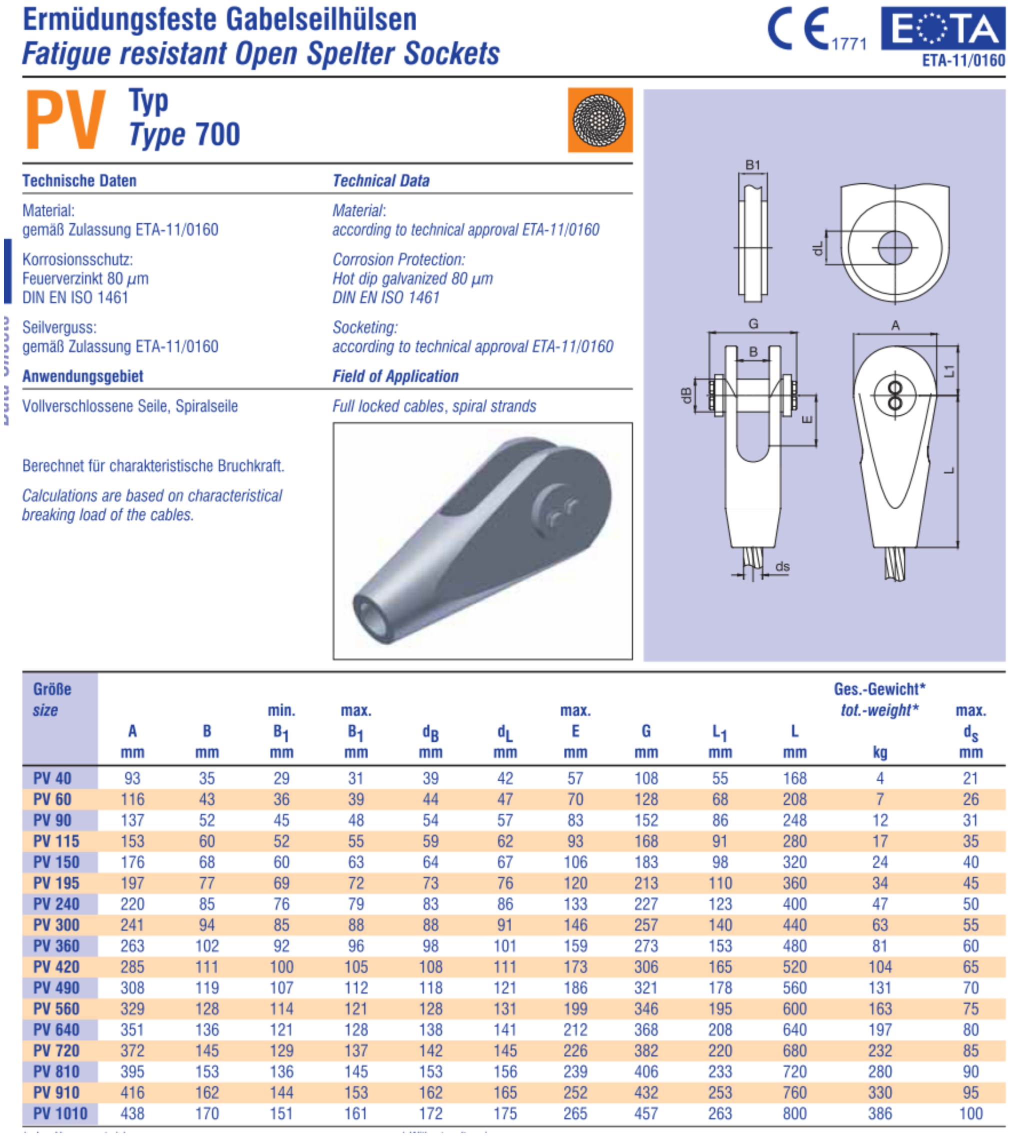
Field of Application

Full locked cables, spiral strands

Größe *size*	A mm	B mm	min. B_1 mm	max. B_1 mm	d_B mm	max. E mm	L_1 mm	L mm	Ges.-Gewicht* *tot.-weight** kg	max. d_s mm
PV 40	90	103	40	42	39	48	55	170	3	21
PV 60	110	120	50	53	44	58	68	210	5	26
PV 90	135	146	60	64	54	72	83	255	9	31
PV 115	160	165	70	74	64	82	98	295	15	35
PV 150	160	165	70	74	64	82	98	295	15	40
PV 195	180	190	80	85	73	96	110	340	23	45
PV 240	200	210	90	96	83	106	123	380	31	50
PV 300	230	235	100	107	88	120	140	425	44	55
PV 360	250	251	110	118	98	130	153	465	58	60
PV 420	270	281	120	129	108	144	165	510	76	65
PV 490	290	296	130	139	118	154	178	550	95	70
PV 560	320	335	140	150	128	168	195	595	149	75
PV 640	340	359	150	161	138	178	208	635	183	80
PV 720	360	374	160	172	142	192	220	680	215	85
PV 810	380	401	170	183	153	202	233	720	262	90
PV 910	410	434	180	194	162	231	260	780	324	95
PV 1010	430	451	190	205	172	226	263	805	369	100
PV 1110	450	466	200	216	182	240	275	850	424	105
PV 1220	480	498	205	222	187	262	295	900	527	110
PV 1340	503	520	218	237	202	264	317	935	625	115
PV 1450	530	544	230	251	207	302	335	1015	749	120
PV 1580	550	555	238	259	217	288	350	1020	808	125
PV 1730	570	590	247	269	227	300	365	1063	913	130
PV 1860	590	605	256	280	237	315	380	1105	1015	135
PV 2000	620	622	267	290	247	324	395	1148	1132	140

6. Anclajes y conexiones

6.1 Aspectos básicos



Ermüdungsfeste Gabelseilhülsen
Fatigue resistant Open Spelter Sockets

CE 1771 EOTA ETA-11/0160

PV Typ
Type 700

Technische Daten	***Technical Data***
Material: gemäß Zulassung ETA-11/0160	*Material:* *according to technical approval ETA-11/0160*
Korrosionsschutz: Feuerverzinkt 80 µm DIN EN ISO 1461	*Corrosion Protection:* *Hot dip galvanized 80 µm* *DIN EN ISO 1461*
Seilverguss: gemäß Zulassung ETA-11/0160	*Socketing:* *according to technical approval ETA-11/0160*
Anwendungsgebiet	***Field of Application***
Vollverschlossene Seile, Spiralseile	*Full locked cables, spiral strands*

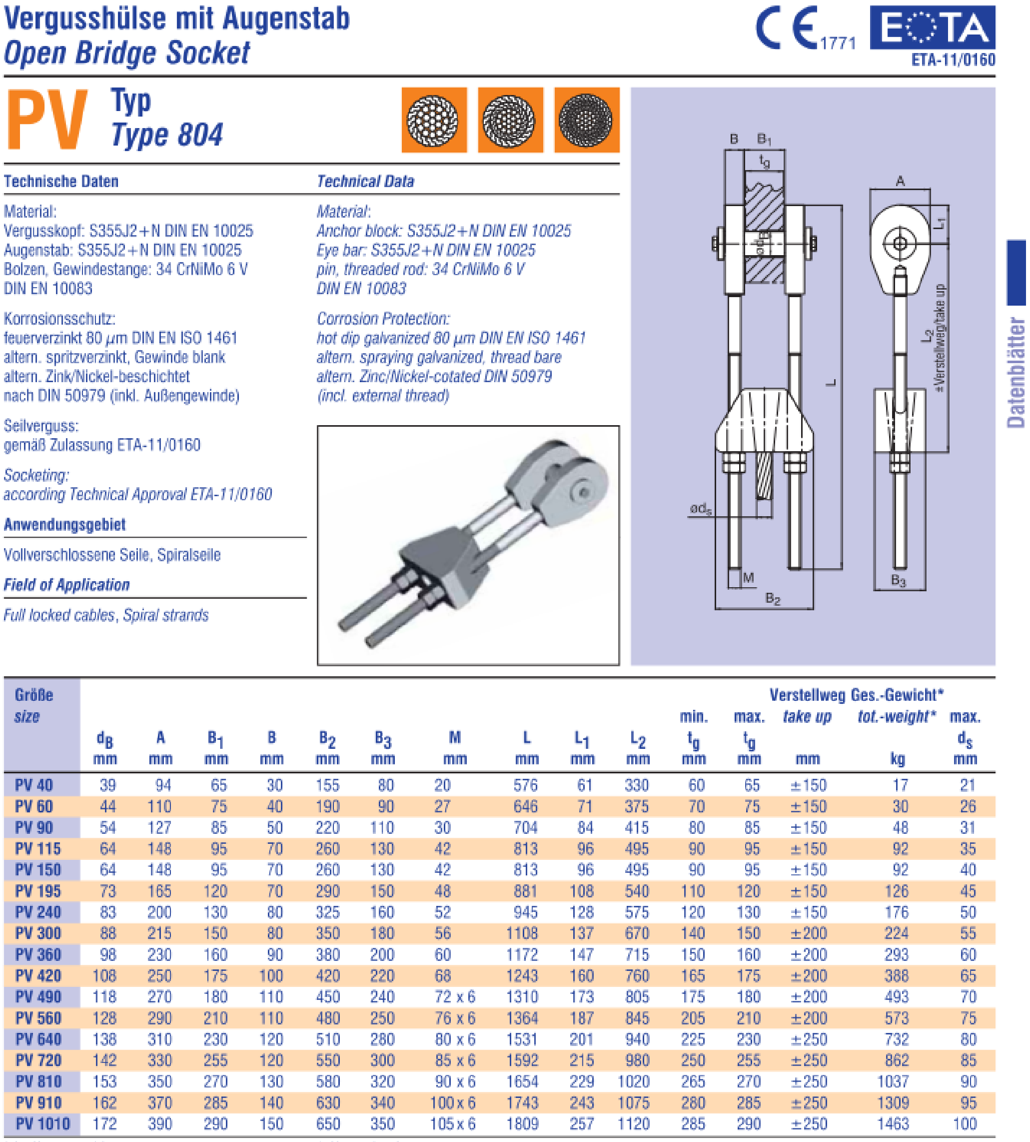
Berechnet für charakteristische Bruchkraft.

Calculations are based on characteristical breaking load of the cables.

Größe *size*	A mm	B mm	min. B_1 mm	max. B_1 mm	d_B mm	d_L mm	max. E mm	G mm	L_1 mm	L mm	Ges.-Gewicht* *tot.-weight** kg	max. d_S mm
PV 40	93	35	29	31	39	42	57	108	55	168	4	21
PV 60	116	43	36	39	44	47	70	128	68	208	7	26
PV 90	137	52	45	48	54	57	83	152	86	248	12	31
PV 115	153	60	52	55	59	62	93	168	91	280	17	35
PV 150	176	68	60	63	64	67	106	183	98	320	24	40
PV 195	197	77	69	72	73	76	120	213	110	360	34	45
PV 240	220	85	76	79	83	86	133	227	123	400	47	50
PV 300	241	94	85	88	88	91	146	257	140	440	63	55
PV 360	263	102	92	96	98	101	159	273	153	480	81	60
PV 420	285	111	100	105	108	111	173	306	165	520	104	65
PV 490	308	119	107	112	118	121	186	321	178	560	131	70
PV 560	329	128	114	121	128	131	199	346	195	600	163	75
PV 640	351	136	121	128	138	141	212	368	208	640	197	80
PV 720	372	145	129	137	142	145	226	382	220	680	232	85
PV 810	395	153	136	145	153	156	239	406	233	720	280	90
PV 910	416	162	144	153	162	165	252	432	253	760	330	95
PV 1010	438	170	151	161	172	175	265	457	263	800	386	100

6. Anclajes y conexiones

6.1 Aspectos básicos



Vergusshülse mit Augenstab
Open Bridge Socket

CE 1771 EOTA ETA-11/0160

PV Typ *Type 804*

Technische Daten	*Technical Data*
Material: Vergusskopf: S355J2+N DIN EN 10025 Augenstab: S355J2+N DIN EN 10025 Bolzen, Gewindestange: 34 CrNiMo 6 V DIN EN 10083	*Material:* *Anchor block: S355J2+N DIN EN 10025* *Eye bar: S355J2+N DIN EN 10025* *pin, threaded rod: 34 CrNiMo 6 V* *DIN EN 10083*
Korrosionsschutz: feuerverzinkt 80 µm DIN EN ISO 1461 altern. spritzverzinkt, Gewinde blank altern. Zink/Nickel-beschichtet nach DIN 50979 (inkl. Außengewinde)	*Corrosion Protection:* *hot dip galvanized 80 µm DIN EN ISO 1461* *altern. spraying galvanized, thread bare* *altern. Zinc/Nickel-cotated DIN 50979* *(incl. external thread)*

Seilverguss:
gemäß Zulassung ETA-11/0160

Socketing:
according Technical Approval ETA-11/0160

Anwendungsgebiet

Vollverschlossene Seile, Spiralseile

Field of Application

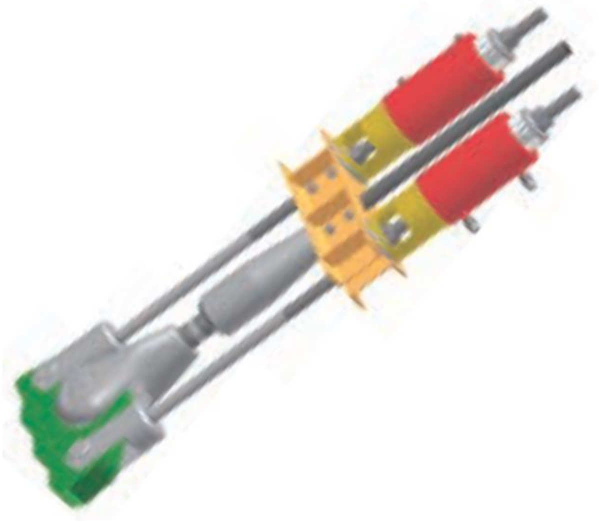
Full locked cables, Spiral strands

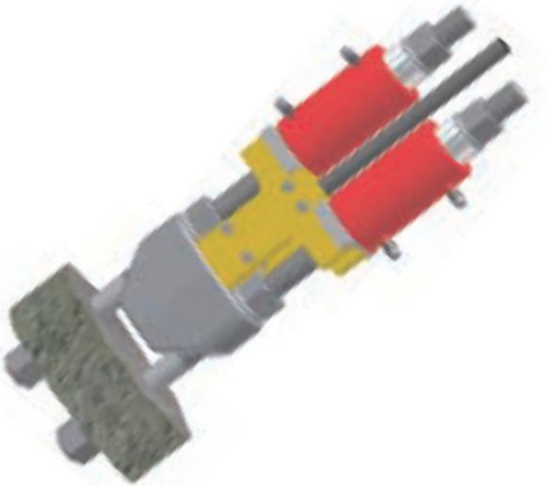
Datenblätter

Größe *size*	d_B mm	A mm	B_1 mm	B mm	B_2 mm	B_3 mm	M mm	L mm	L_1 mm	L_2 mm	min. t_g mm	max. t_g mm	Verstellweg *take up* mm	Ges.-Gewicht* *tot.-weight** kg	max. d_s mm
PV 40	39	94	65	30	155	80	20	576	61	330	60	65	±150	17	21
PV 60	44	110	75	40	190	90	27	646	71	375	70	75	±150	30	26
PV 90	54	127	85	50	220	110	30	704	84	415	80	85	±150	48	31
PV 115	64	148	95	70	260	130	42	813	96	495	90	95	±150	92	35
PV 150	64	148	95	70	260	130	42	813	96	495	90	95	±150	92	40
PV 195	73	165	120	70	290	150	48	881	108	540	110	120	±150	126	45
PV 240	83	200	130	80	325	160	52	945	128	575	120	130	±150	176	50
PV 300	88	215	150	80	350	180	56	1108	137	670	140	150	±200	224	55
PV 360	98	230	160	90	380	200	60	1172	147	715	150	160	±200	293	60
PV 420	108	250	175	100	420	220	68	1243	160	760	165	175	±200	388	65
PV 490	118	270	180	110	450	240	72 x 6	1310	173	805	175	180	±200	493	70
PV 560	128	290	210	110	480	250	76 x 6	1364	187	845	205	210	±200	573	75
PV 640	138	310	230	120	510	280	80 x 6	1531	201	940	225	230	±250	732	80
PV 720	142	330	255	120	550	300	85 x 6	1592	215	980	250	255	±250	862	85
PV 810	153	350	270	130	580	320	90 x 6	1654	229	1020	265	270	±250	1037	90
PV 910	162	370	285	140	630	340	100 x 6	1743	243	1075	280	285	±250	1309	95
PV 1010	172	390	290	150	650	350	105 x 6	1809	257	1120	285	290	±250	1463	100

