Stretto di Messina

Concessionaria per la progettazione, realizzazione e gestione del collegamento stabile tra la Sicilia e il Continente Organismo di Diritto Pubblico
(Legge n° 1158 del 17 dicembre 1971, modificata dal D.Lgs. n°114 del 24 aprile 2003)

EurolinK

PONTE SULLO STRETTO DI MESSINA

PROGETTO DEFINITIVO

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Opera - tratto d'opera - parte d'opera	Generale	
Titolo del documento	Design report - Suspended deck at towers and terminal structures	

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INDICE

1 Introduction

This report describes the design of the following structural elements of the buffering system:

- Longitudinal and transverse system of devices preventing movements at normal operation conditions and allowing movements with ability to dissipate energy during severe load conditions such as earthquake,
- Behaviour and characteristics of hydraulic buffers,
- Terminal structure restraint.

The design is based on the principles shown in the Tender and Progetto Definitivo stage.

It was found advantageous to introduce change to the design of the transverse link and buffer arrangement so the self weight of the transverse beam will not be carried by the buffers resulting in risk of oil leaking.

Calculations are carried out using a global FE-model with the output for:

- Internal forces of all steel members in the form of static analysis,
- Internal forces of all steel members in the form of time history analysis,
- Displacements in buffers in the form of static analysis,
- Characteristics of hydraulic buffers.

1.1 Report Outline

This report consists of following sections:

- Section 1 - includes this introduction,
- Section 2 - provides a list of reference materials, including design specifications, design codes, material specifications and reference drawings,
- Section 3 - provides description of materials that are used for each component,
- Section 4 - describes the applied design principles,

- Section 5 - includes a summary of design verifications,
- Section 6 - includes description of behaviour and characteristics of hydraulic buffers,
- Section 7 - includes description of restraint at terminal structure.

Detailed design verifications are included in Appendices.

1.2 Structure Arrangement

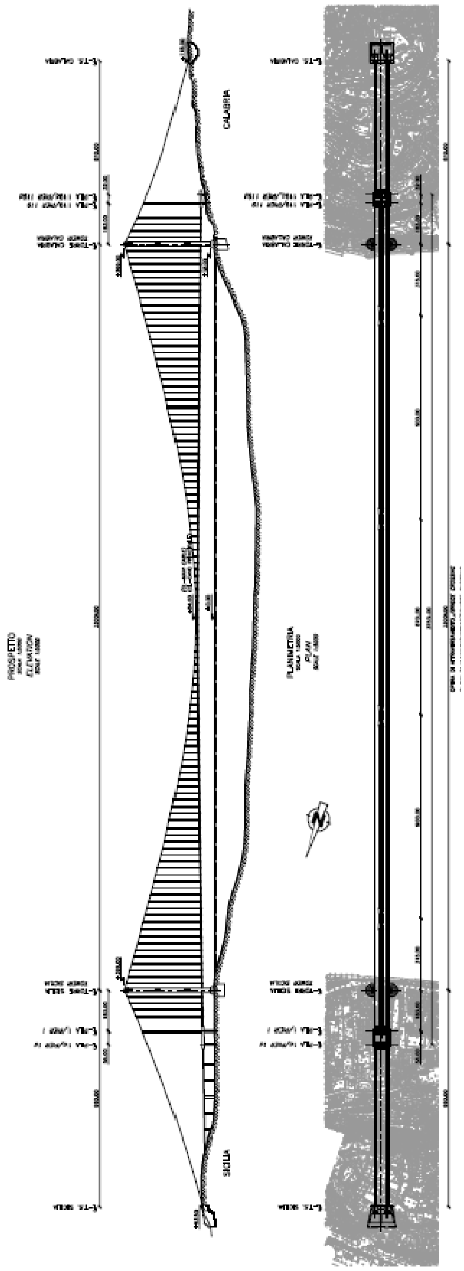

Figure 1-1: Bridge elevation and plan.

2 Design References

2.1 Design Specifications

CG.10.00-P-RG-D-P-GE-00-00-00-00-00-02 - "Design Basis, Structural, Annex," COWI 2010

GCG.F.05.03 "Design Development – Requirements and Guidelines," Stretto di Messina, 2004 October 22.

GCG.G.03.02 "Structural Steel Works and Protective Coatings," Stretto di Messina, 2004 July 30.

2.2 Design Codes

"Norme tecniche per le costruzioni," 2008 (NTC08).