6. Anclajes y conexiones

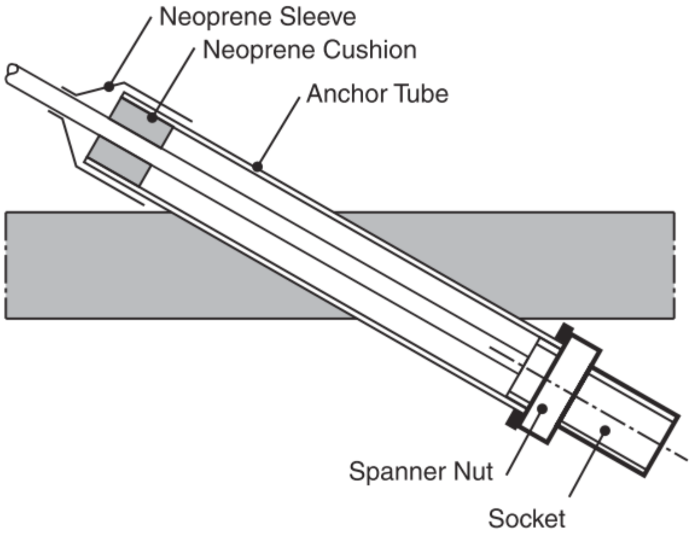
6.1 Aspectos básicos

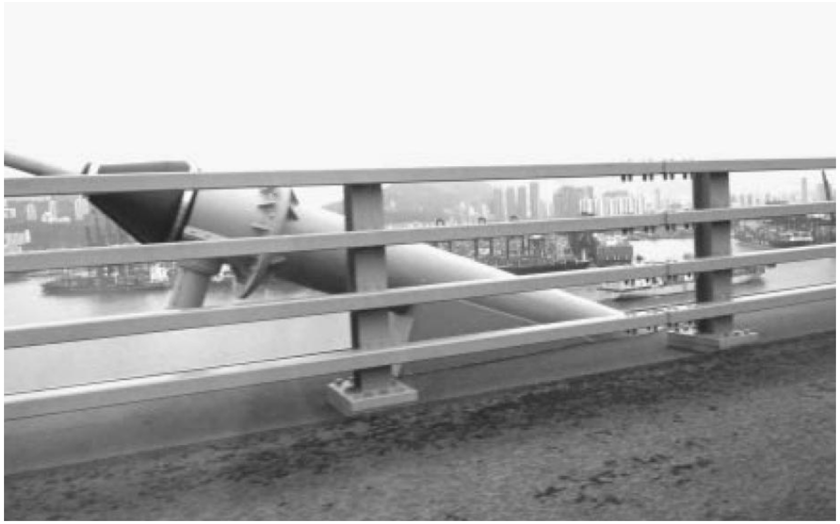


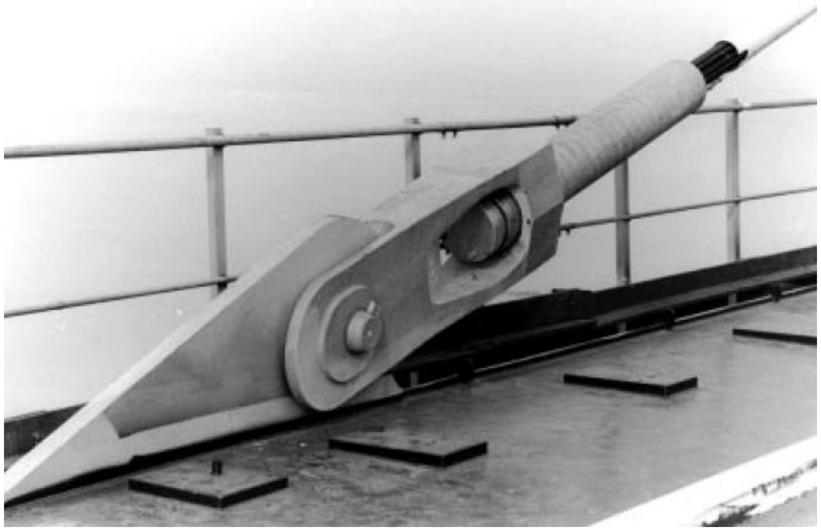


6. Anclajes y conexiones

6.1 Aspectos básicos

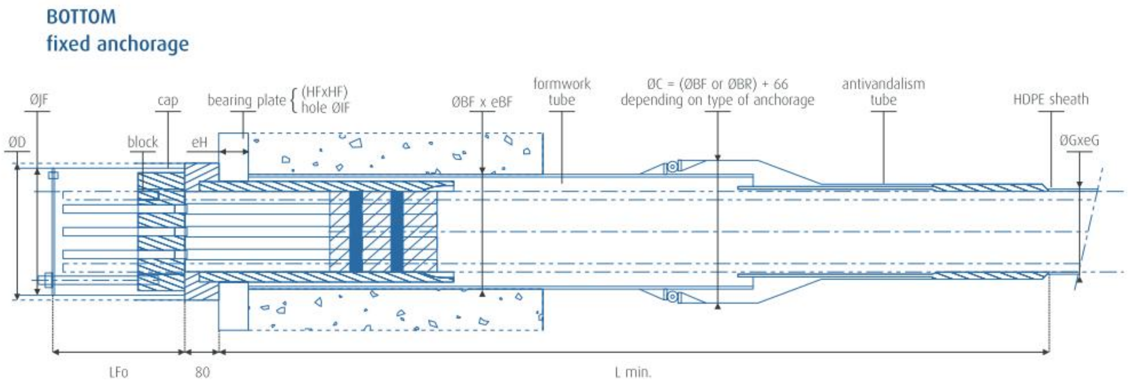




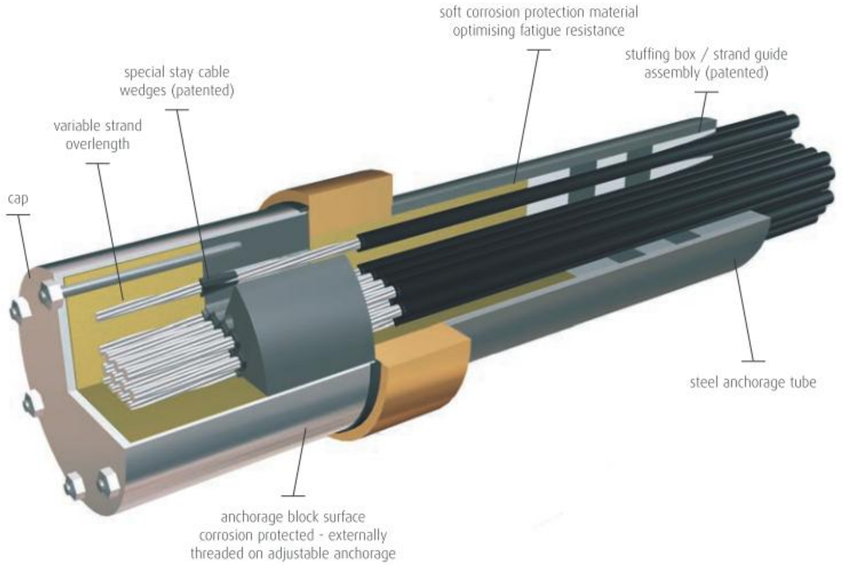


6. Anclajes y conexiones

6.1 Aspectos básicos



Bundle of Freyssinet Monostrand in a co-extruded HDPE sheath with double helical fillets

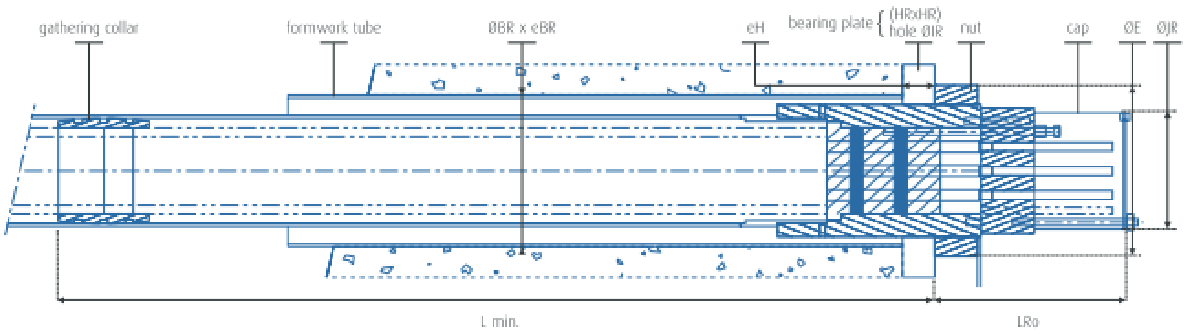


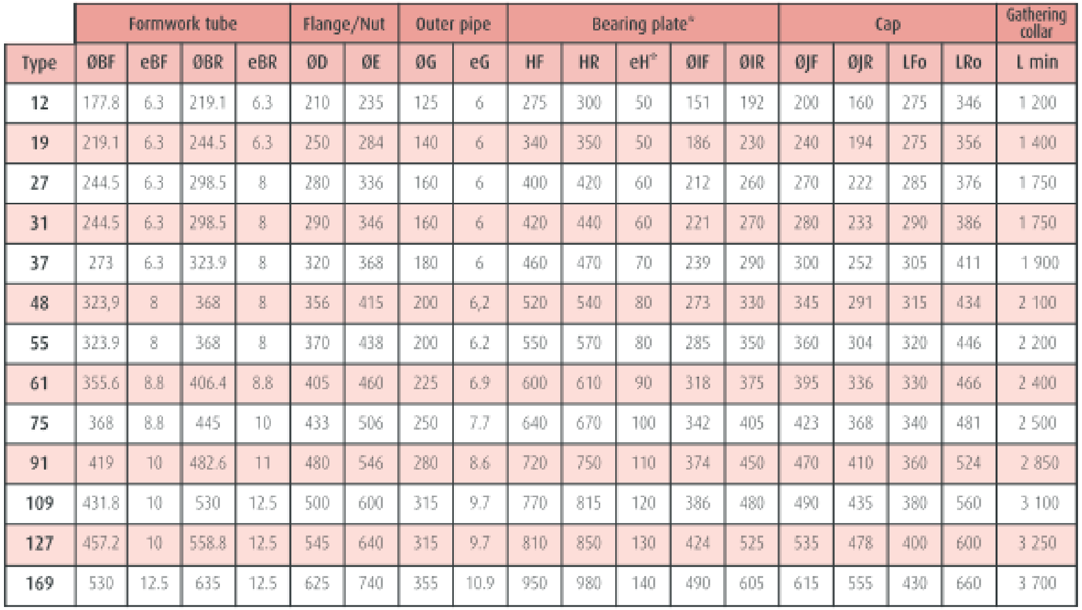
6. Anclajes y conexiones

6.1 Aspectos básicos

(LCPC, Nantes, France)

TOP
adjustable anchorage



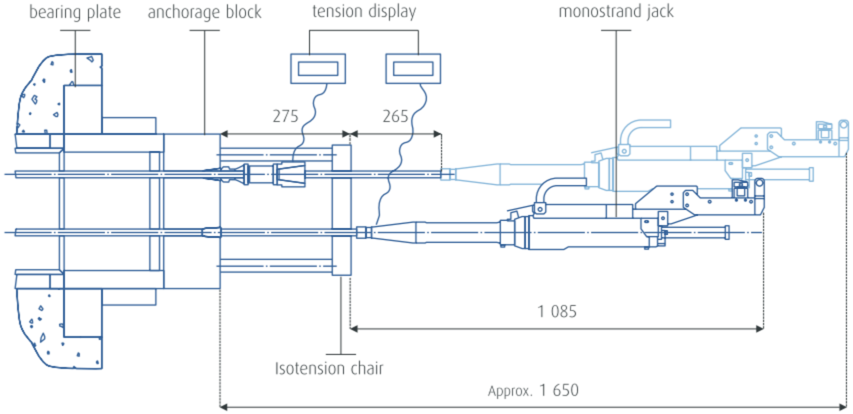


	Formwork tube				Flange/Nut		Outer pipe		Bearing plate*					Cap				Gathering collar
Type	**ØBF**	**eBF**	**ØBR**	**eBR**	**ØD**	**ØE**	**ØG**	**eG**	**HF**	**HR**	**eH***	**ØIF**	**ØIR**	**ØJF**	**ØJR**	**LFo**	**LRo**	**L min**
12	177.8	6.3	219.1	6.3	210	235	125	6	275	300	50	151	192	200	160	275	346	1 200
19	219.1	6.3	244.5	6.3	250	284	140	6	340	350	50	186	230	240	194	275	356	1 400
27	244.5	6.3	298.5	8	280	336	160	6	400	420	60	212	260	270	222	285	376	1 750
31	244.5	6.3	298.5	8	290	346	160	6	420	440	60	221	270	280	233	290	386	1 750
37	273	6.3	323.9	8	320	368	180	6	460	470	70	239	290	300	252	305	411	1 900
48	323,9	8	368	8	356	415	200	6,2	520	540	80	273	330	345	291	315	434	2 100
55	323.9	8	368	8	370	438	200	6.2	550	570	80	285	350	360	304	320	446	2 200
61	355.6	8.8	406.4	8.8	405	460	225	6.9	600	610	90	318	375	395	336	330	466	2 400
75	368	8.8	445	10	433	506	250	7.7	640	670	100	342	405	423	368	340	481	2 500
91	419	10	482.6	11	480	546	280	8.6	720	750	110	374	450	470	410	360	524	2 850
109	431.8	10	530	12.5	500	600	315	9.7	770	815	120	386	480	490	435	380	560	3 100
127	457.2	10	558.8	12.5	545	640	315	9.7	810	850	130	424	525	535	478	400	600	3 250
169	530	12.5	635	12.5	625	740	355	10.9	950	980	140	490	605	615	555	430	660	3 700

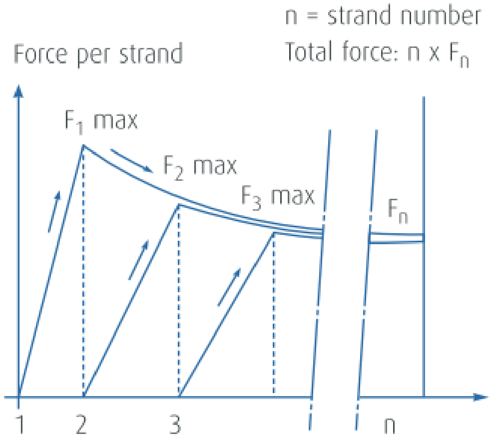
*Dimensions in mm. * The bearing plate dimensions shown above correspond to concrete structure with* $\acute{O}_{28\ days} \geq 36$ *MPa.*
For steel structures, plan dimensions are valid as minimum, thickness eH is to be designed.