EN 1993 Eurocode 3: Design of Steel Structures – Part 1-1: General rules and rules for buildings

EN 1993 Eurocode 3: Design of Steel Structures – Part 1-5: Plated structural elements

EN 1993 Eurocode 3: Design of Steel Structures – Part 1-8: Design of joints

EN 1993 Eurocode 3: Design of Steel Structures – Part 1-9: Fatigue

EN 1993 Eurocode 3: Design of Steel Structures – Part 1-10: Selection of steel for fracture toughness and through thickness properties

EN 1993 Eurocode 3: Design of Steel Structures – Part 2: Steel Bridges

EN 1998 Eurocode 8: Design of structures for earthquake resistance

2.3 Material Specifications

EN 10025-1:2004 Hot-rolled products of structural steels – Part 1: General delivery conditions.

EN 10025-2:2004 Hot-rolled products of structural steels – Part 2: Technical delivery conditions for non-alloy structural steels.

EN 10025-3:2004 Hot-rolled products of structural steels – Part 3: Technical delivery conditions for normalized / normalized weldable fine grain structural steels.

EN 10025-4:2004 Hot-rolled products of structural steels – Part 4: Technical delivery conditions for thermo mechanical rolled weldable fine grain structural steels.

EN 10164:1993 Steel products with improved deformation properties perpendicular to the surface of the product – Technical delivery conditions.

EN ISO 898-1:2001 Mechanical properties of fasteners made of carbon steel and alloy steel – Part 1: Bolts, screws and studs (ISO 898-1:1999).

EN 20898-2:1994 Mechanical properties of fasteners – Part 2: Nuts with special proof load values – coarse thread (ISO 898-2:1992).

UNI EN 14399:2005-3 High-strength structural bolting assemblies for preloading - Part 3: System HR - Hexagon bolt and nut assemblies

EN 10293:2005 Steel castings for general engineering uses

2.4 Complementary Reports

CG.10.00-P-RG-D-P-SV-00-00-00-00-00-01 - "Global IBDAS Model, Description", COWI 2010

CG.10.00-P-SP-D-P-SS-A0-A4-00-00-00-01 - "Performance Specification - Buffers"

2.5 Drawings

The drawings relevant for this report are listed in Table 2-1.

Drawing Title	Drawing Number
Articulation system - General arrangement	CG1000-P-AX-D-P-SS-A0-00-00-00-00-01
Articulation system - Support of suspended deck at towers	CG1000-P-AX-D-P-SS-A0-00-00-00-00-02
Articulation system - Longitudinal supports	CG1000-P-BX-D-P-SS-A0-00-00-00-00-01
Articulation system - Transverse supports (1)	CG1000-P-BX-D-P-SS-A0-00-00-00-00-02
Articulation system - Transverse supports (2)	CG1000-P-BX-D-P-SS-A0-00-00-00-00-03
Articulation system - Hydraulic systems	CG1000-P-BX-D-P-SS-A0-00-00-00-00-05
Articulation system - Bridge bearings , Overview	CG1000-P-DX-D-P-SS-A0-AP-00-00-00-01
Articulation system - Bridge bearings , Details	CG1000-P-BX-D-P-SS-A0-AP-00-00-00-01
Articulation system - Expansion joints, Overview	CG1000-P-DX-D-P-SS-A0-GE-00-00-00-01
Articulation system - Expansion joints railway (1)	CG1000-P-DX-D-P-SS-A0-GE-00-00-00-02
Articulation system - Expansion joints railway (2)	CG1000-P-DX-D-P-SS-A0-GE-00-00-00-03
Articulation system - Expansion joints roadway	CG1000-P-DX-D-P-SS-A0-GE-00-00-00-04

Table 2-1: Articulation drawings

3 Materials

The mechanical properties of the articulation construction materials are described in this section.

The design of some of the articulation components are carried out based on manufacturers specifications and technical performance specifications provided by COWI. The mechanical properties of construction materials should be found in the manufacturers' documentation.

3.1 Structural Steel

The buffering system components are fabricated from steel Grade S 460 ML, produced in accordance with EN 10025-4. The steel is assumed to satisfy the requirements for mechanical properties listed in Table 3-1: and the NTC08, Section 11.3.4.1. The steel supplier has confirmed that the mechanical properties will not vary with material thickness for thicknesses smaller than 100 mm, as is typical for rolled steel products.