6. Anclajes y conexiones

6.1 Aspectos básicos

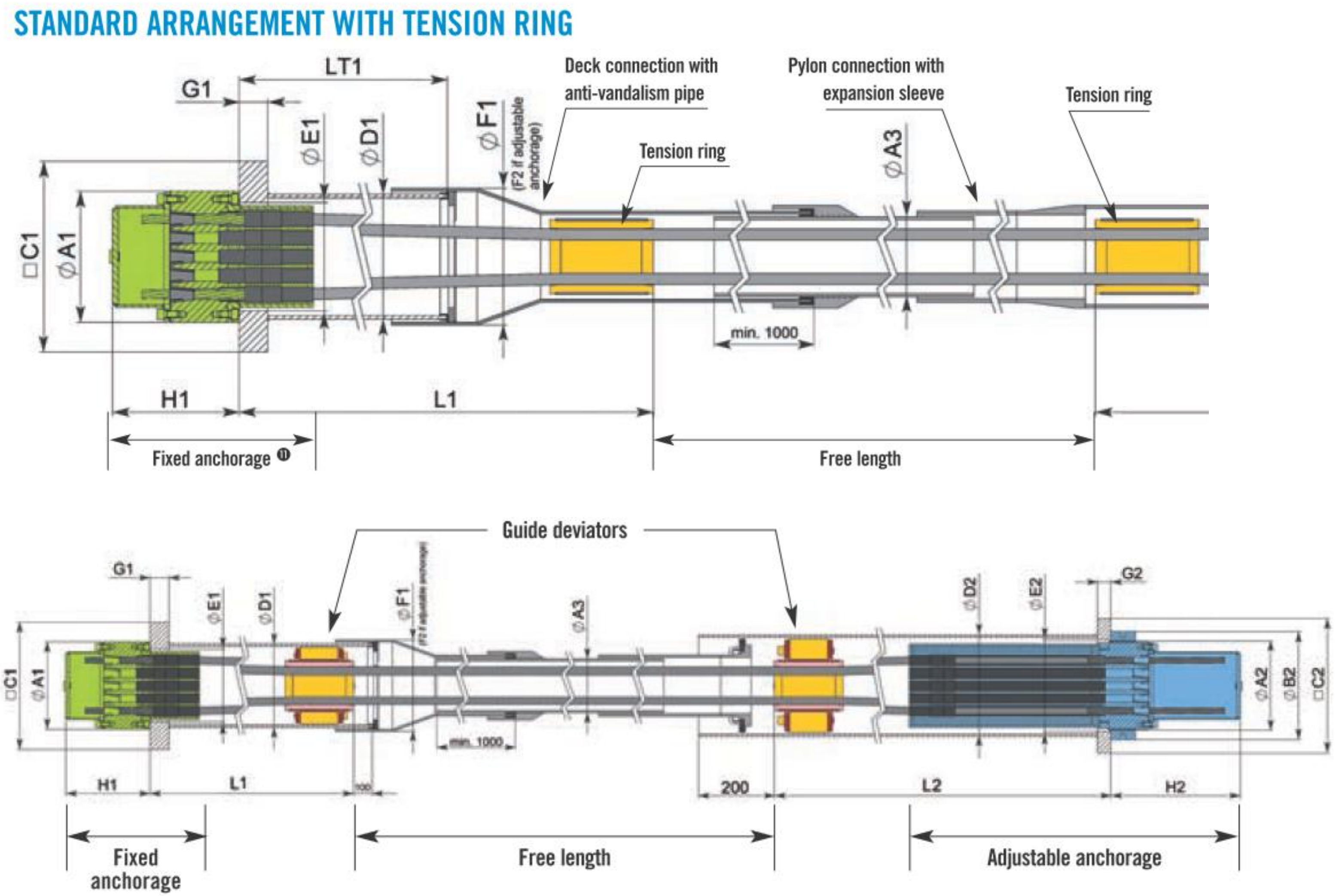


Isotension® principle diagram



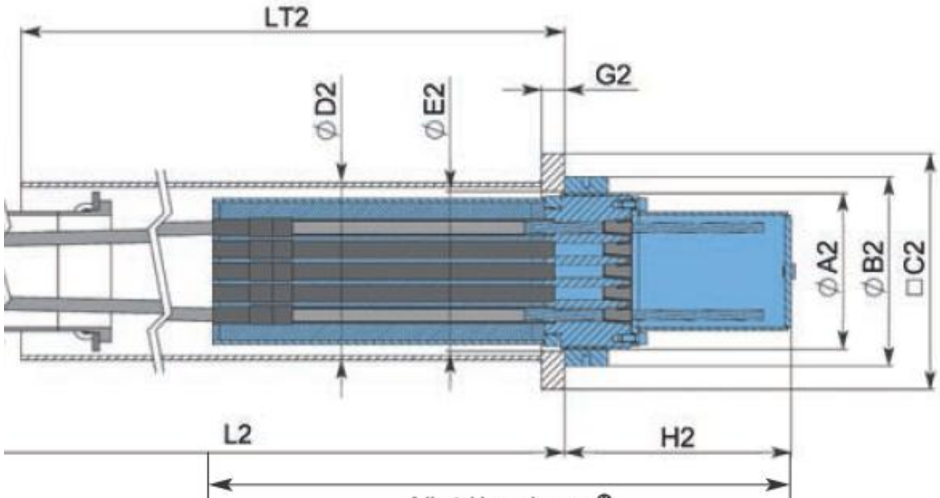
6. Anclajes y conexiones

6.1 Aspectos básicos



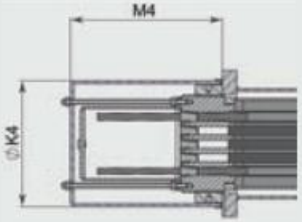
6. Anclajes y conexiones

6.1 Aspectos básicos

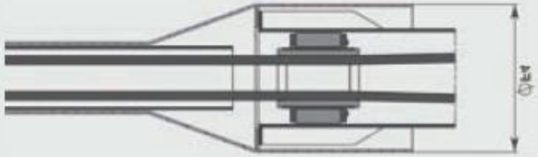


Adjustable anchorage ⑪

OPTIONAL ITEMS

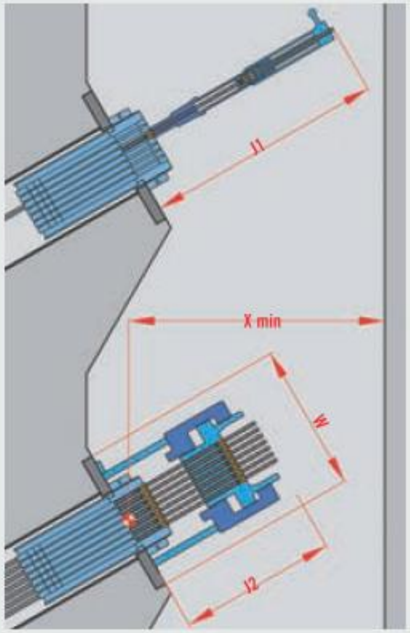


Optional anchorage cap
for adjustable anchorage in severe environments class C5-M and -I as per ISO 12944



Optional anti-vandalism pipe
for future provision of damper

Required clearances
In case of facing adjustable anchorages, it is recommended to provide two times the minimum clearance. *If reduced clearances are required, please contact VSL.*

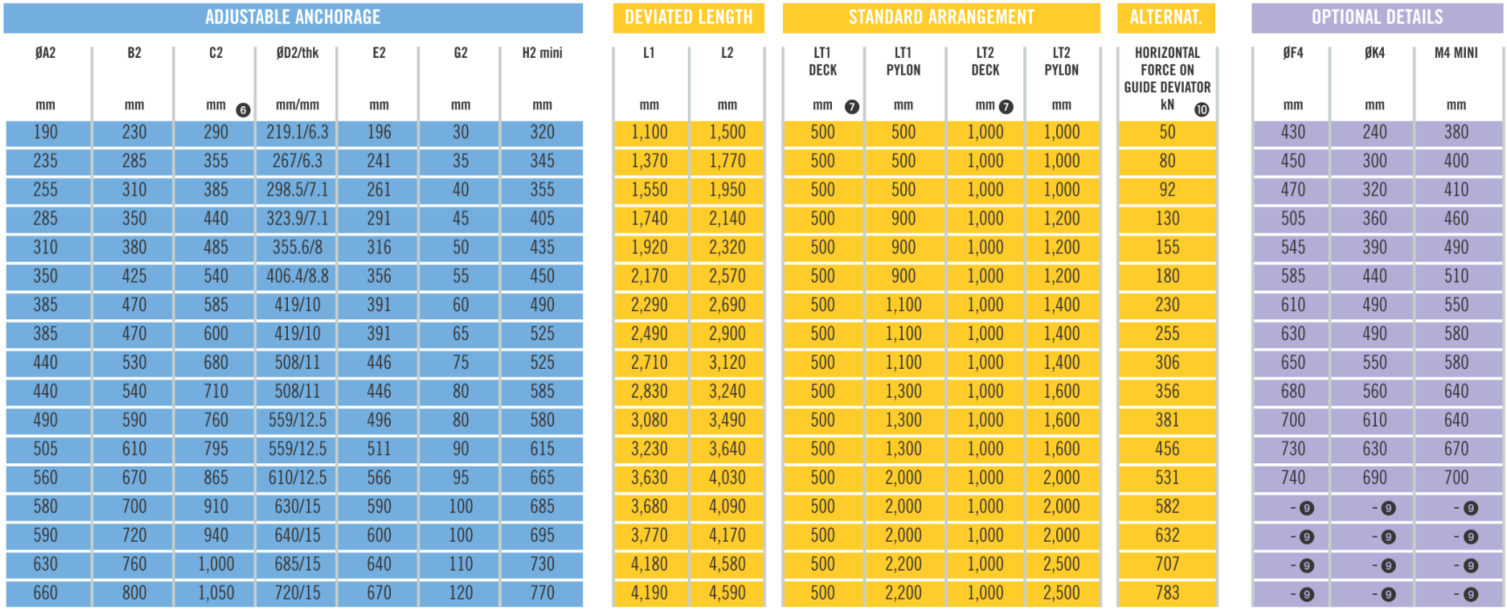


Required jack clearances

ANCHORAGE UNIT	W mm	J1 mm	J2 mm	Xmin mm
6-12 to 6-19	490	1,000	1,000	1,500
6-22 to 6-43	620	1,050	1,100	1,500
6-55 to 6-73	780	1,100	1,200	1,500
6-85 to 6-91	780	1,150	1,300	1,500
6-109 to 6-127	970	1,200	1,500	1,800
6-139 to 6-187	- ⑨	1,250	- ⑨	2,000

6. Anclajes y conexiones

6.1 Aspectos básicos

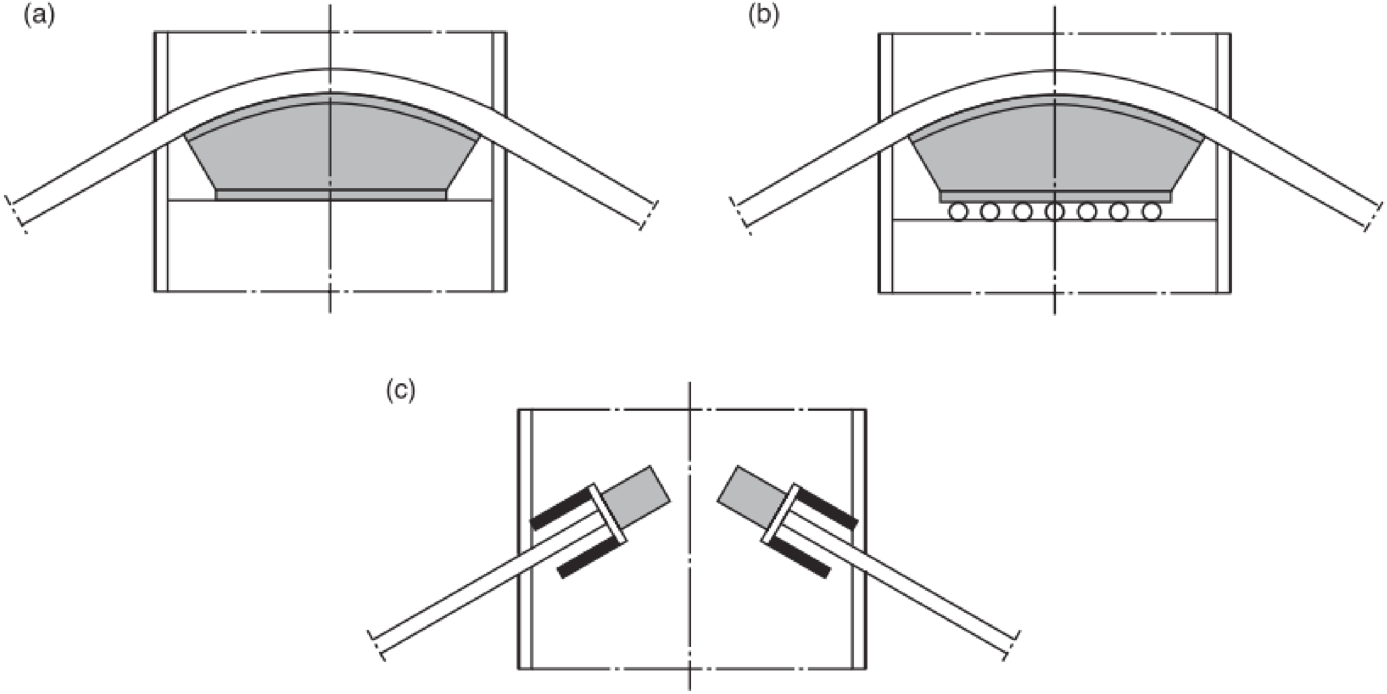


ADJUSTABLE ANCHORAGE							DEVIATED LENGTH		STANDARD ARRANGEMENT				ALTERNAT.	OPTIONAL DETAILS		
ØA2 mm	B2 mm	C2 mm ⑥	ØD2/thk mm/mm	E2 mm	G2 mm	H2 mini mm	L1 mm	L2 mm	LT1 DECK mm ⑦	LT1 PYLON mm	LT2 DECK mm ⑦	LT2 PYLON mm	HORIZONTAL FORCE ON GUIDE DEVIATOR kN ⑩	ØF4 mm	ØK4 mm	M4 MINI mm
190	230	290	219.1/6.3	196	30	320	1,100	1,500	500	500	1,000	1,000	50	430	240	380
235	285	355	267/6.3	241	35	345	1,370	1,770	500	500	1,000	1,000	80	450	300	400
255	310	385	298.5/7.1	261	40	355	1,550	1,950	500	500	1,000	1,000	92	470	320	410
285	350	440	323.9/7.1	291	45	405	1,740	2,140	500	900	1,000	1,200	130	505	360	460
310	380	485	355.6/8	316	50	435	1,920	2,320	500	900	1,000	1,200	155	545	390	490
350	425	540	406.4/8.8	356	55	450	2,170	2,570	500	900	1,000	1,200	180	585	440	510
385	470	585	419/10	391	60	490	2,290	2,690	500	1,100	1,000	1,400	230	610	490	550
385	470	600	419/10	391	65	525	2,490	2,900	500	1,100	1,000	1,400	255	630	490	580
440	530	680	508/11	446	75	525	2,710	3,120	500	1,100	1,000	1,400	306	650	550	580
440	540	710	508/11	446	80	585	2,830	3,240	500	1,300	1,000	1,600	356	680	560	640
490	590	760	559/12.5	496	80	580	3,080	3,490	500	1,300	1,000	1,600	381	700	610	640
505	610	795	559/12.5	511	90	615	3,230	3,640	500	1,300	1,000	1,600	456	730	630	670
560	670	865	610/12.5	566	95	665	3,630	4,030	500	2,000	1,000	2,000	531	740	690	700
580	700	910	630/15	590	100	685	3,680	4,090	500	2,000	1,000	2,000	582	- ⑨	- ⑨	- ⑨
590	720	940	640/15	600	100	695	3,770	4,170	500	2,000	1,000	2,000	632	- ⑨	- ⑨	- ⑨
630	760	1,000	685/15	640	110	730	4,180	4,580	500	2,200	1,000	2,500	707	- ⑨	- ⑨	- ⑨
660	800	1,050	720/15	670	120	770	4,190	4,590	500	2,200	1,000	2,500	783	- ⑨	- ⑨	- ⑨

⑤ *Galvanized strand in accordance with NF A 35-035*
⑥ *Square bearing plate based on concrete strength of 45MPa cube (36MPa cylinder); dimensions can be adjusted for other concrete strength or steel structures*
⑦ *Can be reduced if required; please contact VSL*
⑧ *Larger units available on request*
⑨ *Dimensions available on request*
⑩ *SLS Level*
⑪ *Fixed or adjustable anchorages are interchangeable between pylon and deck, see dimensions L1 and L2*