Grade	Yield Strength, f_{yk} (MPa)	Tensile Strength, f_{tk} (MPa)
S 460 ML	460	540

Table 3-1: Structural steel mechanical properties for thicknesses smaller than 100 mm

All structural steel is also assumed to have the following properties in accordance with NTC08, Section 11.3.4.1:

- Elastic modulus: $E = 210{,}000$ MPa
- Poisson's ratio: $\nu = 0.3$
- Shear modulus: $G = 77{,}000$ MPa
- Coefficient of thermal expansion: $\alpha = 12 \times 10^{-6} / °C$
- Density: $\rho = 7{,}850$ kg/m^3

The material partial factors (safety coefficients) used to verify structural steel elements are in accordance with NTC08, Sections 4.2.4.1.1, 4.2.4.1.4 and are listed in Table 3-2.

Verification	Partial Factor
Resistance of Class 1, 2, 3 and 4 sections	$\gamma_{M0} = 1.05$
Resistance to instability of members in road and rail bridges	$\gamma_{M1} = 1.10$
Resistance to fracture of sections under tension (weakened by holes)	$\gamma_{M2} = 1.25$
Fatigue resistance (useful fatigue life criterion with significant failure consequences)	$\gamma_{mf} = 1.35$

Table 3-2: Material partial factors for structural steel

3.2 High Strength Bolts

High strength structural bolts of Grade 10.9, produced in accordance with EN ISO 898, are used for all bolted connections and splices of the buffering system. High strength bolts are assumed to have the mechanical properties listed in Table 3-3, in accordance with NTC08 Section 11.3.4.6.1.

Grade	Yield Strength, f_{yb} (MPa)	Tensile Strength, f_{tb} (MPa)
10.9	900	1000

Table 3-3: Structural bolts mechanical properties

The material partial factors (safety coefficients) used to verify bolted connections and splices are in accordance with NTC08, Section 4.2.8.1.1 and are listed in Table 3-4.

Verification	Partial Factor
Resistance to bolt shear	$\gamma_{M2} = 1.25$
Resistance to bolt tension	
Resistance to bearing of plates	
ULS slip resistance	$\gamma_{M3} = 1.25$
SLS slip resistance	$\gamma_{M3} = 1.15$
Bolt preload force	$\gamma_{M7} = 1.10$

Table 3-4: Material partial factors for bolted connections and splices

3.3 Welding Consumables

Welding consumables shall comply with the requirements of EN 1993-1-8, Section 4.2.

Welding procedures shall be planned so as the properties of the thermo-mechanically roughened plates will not be reduced.

Matching filler materials shall be used in compliance with the mechanical properties of the base material.

The material partial factor, $\gamma_{M2} = 1.25$ used to verify welded connections and splices shall be in accordance with NTC08, Section 4.2.8.1.1.

3.4 Self-Lubricating Bearings

The transverse buffers are supported by a beam spanning between the tower leg and the diagonal cross beams. The support beam has pinned connection at both ends. The beam comprises two box sections, one of which fits inside the other and is supported by self-lubricating manganese-bronze bearings to allow axial movements to take place. The buffers are attached to either side of this sliding section. Hence, the beam is able to support the buffers whilst also allowing them to operate as required along their longitudinal axis, ref to Figure 3-1 and Figure 3-2.

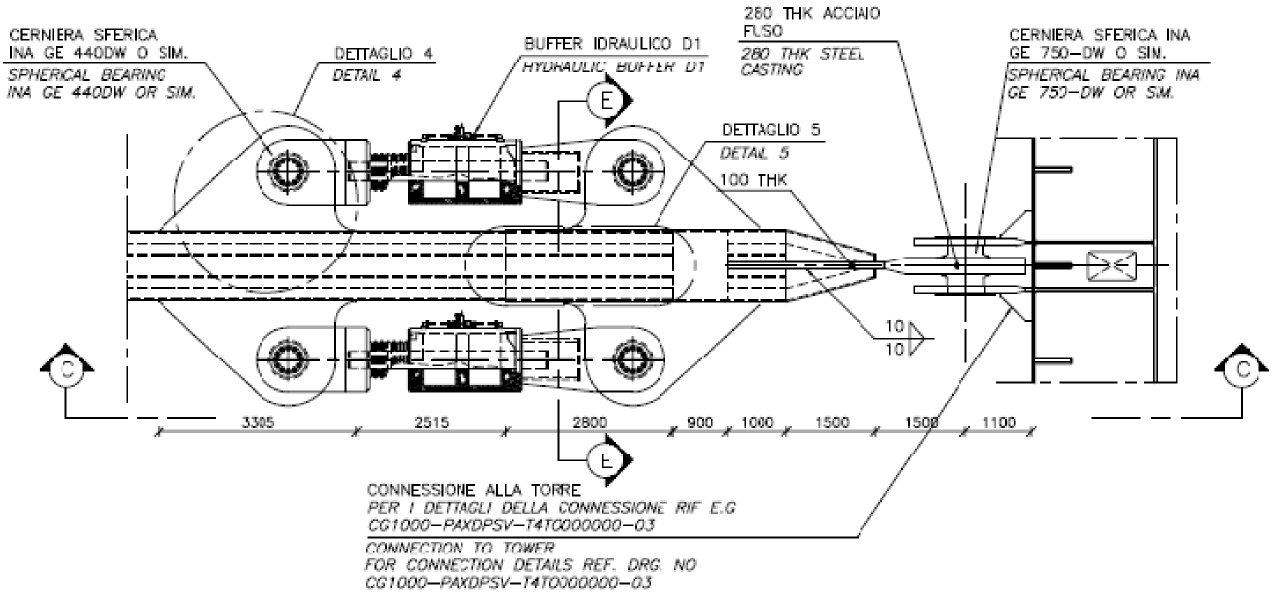

Figure 3-1: Plan view of transverse beams with buffers

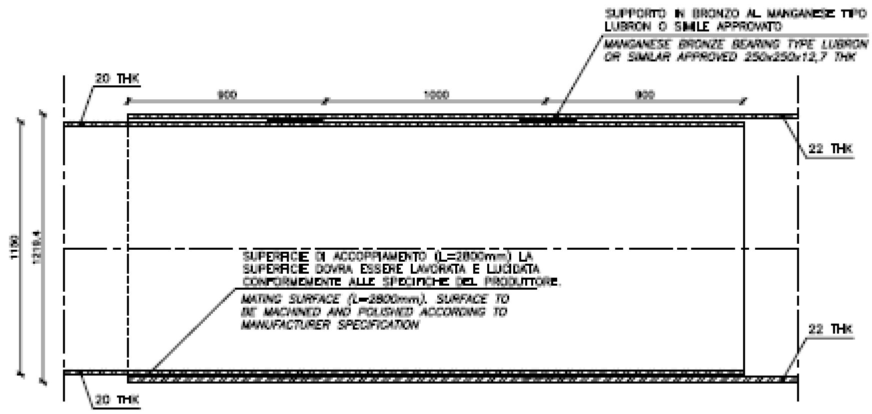

Figure 3-2: Mating surface of sliding section

4 Design Principles

4.1 General Arrangement of Buffering System

The design principles are based on the document 'Basis of design and expected performance level for the bridge', document no. GCG.F.04.01 provided by Stretto di Messina.

The design of steel structures is carried out following requirements stated in Eurocode 3 supplemented with rules in Part 1-1, 1-5, 1-8 and 1-9.

Transverse and longitudinal wind, temperature and earthquake acting on the bridge will result in large longitudinal and horizontal movements of the structure. Large movements of the bridge girder will result in pronounced wear of the mechanical elements. It is therefore important to reduce the movements in order to obtain a cost effective design and reduce interruption to traffic due to repair and maintenance of the bridge components.

The objective is to introduce a system of devices preventing from movements during normal operation conditions and allowing for movements in the cause of severe load condition such as earthquake. The accumulated energy will be dissipated to lower parts of bridge towers.

The hydraulic buffers will be located at the towers in both longitudinal and transverse direction. In the longitudinal direction the system consisting of 4 buffers will be linking the towers with deck diaphragm at each side of the bridge deck. In the transverse direction the system will comprise a transverse beam with 2 buffers. The transverse beam will be connected to four cross beams in the form of steel boxes spanning diagonally beneath the bridge deck. In the point of intersection the pin connection will be located allowing for rotations of all beams and preventing from transferring of deformations of main road girders to side drop in spans due to transverse loads. The four beams diagonally placed will be connected to the main road girders and side road girder by the connection in the form of bolted splices allowing for the resistance of small bending moments. The transverse beam will be connected to the tower by an eye-connection transferring only axial forces and shear, ref. Figure 4-1.