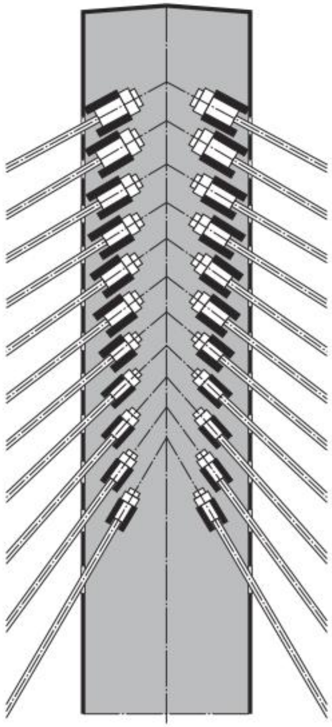
6. Anclajes y conexiones

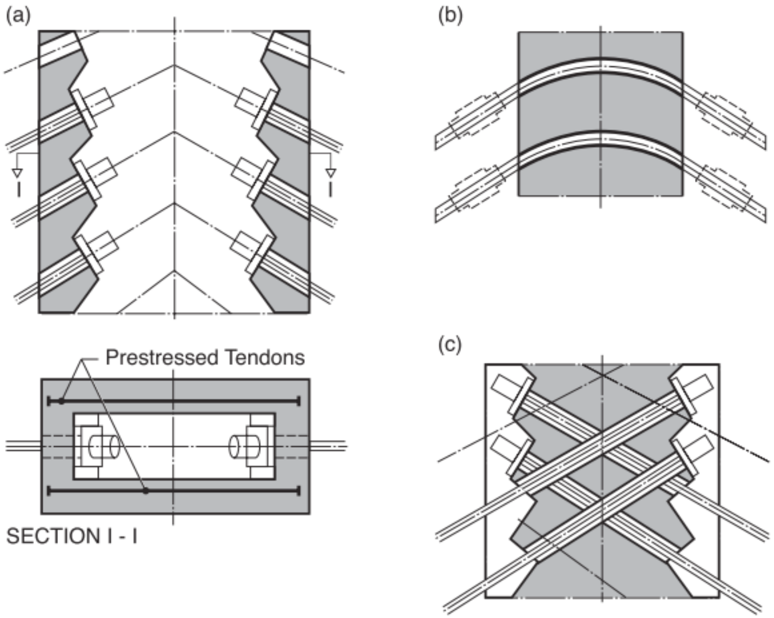
6.2 Anclaje en Pilono



6. Anclajes y conexiones

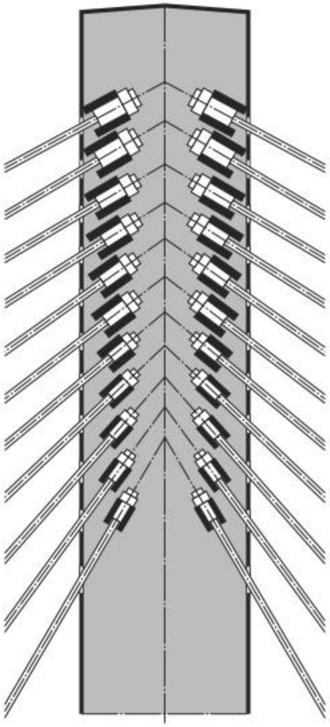
6.2 Anclaje en Pilono

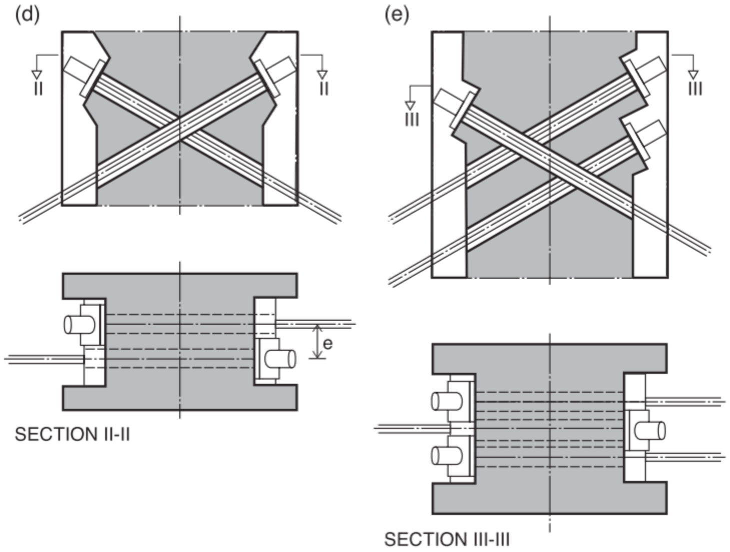




6. Anclajes y conexiones

6.2 Anclaje en Pilono





6. Anclajes y conexiones

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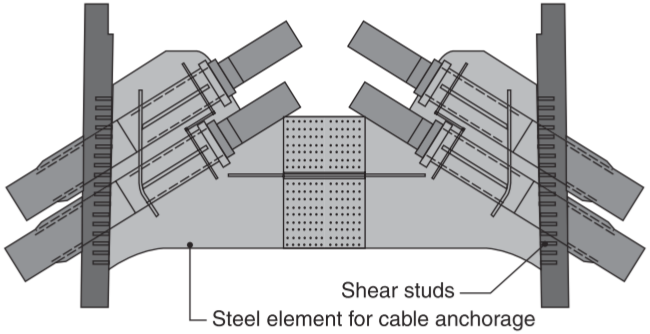
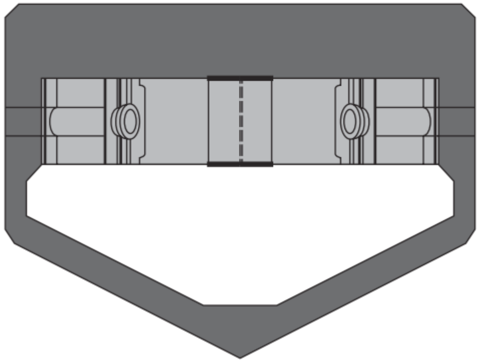




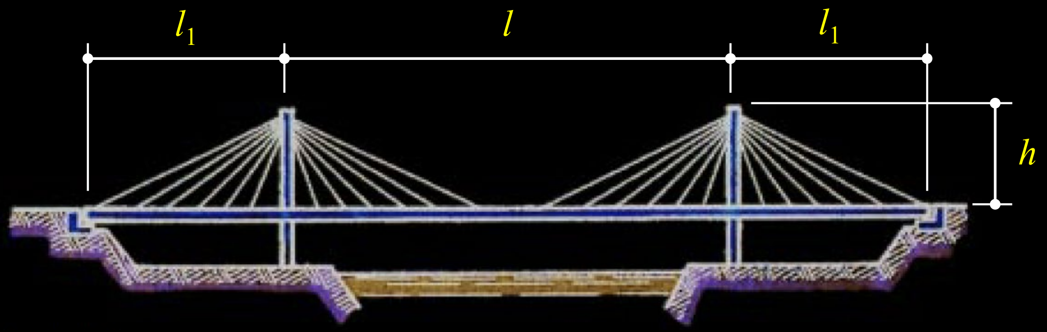
Cable-supported bridges – Cable-Stayed Bridges: Conceptual Design

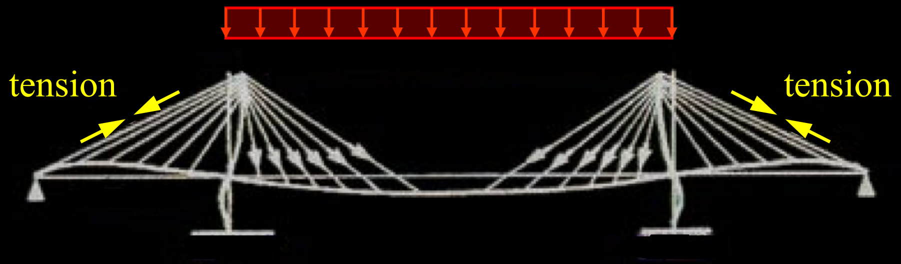
- Basic proportions of cable-stayed bridges:

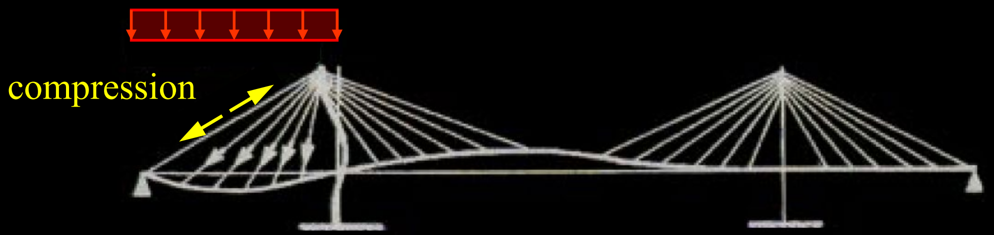
  The geometry of cable-stayed bridges is determined by the following ratios:

  → Side spans (l_1) to main span (l) ratio:

  - Backstays govern the stiffness of the bridge and are subject to significant stress reversals
  - l_1 / l ratio determines the fatigue stress range in the backstays and demands for tie-down devices / counterweights at anchor piers







Cable-supported bridges – Cable-Stayed Bridges: Conceptual Design

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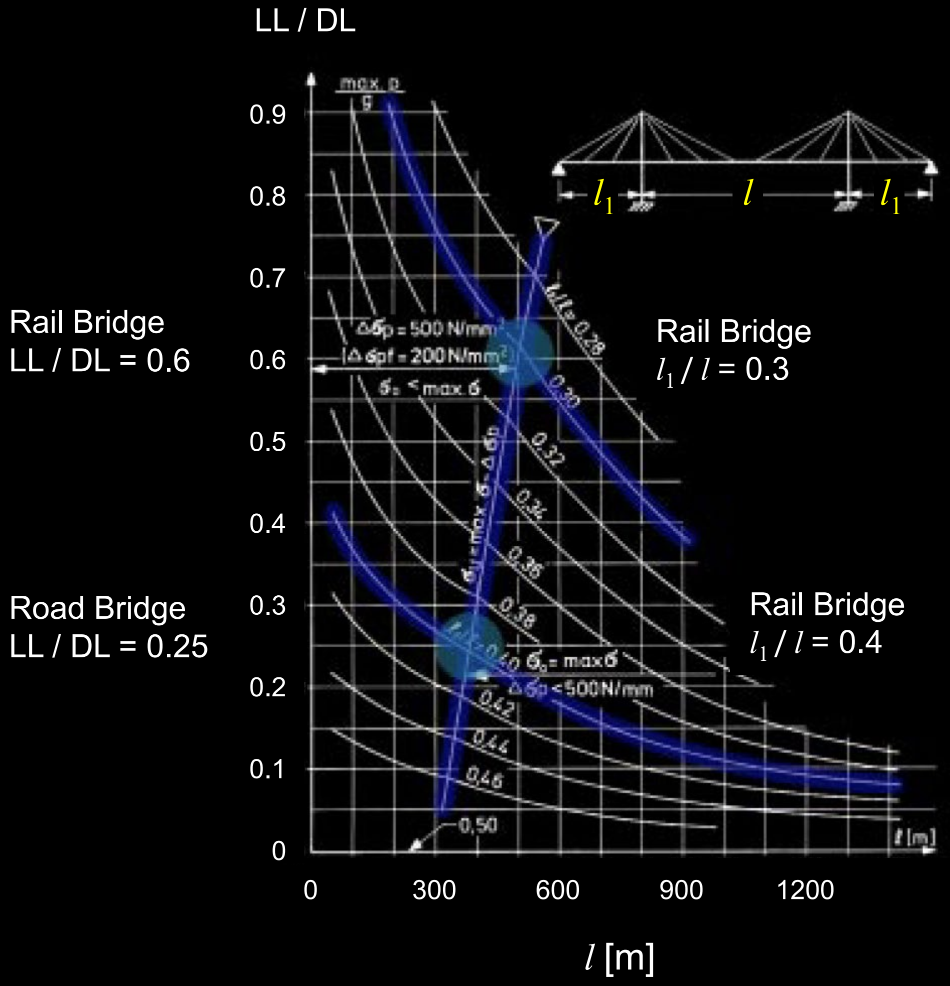
  - l_1 / l ratio determines the fatigue stress range in the backstays and demands for tie-down devices / counterweights at anchor piers
  - Optimum l_1 / l ratio depends on LL / DL ratio:
    - Road bridges, $l_1 / l = 0.4 \dots 0.5$
    - Rail bridges, $l_1 / l = 0.3 \dots 0.4$

  → Tower height (h) to main span (l) ratio:

  - Controlled by flattest stay: optimum angle ≈ 23 deg (inclination ca. 40%)
  - Optimum h / l ratio ≈ 1/5 (compare to 1/10 for suspension bridges)

Recommended side span / main span ratios [Svensson 2012]



Cable-supported bridges – Cable-Stayed Bridges: Conceptual Design

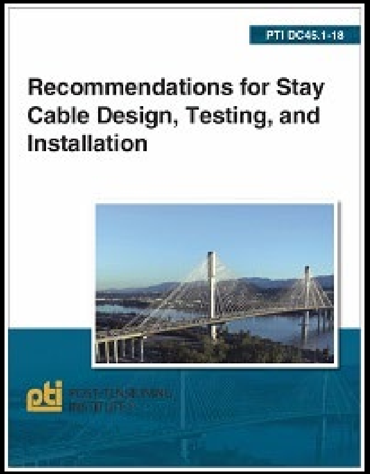
- Design Development:

→ Project Specific Design Criteria:

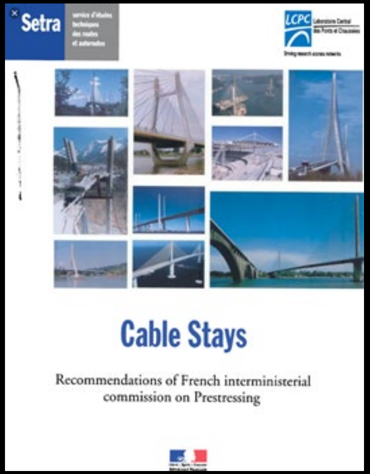
Long-span, cable-supported bridges are typically not fully covered by the provisions of standard bridge codes. Topics that may require development of project-specific criteria (→ service criteria agreement) may include:

  - Load combinations
  - Serviceability requirements, e.g. deflection limits
  - Wind loading / Aerodynamic vibrations
  - Stay cable systems acceptance criteria
  - Progressive collapse requirements (e.g. accidental cable loss)

→ Guideline documents for stay cable design, testing and installation have been developed to supplement the standard bridge codes

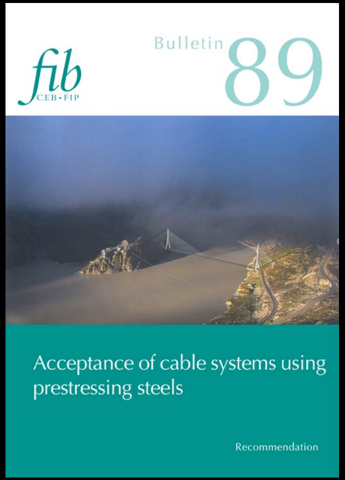

PTI DC45.1-18

Recommendations for Stay Cable Design, Testing, and Installation


Setra

Cable Stays

Recommendations of French interministerial commission on Prestressing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Bulletin 89

Acceptance of cable systems using prestressing steels

Recommendation

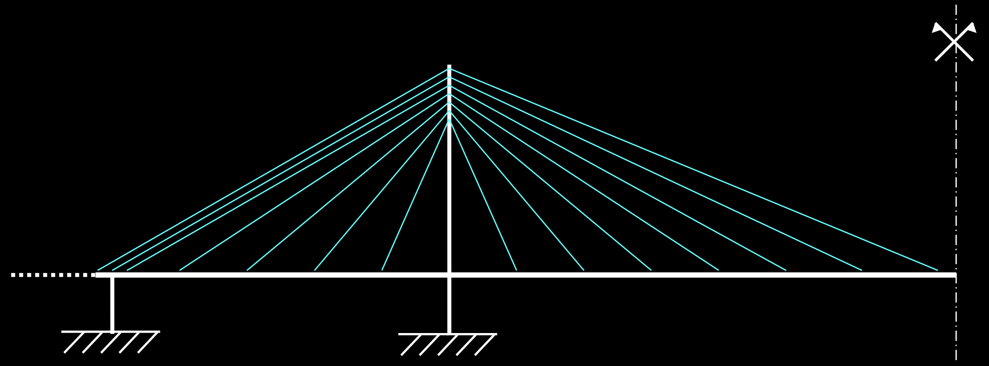
Cable-supported bridges – Cable-Stayed Bridges: Structural Response

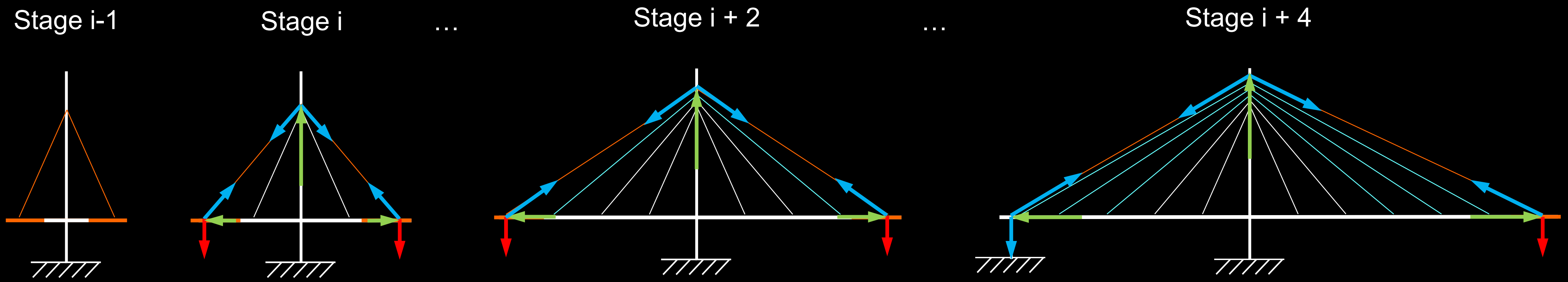
- Basic load-carrying mechanism of a cable-stayed bridge:

→ Response to Dead Load:

Stay cables:

- Each stay cable can be assumed to support a tributary length of the girder
- Backstays are the exception: they are used to resist the unbalanced load in the main span





Cable-supported bridges – Cable-Stayed Bridges: Structural Response

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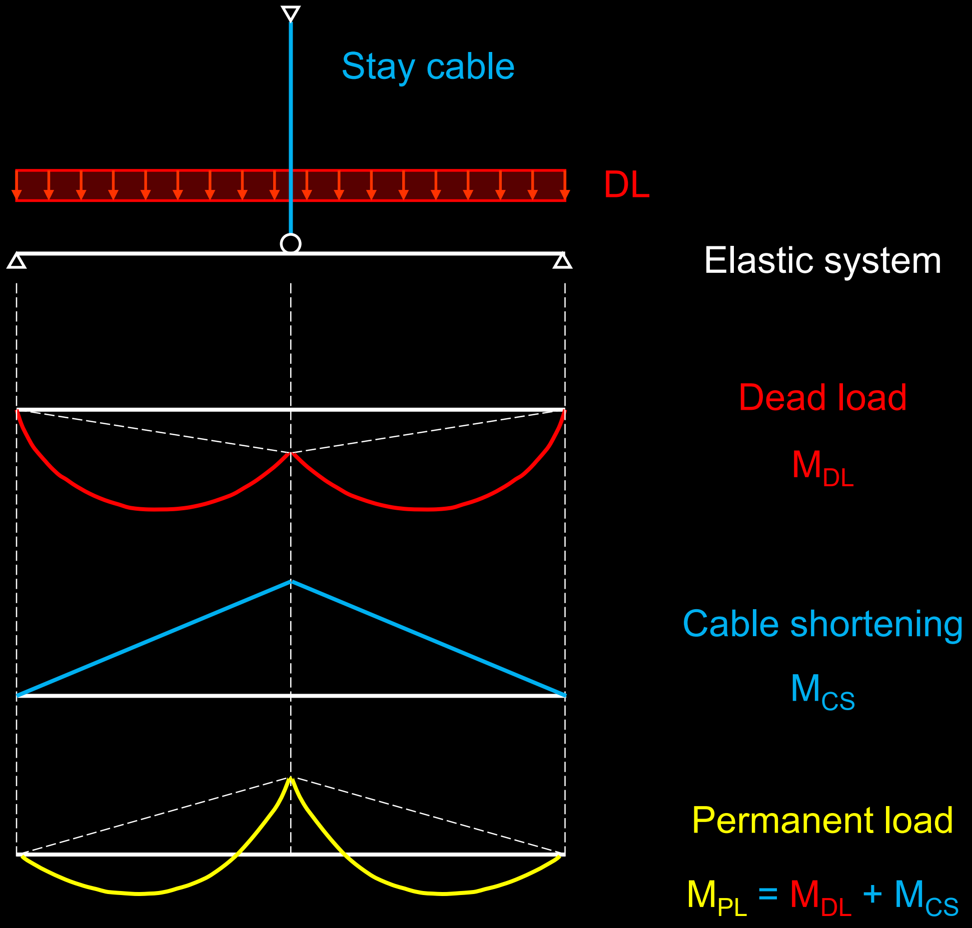
Girder:

- DL application on the elastic system results in significant deflections and corresponding moments
- Appropriate cable shortenings are required to restore the girder to the target profile and moment diagram



Cable-supported bridges – Cable-Stayed Bridges: Structural Response

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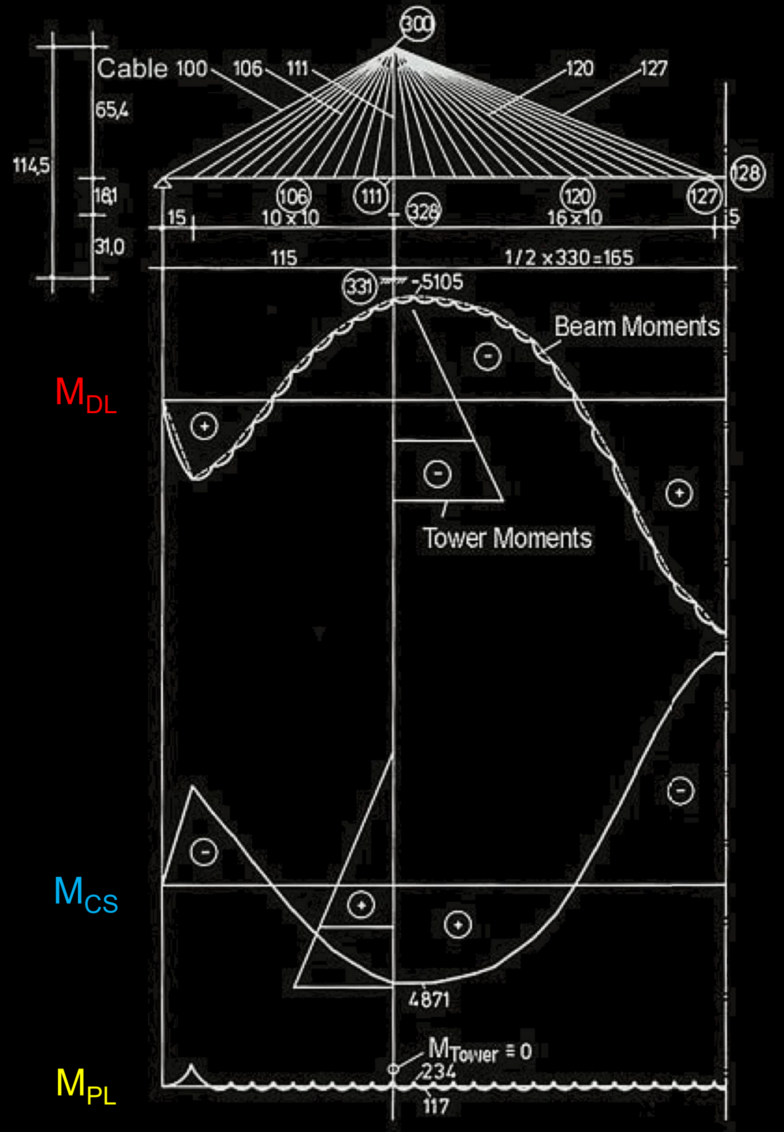


Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Basic load-carrying mechanism of a cable-stayed bridge:

→ Response to Live Load - Characteristic Influence Lines:

Stay cables:

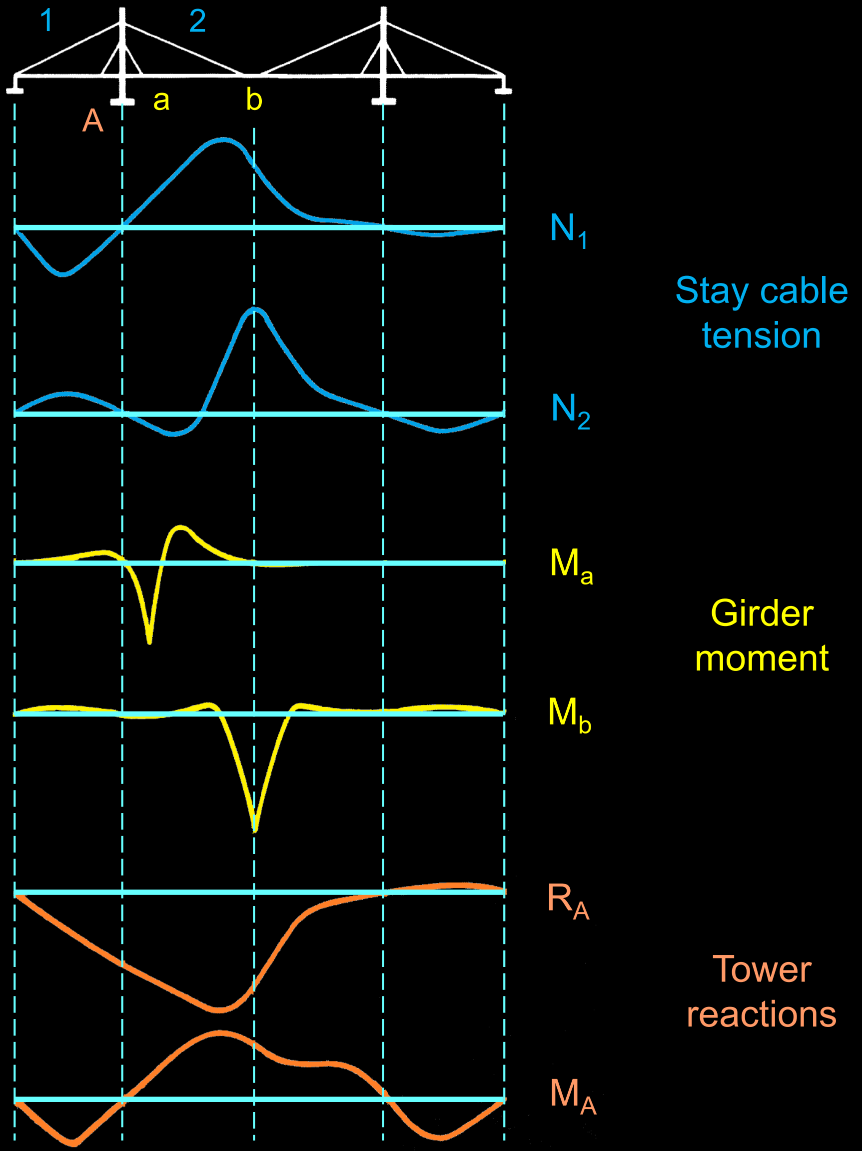
- The backstay function is fundamental to the efficiency of the bridge
- Backstays have very "broad" influence line: design controlled by fatigue in railway bridges (fatigue loads extending over large portion of span)

Girder:

- Behaviour similar to beam on elastic foundation
- Function of girder stiffness, cable stiffness and cable spacing

Towers / Anchor Piers:

- Provided that the tower is anchored through backstays to an anchor pier, the tower resists mainly vertical reactions
- In the absence of an anchor pier, the influence of the tower stiffness to the girder response is much more pronounced (see also multi-span cable-stayed bridges)

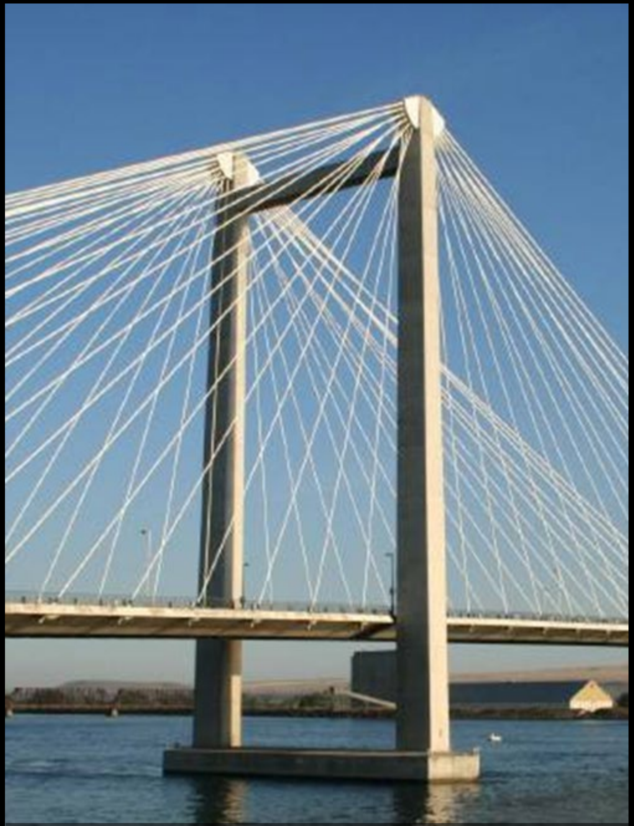


Cable-supported bridges – Cable-Stayed Bridges: Structural Response

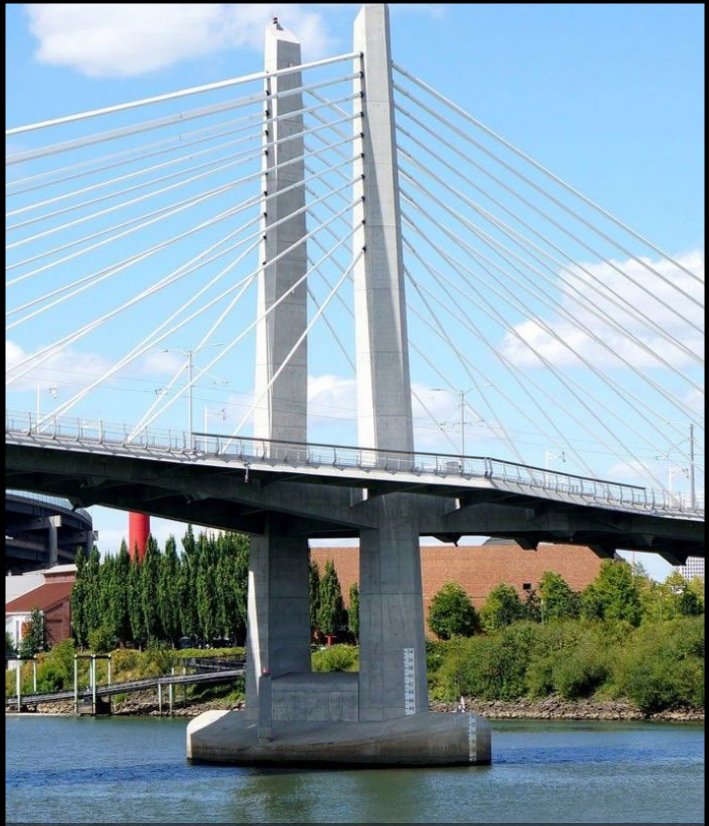
- Particularities of cable-stayed bridges:

→ Support and articulation

  - Girder must be continuous through towers (highest axial compression), but can be articulated at mid-span (not recommended)
  - Girder is commonly articulated at anchor piers, but may also be made continuous with the approach span girder
  - The connection between the girder and towers / anchor piers in the vertical, longitudinal and transverse directions can be tailored to best fit the governing loading and site conditions:
    - ✓ The concepts presented in the Support and Articulation section are generally applicable



Floating Deck – No connection to tower



Intergral Deck – monolithic connection to tower

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:

→ Tower stability

- Towers are typically slender and subject to high axial compressive forces → 2nd order effects important
- Towers are often most vulnerable during the construction phase: boundary and loading conditions are less favourable than in the final state
- Flexural stiffness and strength are a function of the axial load

Buckling load depends on EI and kL:

$$P_{cr} = \pi^2 \frac{EI}{(kL)^2}$$

EI varies based on the level of cracking

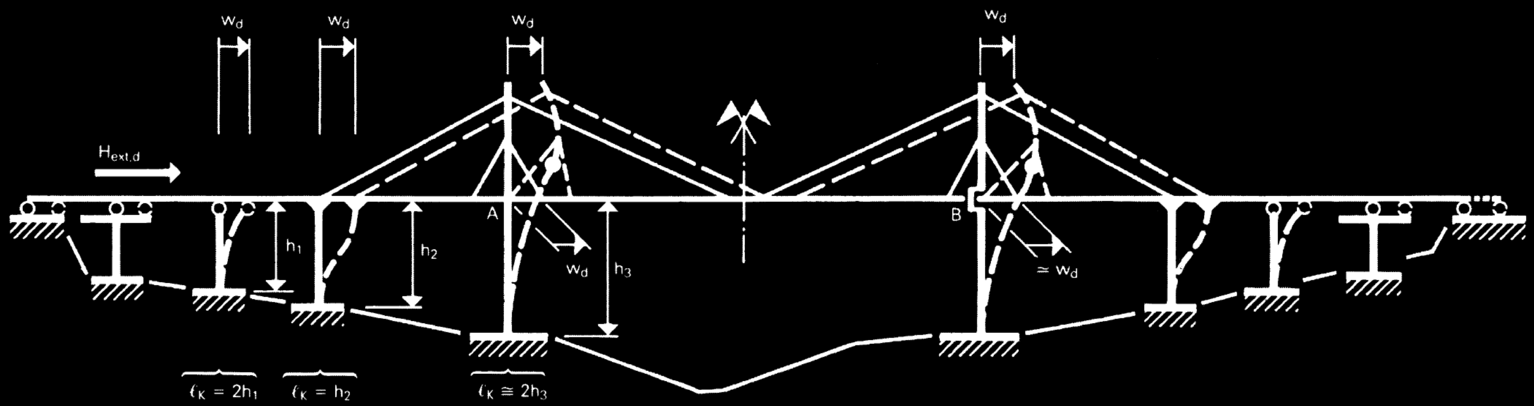
$k_{\min} = 0.8$

$k_{\max} = 2.0$

$$\left(\frac{k_{\max}}{k_{\min}}\right)^2 = 6.25$$

$k \approx 1.0 << 2.0$

Anchorage point



Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:

→ Tower stability - Example

Arthur Ravenel Jr. (Cooper River) Bridge, SC, USA, 2005. Parsons Brinkerhoff Quade & Douglas

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

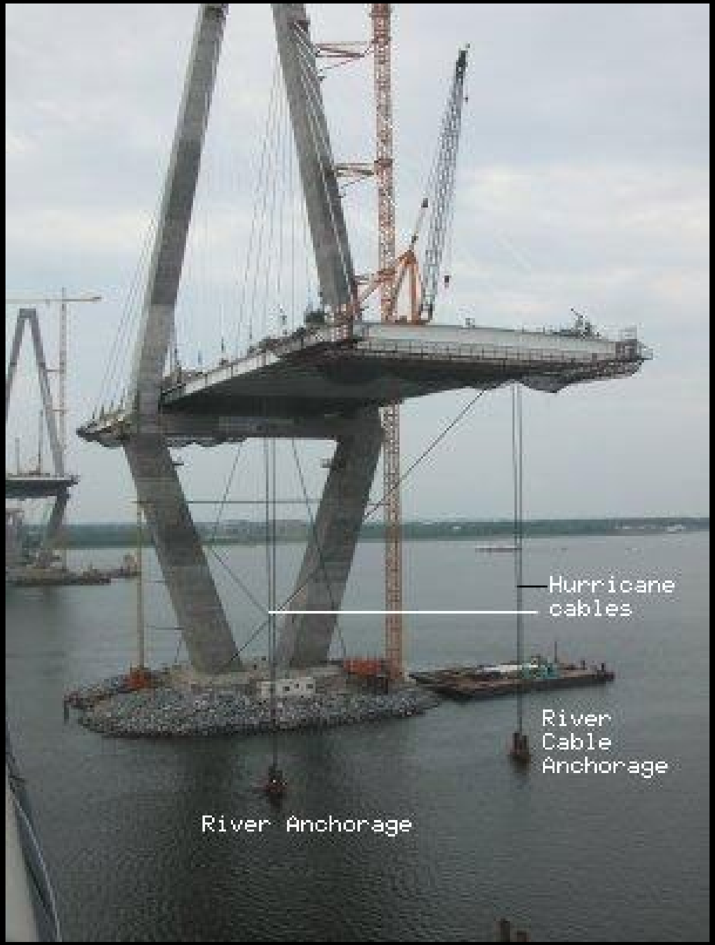
- Particularities of cable-stayed bridges:

→ Tower stability - Example

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:

→ Tower stability - Example



Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:

→ Tower stability - Example

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:

→ Redundancy requirements: Accidental cable loss

  - Modern cable-stayed bridges are designed with closely-spaced stay cables so that accidental loss of a cable will not result in progressive collapse
  - Furthermore, stay cables are considered replaceable components and therefore cable exchange must be possible during service
  - Planned cable exchange is performed strand by strand and therefore imposes static loading to the structure
  - Accidental cable loss, depending on the cause, can be relatively sudden (i.e. relative to the eigenfrequencies of the bridge) and must therefore be treated as dynamic loading

Seohae Grand Bridge, South Korea, 2000. TYLI

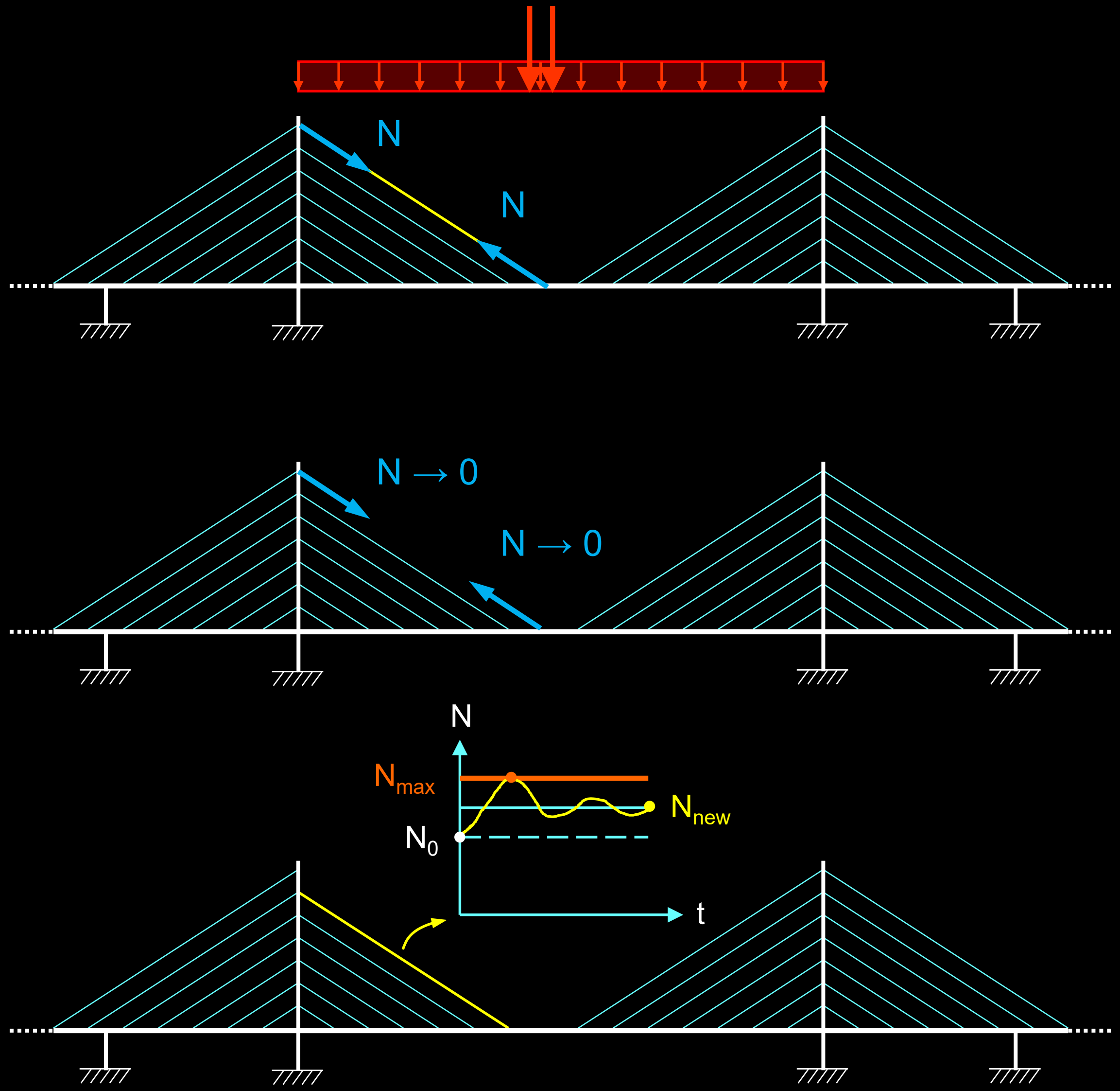
Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:

→ Redundancy requirements: Accidental cable loss

Time-history analysis approach:

1. Apply LL that maximises the axial force of the stay cable in question to the intact structure and obtain the total axial force in the cable for the considered load combination
2. Remove stay cable in question from model and replace with corresponding reactions to tower and girder (initial conditions)
3. Run time-history analysis by removing cable reactions (reduce cable reaction to zero over a short time step)
4. Record response of structure over time, capture peak and final force effects and check that structure remains stable
5. Repeat steps 1 to 4 for all cables



Cable-supported bridges – Cable-Stayed Bridges: Structural Response

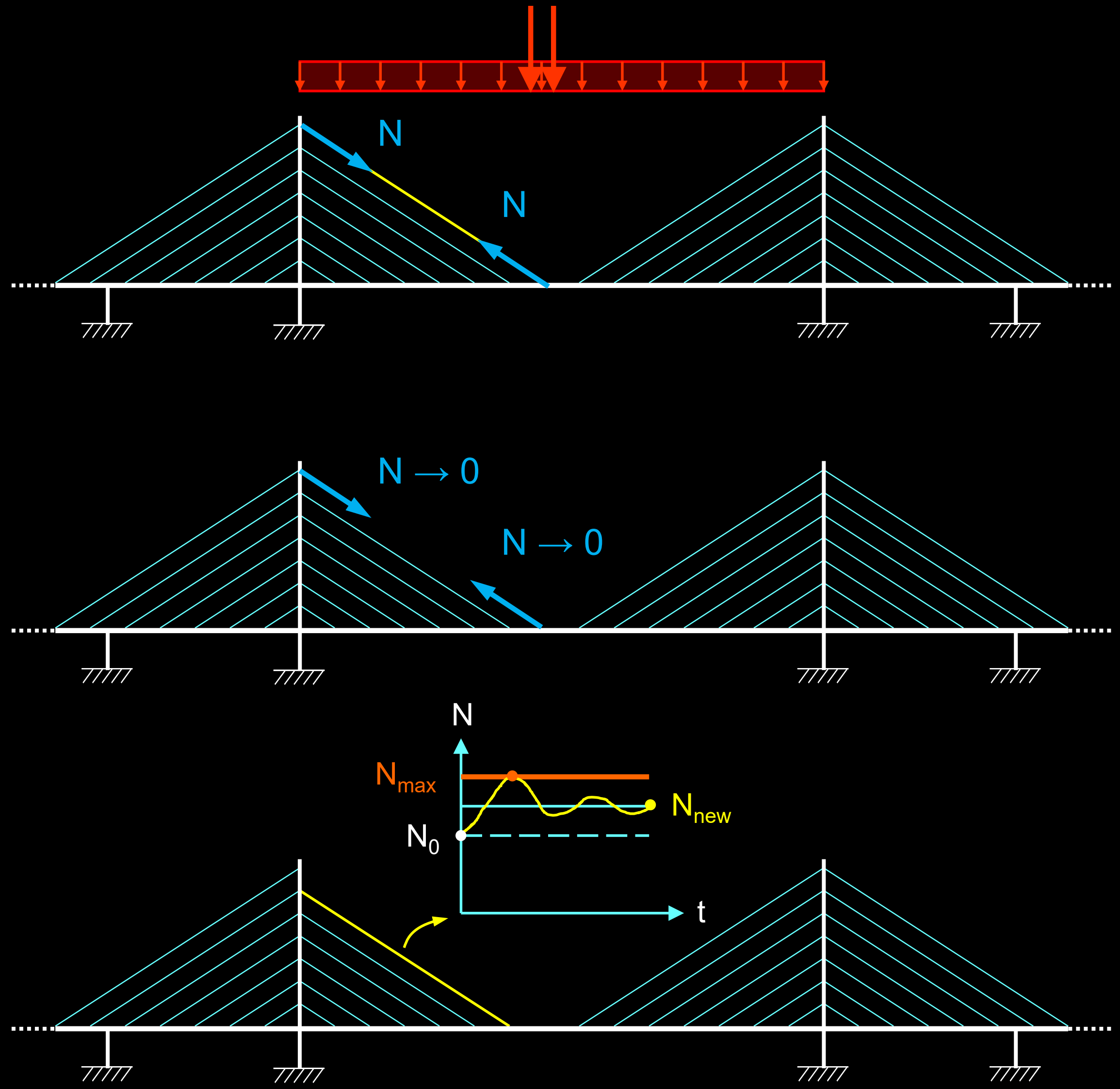
- Particularities of cable-stayed bridges:

→ Redundancy requirements: Accidental cable loss

Time-history analysis approach:

- Most precise approach
- Can consider geometric and material nonlinearities
- Selected material damping coefficients and time-step of cable loss can affect response significantly
- Labour/data intensive
- Can be avoided if a dynamic amplification factor of 2.0 is used in conjunction with a static approach (conservative)
- Can be used selectively to prove out dynamic amplification factors less than 2.0

$$N_{\max} = N_0 + \left(N_{new} - N_0\right)\cdot DAF \rightarrow \quad DAF = \frac{N_{\max} - N_0}{N_{new} - N_0}$$



Cable-supported bridges – Cable-Stayed Bridges: Structural Response

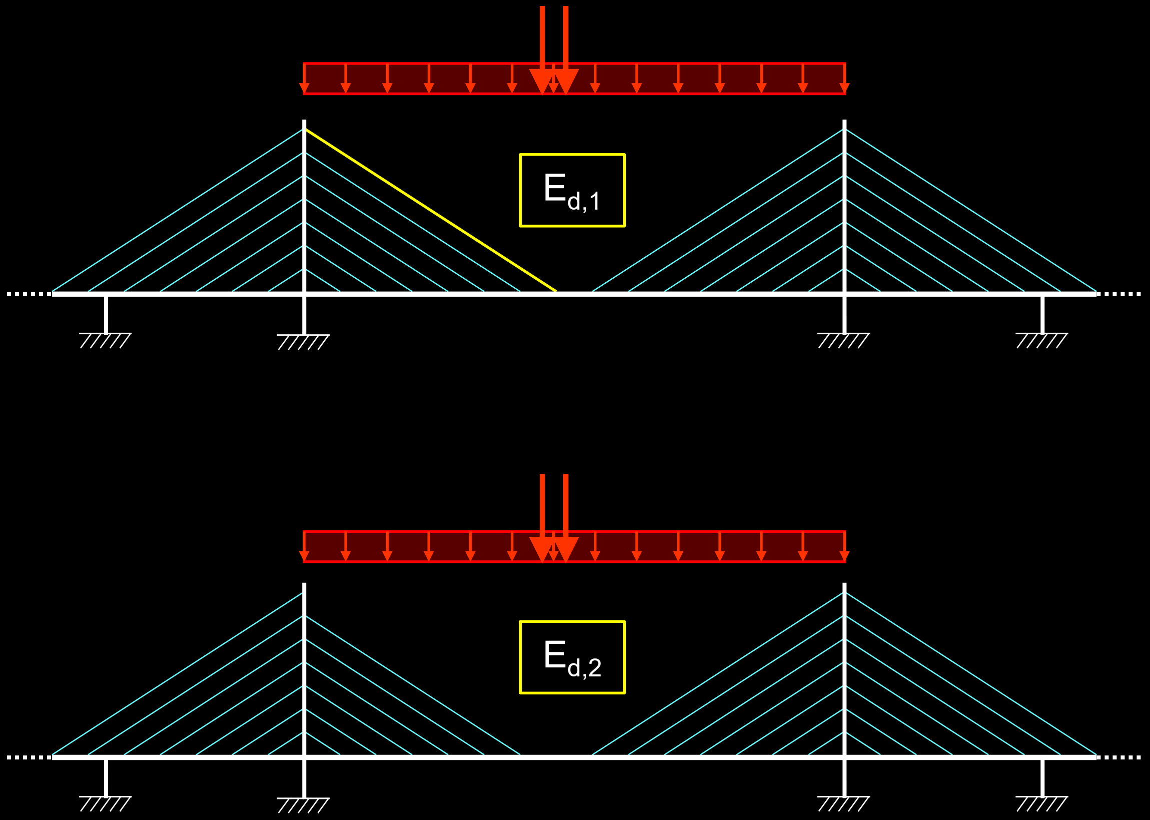
- Particularities of cable-stayed bridges:

→ Redundancy requirements: Accidental cable loss

Eurocode (static) approach:

1. Apply LL that maximises the axial force of the stay cable in question to the intact structure and calculate design effect: $E_{d,1}$
2. Remove stay cable in question from model and calculate design effect under the same loading: $E_{d,2}$
3. Calculate the difference between the design effects: $\Delta E = E_{d,2} - E_{d,1}$
4. Total design effect = $E_d = E_{d,1} + 2\,\Delta E$

Dynamic Amplification Factor



Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:

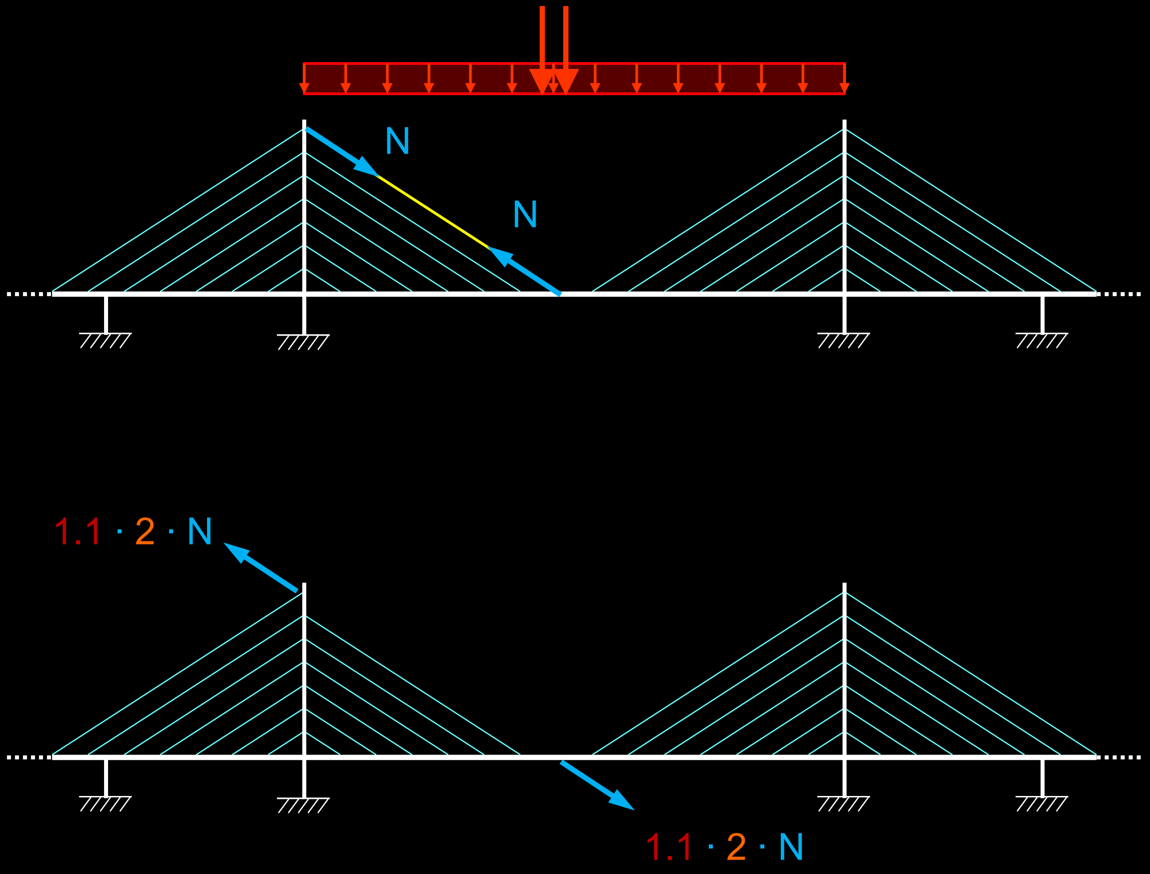
→ Redundancy requirements: Accidental cable loss

PTI (static) approach:

1. Apply LL that maximises the axial force of the stay cable in question to the intact structure and obtain the total axial force (N) in the cable for the following load combination:

   1.1 DC + 1.35 DW + 0.75 (LL+IM)

2. Remove stay cable in question from model and replace with corresponding reactions (N) to tower and girder, applied in the opposite directions and multiplied with a load factor of 1.1 and a dynamic amplification factor of 2.0 (unless a lower factor can be determined from a non-linear dynamic analysis, but not < 1.5)
3. Superimpose effects of Steps 1 & 2 to obtain total load effects



Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:

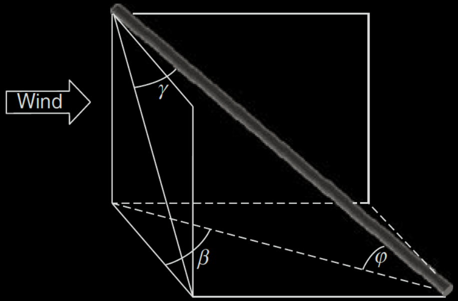
→ Stay cable vibration (see also lecture on Common Aspects)

Cable vibrations can be generated by:

- Wind: dry/wet galloping (most cases), buffeting or vortex-shedding (rarely)
- Loading of bridge girder or towers

Rain-wind-induced vibrations:

- Creation of water rivulets along a significant length of the cable → apparent modification in cable shape → galloping
- Wind tunnel testing show that cables are particularly vulnerable when:
  - ✓ Smooth
  - ✓ Lightly damped
  - ✓ Declining in direction of wind
  - ✓ Modal frequencies = 0.5 … 3.3 Hz
  - ✓ Wind speed = 5 … 18 m/s
  - ✓ Relative yaw angle (γ) = 0 … 45 deg




Fred Hartman Bridge, Baytown, TX, USA, 1995. LAP / URS


Vibration-induced fatigue cracks at stay anchorage guide pipes

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:

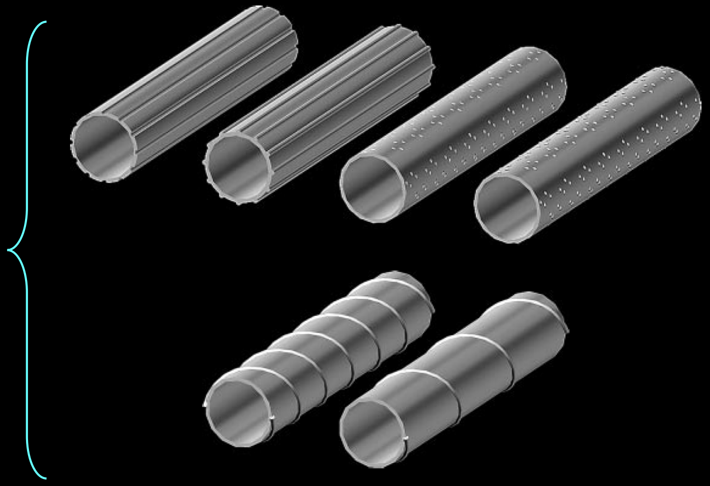
→ Stay cable vibration (see also lecture on Common Aspects)

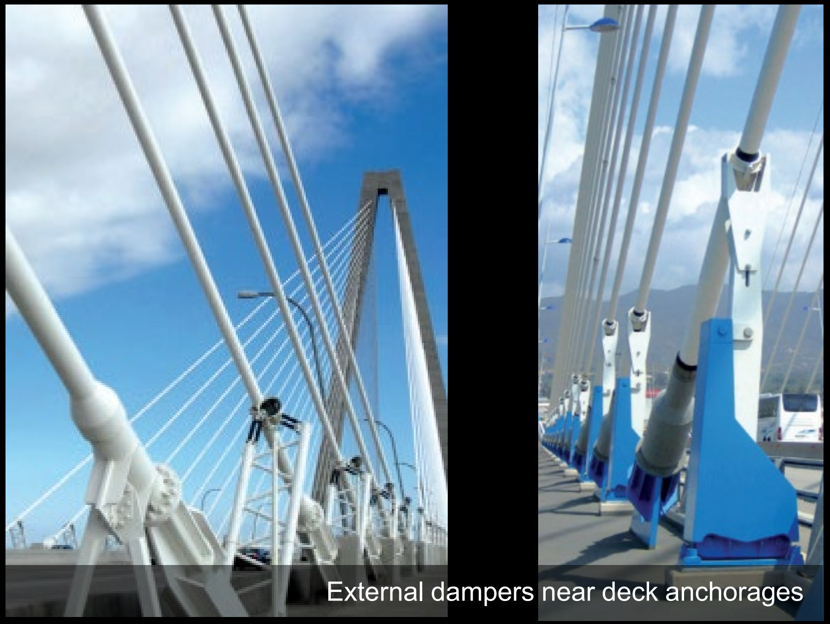
Cable vibrations can be generated by:

- Wind: dry/wet galloping (most cases), buffeting or vortex-shedding (rarely)
- Loading of bridge girder or towers

Rain-wind-induced vibrations:

- Creation of water rivulets along a significant length of the cable → apparent modification in cable shape → galloping
- Wind tunnel testing show that cables are particularly vulnerable when:
  - ✓ Smooth → provide surface modifications to HDPE pipe
  - ✓ Lightly damped → provide mechanical damping
  - ✓ Declining in direction of wind
  - ✓ Modal frequencies = 0.5 … 3.3 Hz
  - ✓ Wind speed = 5 … 18 m/s
  - ✓ Relative yaw angle (γ) = 0 … 45 deg


Types of surface modifications to HDPE pipe


External dampers near deck anchorages

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:

→ Time-dependent effects

- The principles discussed for cantilever-constructed bridges with respect to:
    - ✓ Creep + shrinkage
    - ✓ Camber
    - ✓ Erection equipment weight
    - ✓ Prestressing
    - ✓ Change in structural system

  are also applicable to cable-stayed bridges

    - ➢ Note that the contribution of tower creep to the total girder deflection is significant.
- Due to the relative flexibility of the girder-tower system during erection, it is easier to adjust the profile by adjusting the cable lengths compared to conventional cantilever-constructed bridges.
- However, errors are cumulative and grow quickly, therefore accurate monitoring and record keeping during erection are paramount to ensure the correct final geometry


Puente Hisgaura, Colombia, 2018

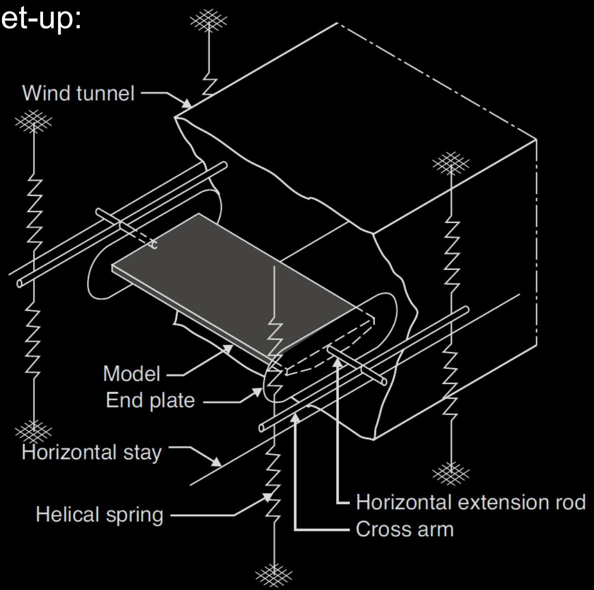
Cable-supported bridges – Cable-Stayed Bridges: Structural Response

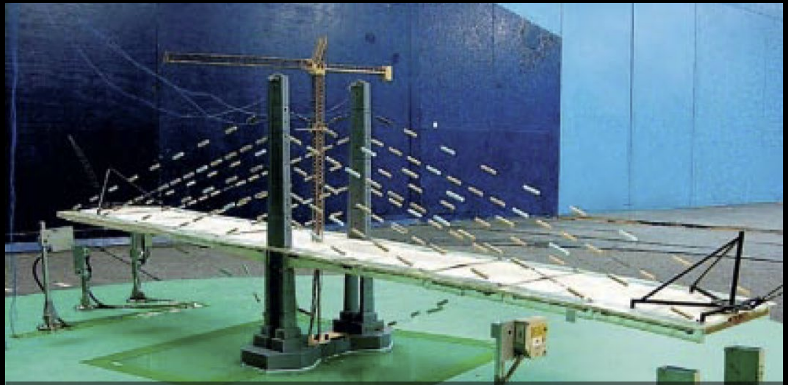
- Particularities of cable-stayed bridges:

→ Wind loading & aerodynamics

- Code provisions apply to bridges with negligible dynamic response, i.e. road and rail bridges of spans up to 40 m (see Conceptual Design)
- For cable-stayed bridges, input from wind specialists is required:
  - ➢ Definition of wind characteristics:
    - Wind speed vs. Return period
    - Wind vs. Directionality
    - Turbulence (terrain roughness)
  - ➢ Wind tunnel testing
    - Virtual testing (CFD) - preliminary
    - Sectional testing
    - Aeroelastic testing

Sectional test set-up:





Golden Ears Bridge, Vancouver, BC, 2009. Buckland & Taylor

Aeroelastic testing of full model during erection (RWDI)

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

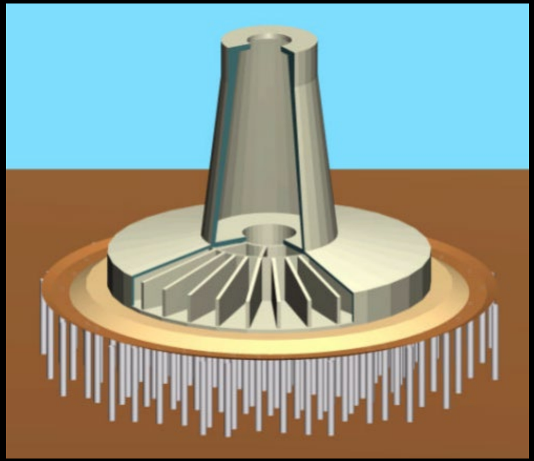
- Particularities of cable-stayed bridges:

→ Seismic design

Depending on the site seismicity, the seismic design of cable-stayed bridges often extends beyond the standard code provisions:

- Input ground motions are developed based on site-specific hazard analyses for multi-level events; identification of faults running through bridge alignment
- Response is determined through non-linear, time-history analyses
- For long-span bridges, spatial effects (asynchronous seismic excitation) may need to be considered
- May involve complex detailing such as dampers, isolation bearings, fuses, special ductile elements

Rion Antirion (Charilaos Trikoupis) Bridge, Greece, 2004. Jacques Combault



Cable-supported bridges – Cable-Stayed Bridges: Construction

- Constructibility Aspects:
  - → Early collaboration between designer and contractor is essential to ensure an economic design and successful execution
  - → Erection method must be developed during the design process to ensure compatibility between design and erection and viability of the former
  - → Guiding principles:
    - Simplicity
    - Repetition / Modularity
  - → Common constructible girder types:
    - Precast concrete segmental
    - Cast-in-place concrete segmental
    - Composite

Ed Hendler Bridge, Pasco/Kennewick, WA, USA, 1978. Arvid Grant & Associates / Leonhardt & Andrä

✓ Precasting → Repetition
✓ Simplicity in connections between segments
○ Economical if same section can be used for approaches: Cost of forms and erection equipment is amortised over greater length
✓ Simple lifting equipment

Cable-supported bridges – Cable-Stayed Bridges: Construction

- Constructibility Aspects:
  - → Early collaboration between designer and contractor is essential to ensure an economic design and successful execution
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    - Simplicity
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  - → Common constructible girder types:
    - Precast concrete segmental
    - Cast-in-place concrete segmental
    - Composite

Sidney Lanier Bridge, Brunswick, GA, USA, 2003. TYLI

- ✓ Repetitive & modular construction
- ○ Suitable for simple open cross sections
- ○ Alternative to precasting for shorter production runs (incl. approaches)
- – Form travellers are complex and expensive (cannot be amortised over the approaches); schedule may require four travellers
- – Traveller imposes significant demands on girder (closely-spaced stays required); traveller may need to be temporarily supported by stays (complex details / load transfer)

Cable-supported bridges – Cable-Stayed Bridges: Construction

- Constructibility Aspects:

→ Early collaboration between designer and contractor is critical to ensure an economic design and successful execution

→ Erection method must be developed during the design process to ensure compatibility between design and erection and viability of the former

→ Guiding principles:

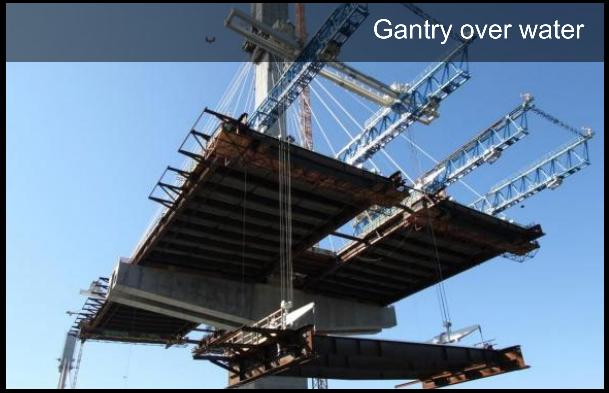
  - Simplicity
  - Repetition / Modularity

→ Common constructible girder types:

  - Precast concrete segmental
  - Cast-in-place concrete segmental
  - Composite


Port Mann Bridge, Vancouver, BC, Canada, 2012. TYLI / IBT


Derrick crane over land


Gantry over water

✓ Repetitive & modular construction
○ Suitable for simple open cross sections
✓ Simple pre-fabrication of plate girders and precast deck panels
✓ No need for formwork (infill strips over girder flanges)
– Cross-section shape not aerodynamic → wind fairings typically needed

Cable-supported bridges – Cable-Stayed Bridges: Construction

- Erection:

→ Cable-stayed bridges are typically most vulnerable during erection

→ Geometry Control:

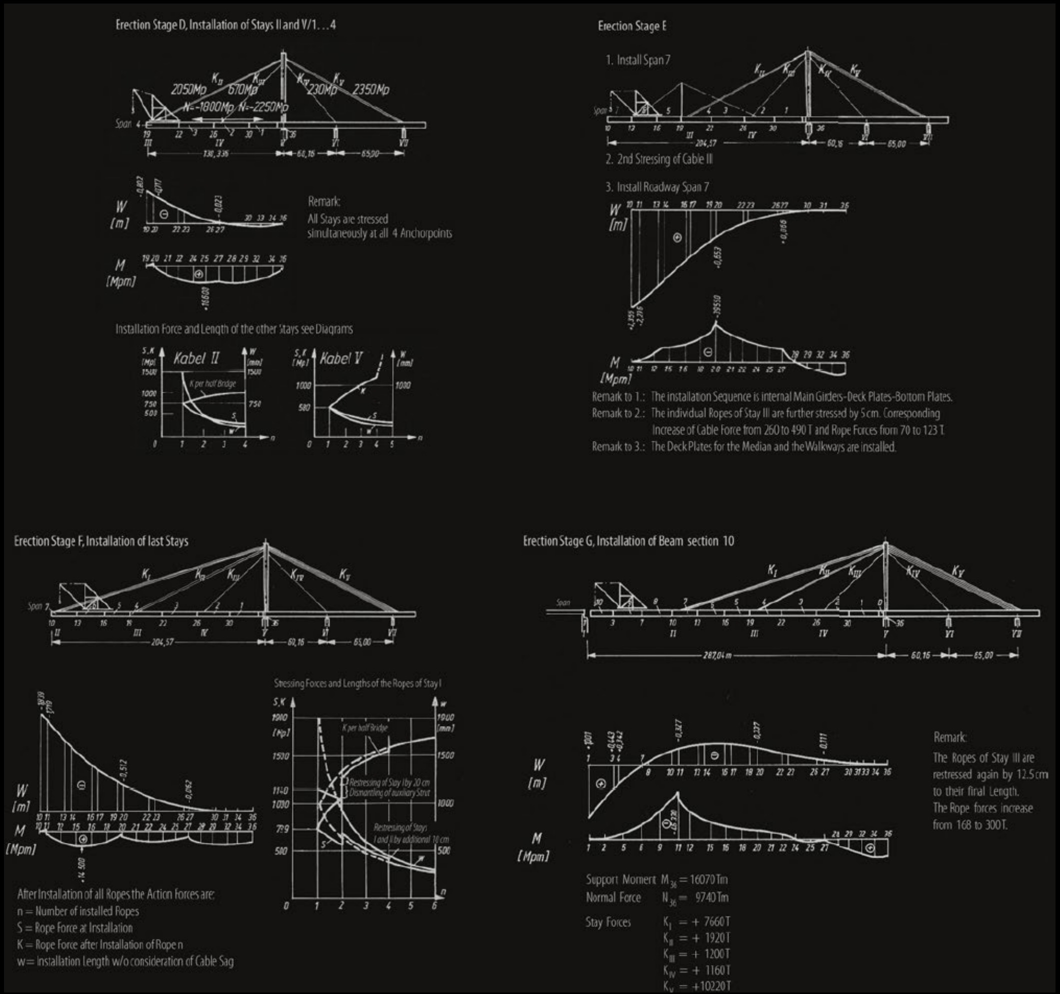
Assembly of information and methodology, used to control positions and dimensions of structural elements during erection (x, y, z, t)

  - Goal: achieve target geometry and stress state at a reference stage (typically @ 10’000 days)
  - Final stress state is dependent upon final geometry and key erection stages (“locked-in” stresses, closures) → must track and control

Key aspects:

  - Modelling of erection sequence
  - Survey monitoring during erection
  - Assessing and controlling during erection (perform adjustments as/if needed)

Sample Erection Manual:



Erection Stage D, Installation of Stays II and V/1…4

Remark:
All Stays are stressed simultaneously at all 4 Anchorpoints

Installation Force and Length of the other Stays see Diagrams

Erection Stage E

1. Install Span 7
2. 2nd Stressing of Cable III
3. Install Roadway Span 7

Remark to 1.: The installation Sequence is internal Main Girders-Deck Plates-Bottom Plates.

Remark to 2.: The individual Ropes of Stay III are further stressed by 5 cm. Corresponding Increase of Cable Force from 260 to 490 T and Rope Forces from 70 to 123 T.

Remark to 3.: The Deck Plates for the Median and the Walkways are installed.

Erection Stage F, Installation of last Stays

Stressing Forces and Lengths of the Ropes of Stay I

After Installation of all Ropes the Action Forces are:
n = Number of installed Ropes
S = Rope Force at Installation
K = Rope Force after Installation of Rope n
w = Installation Length w/o consideration of Cable Sag

Erection Stage G, Installation of Beam section 10

Remark:
The Ropes of Stay III are restressed again by 12.5 cm to their final Length.
The Rope forces increase from 168 to 300 T.

Support Moment M_{36} = 16070 Tm
Normal Force N_{36} = 9740 Tm

Stay Forces
K_I = + 7660 T
K_{II} = + 1920 T
K_{III} = + 1200 T
K_{IV} = + 1160 T
K_V = + 10220 T

Cable-supported bridges – Cable-Stayed Bridges: Construction

- Erection:

→ Cable-stayed installation:

Most effective method to control installation depends on girder type:

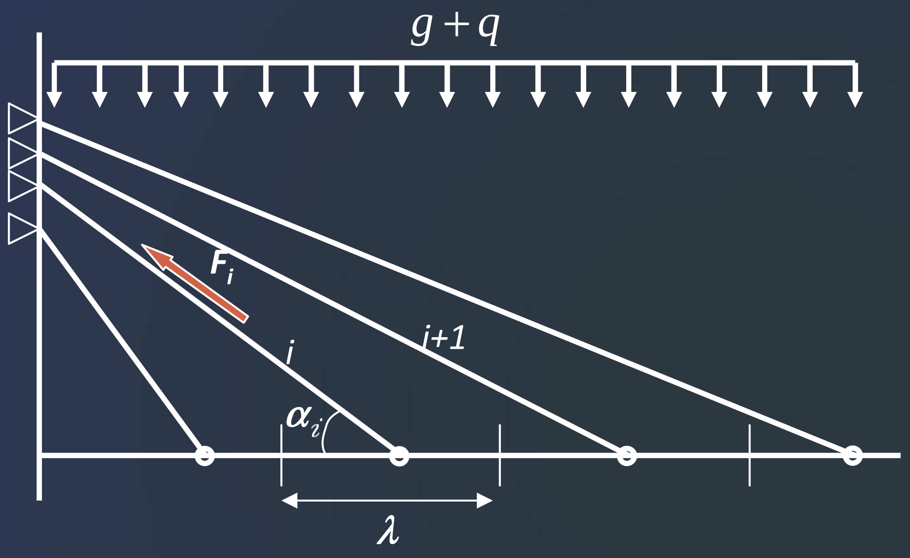
- Flexible girder: based on stay length
  - ✓ Errors in load assumptions will result in different stay forces but not in girder geometry
  - – Requires accurate surveying of as-built structure at each stage to define stay length
- Stiff girder: based on stay force
  - ○ Adjustment of stay length independent of the target force would result in overstressing the girder; shims can be used to correct girder geometry (last resort)

At end of construction, installation within tolerances (among cables and strands) is confirmed by lift-off tests, and final adjustments are made as needed.


Port Mann Bridge, Vancouver, BC, Canada, 2012. TYLI / IBT


St. Croix River Crossing, MN, USA, 2017. COWI / HDR

Predimensionado de los cables



$$F_i \max = \frac{(g+q)\lambda}{sen\alpha_i}$$

$$F_i \min = \frac{g\lambda}{sen\alpha_i}$$

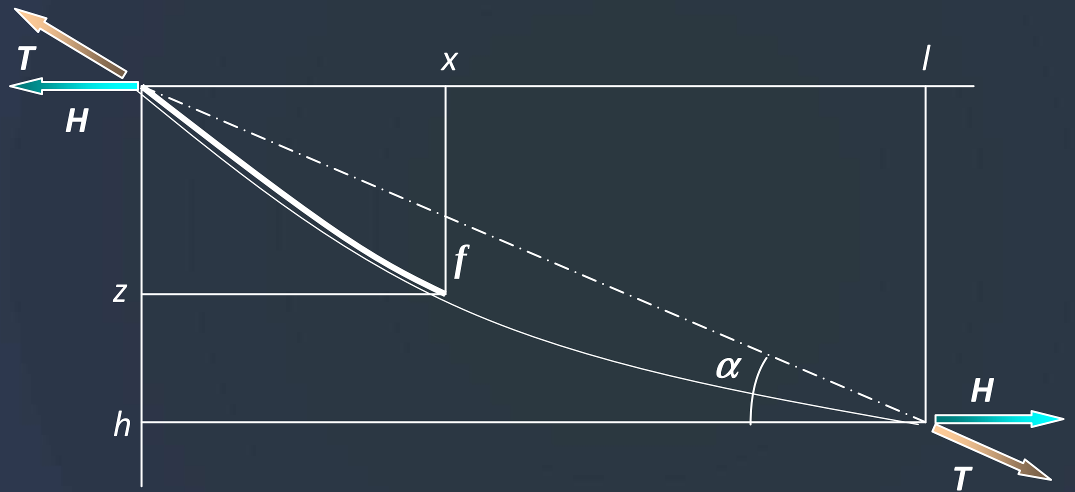
Criterio

$$\sigma \leq 0.45\,\sigma_{GUTS}$$

$$\Delta\sigma \leq 200-300MPa$$

Comportamiento de los cables

Para los tirantes, se puede partir de la solución exacta de la catenaria elástica → Aproximación por una parábola



w =peso del cable por unidad de longitud

$$p = \frac{w}{\cos\alpha} l$$ peso total del cable

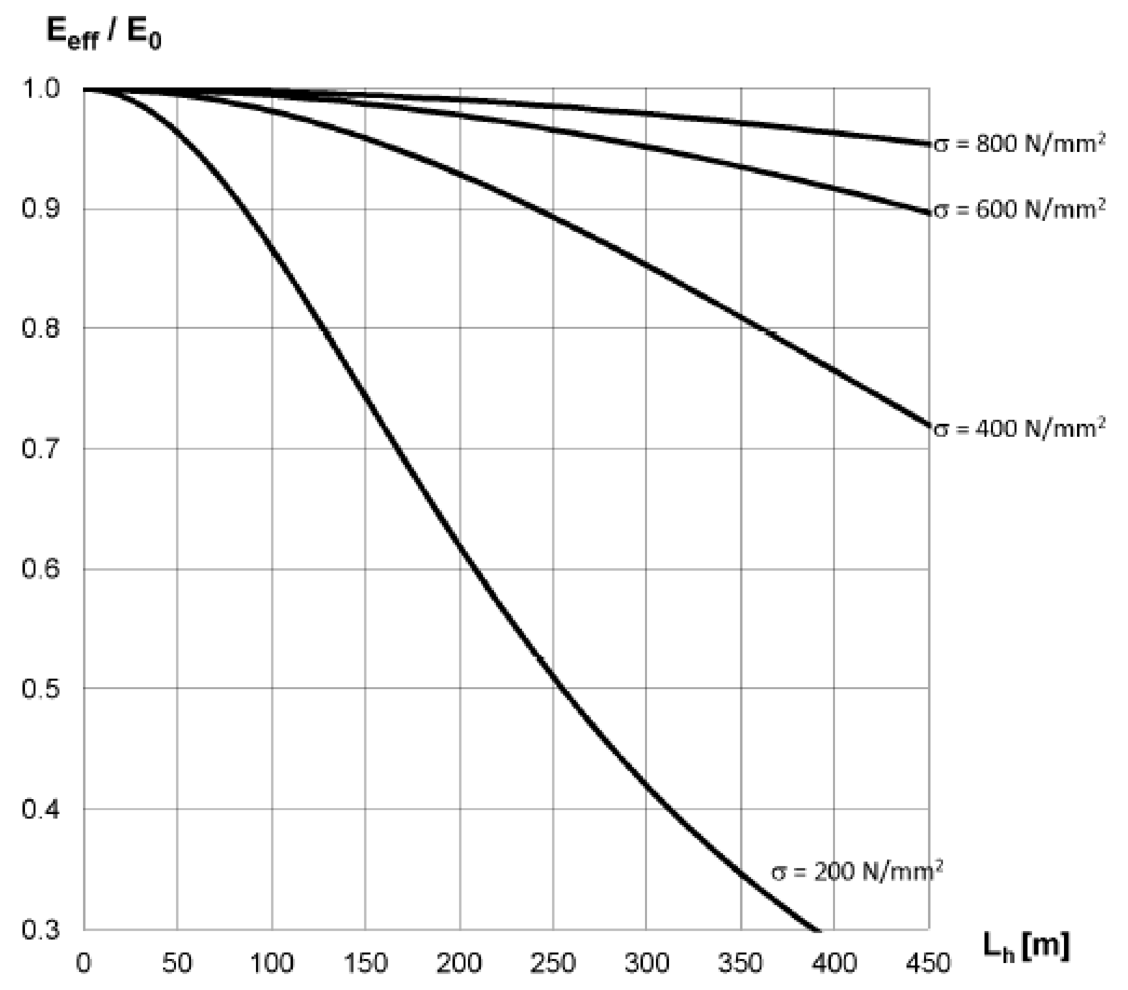
$$H = \frac{p}{8f} l$$

$$T = \frac{p}{8f\cos\alpha} l$$

$$E^* = \frac{E}{1 + \frac{w^2 l^2 EA}{24T^3}}$$

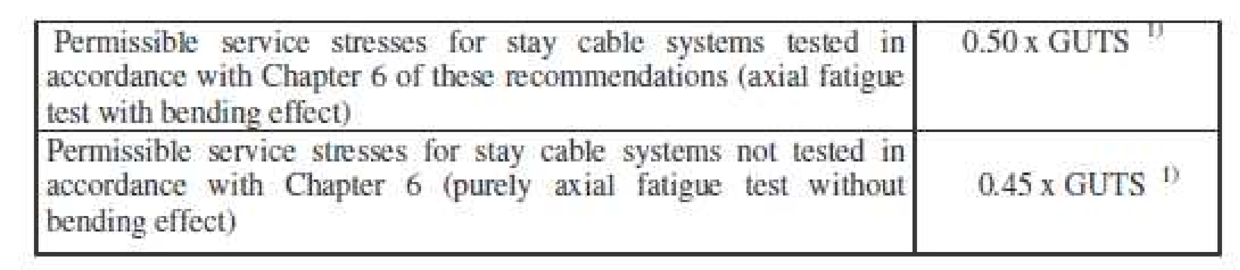
Comportamiento de los cables

$$E^* = \frac{E}{1 + \frac{w^2 l^2 EA}{24T^3}}$$



Consideraciones para el diseño de los cables
(fib – Recommendations for the Acceptance of Cable Stay Systems)

ELS

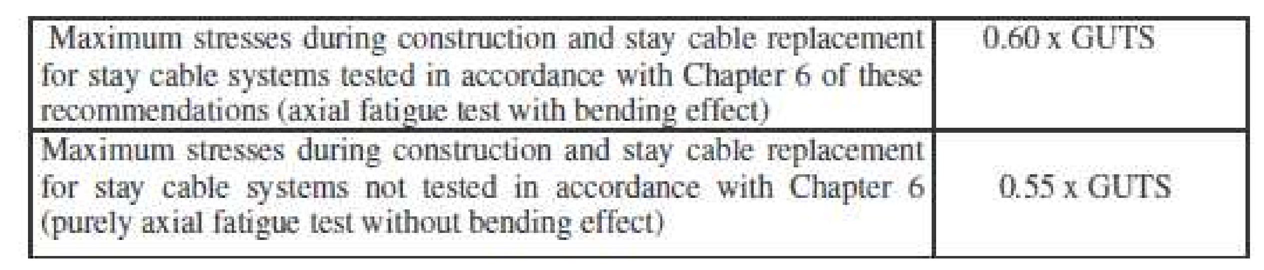


Permissible service stresses for stay cable systems tested in accordance with Chapter 6 of these recommendations (axial fatigue test with bending effect)	0.50 x GUTS 1)
Permissible service stresses for stay cable systems not tested in accordance with Chapter 6 (purely axial fatigue test without bending effect)	0.45 x GUTS 1)

Caso 1

Caso 2

ELS – Construcción y sustitución de cables



Maximum stresses during construction and stay cable replacement for stay cable systems tested in accordance with Chapter 6 of these recommendations (axial fatigue test with bending effect)	0.60 x GUTS
Maximum stresses during construction and stay cable replacement for stay cable systems not tested in accordance with Chapter 6 (purely axial fatigue test without bending effect)	0.55 x GUTS

GUTS = Guaranteed ultimate tensile strength

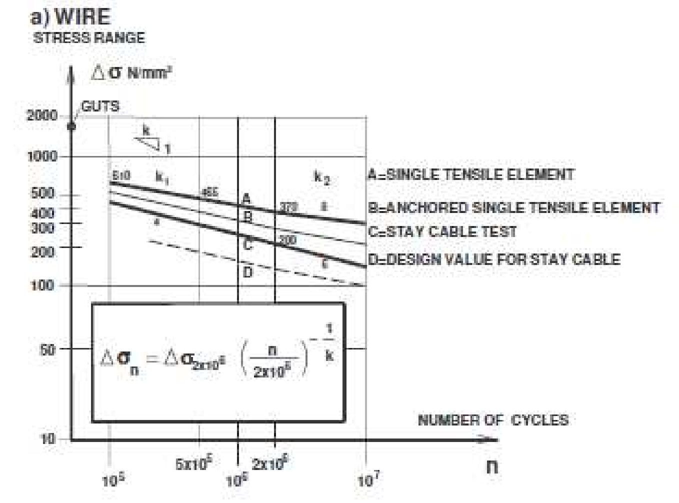
ELU

γ_s= 1.35 (Caso 1) o 1.50 (Caso 2)

Consideraciones para el diseño de los cables
(fib – Recommendations for the Acceptance of Cable Stay Systems)

ELF (Estado límite de fatiga)

		K_1	K_2	$\Delta\sigma$ (MPa) at $2x10^6$ load cycles upper stress of 0.45 GUTS
WIRE (Grade 1770 MPa)	A	$\approx 6^{2)}$	8	370
	C	4	6	200
STRAND (Grade 1860 MPa)	A	$\approx 6^{2)}$	8	300
	C	4	6	200
THREADBAR$^{1)}$ (Grade 1050 MPa)	A	$\approx 7^{2)}$	8	180
	C	5	6	110



$$\Delta\sigma_n = \Delta\sigma_{2x10^6}\left(\frac{n}{2x10^6}\right)^{-\frac{1}{k}}$$