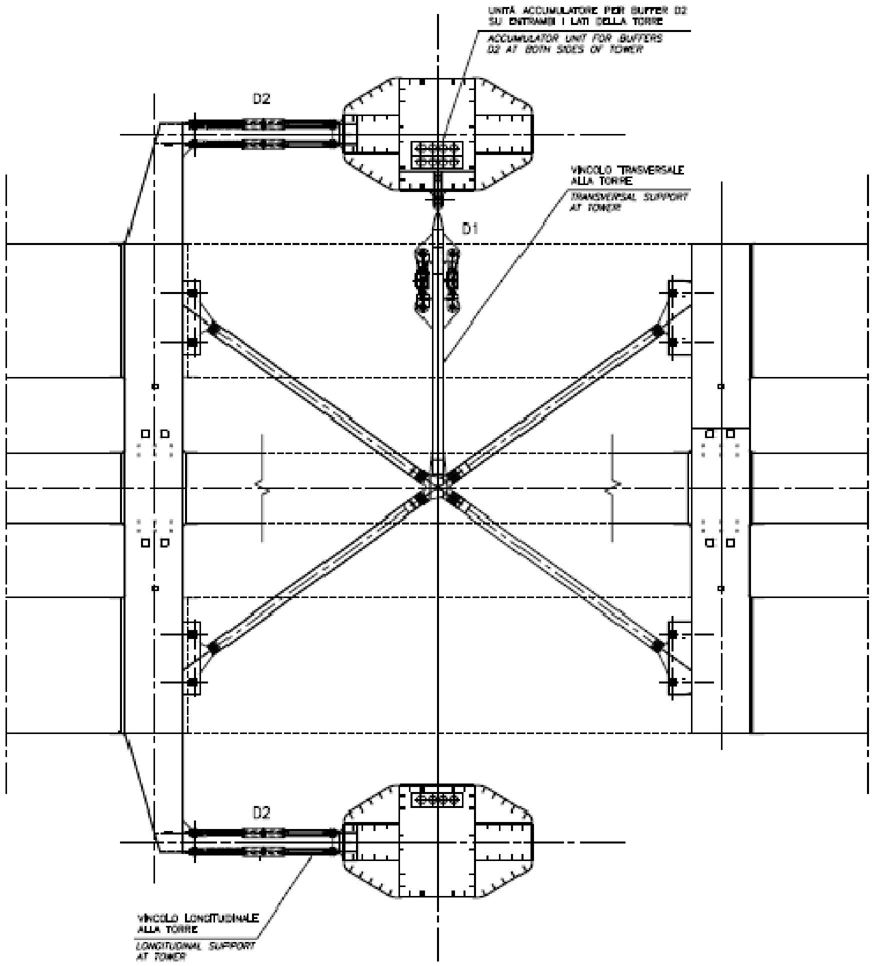

Figure 4-1: Longitudinal and Transverse Buffering System

4.2 IBDAS Modelling

4.2.1 Output from IBDAS

The following types of analysis are available from IBDAS:

- Static analysis (dead load, live load, wind and temperature),
- Seismic response spectrum analysis,
- Dynamic wind analysis (spectral analysis),
- Seismic time-history analysis.

The static, response and spectral analysis are carried out for two static systems: a "free-free" and a "fixed-fixed" static system.

The type of static system refers to the conditions of the longitudinal support of the suspended deck at the towers. In the "fixed-fixed" system the longitudinal support is blocked providing a rigid connection between the deck and the tower. In the "free-free" system the deck can move freely relatively to the tower.

In the "free-free" static system a spring corresponding to the buffer characteristic is implemented in the longitudinal direction. The spring stiffness is 33 kN/m.

In both the "free-free" and the "fixed-fixed" static systems the transverse buffers at the towers are fixed providing a rigid transverse connection.

Based on the type of analysis and static system four limit states are available:

- SLS1
- SLS2
- ULS
- SILS

The limit states are defined in CG.10.00-P-RG-D-P-GE-00-00-00-00-00-02. Further information concerning the IBDAS model is given in CG.10.00-P-RG-D-P-SV-00-00-00-00-00-01.

4.2.2 Seismic response spectrum analysis

The ground motion is defined in four limit states, as stated in CG.10.00-P-RG-D-P-GE-00-00-00-00-00-02. The difference between the limit states is the peak ground acceleration.

The response of the structure subjected to the ground motion is calculated using the modes superposition in the response spectrum approach. A uniform ground motion can be assumed, i.e. where all supports are excited in the same manner. The damping ratio of the entire structure is taken as 5% and is relative to the critical value, considering that large amplitude motions may occur during an earthquake.

The response spectrum analyses are carried out for the 1760 lowest modes of vibration in order to achieve a participating mass of more than 90%.

Results are provided for each of the four limit states. The above described principles shall be applied with the contribution of uniform temperature load case.

4.2.3 Seismic time-history analysis

Time series compatible with the ULS design response spectra is used as seismic inputs for the time-history analysis.

There are in total 8 sets of time series, which have been analysed during the design.

Each set consists of three orthogonal components: two perpendicular horizontal components and one vertical component. The following two combinations are considered:

- 1.0 longitudinal component + 0.8 transverse component + 0.75 vertical component;
- 0.8 longitudinal component + 1.0 transverse component + 0.75 vertical component.

In these two combinations the results from the 8 sets of time series are averaged in accordance with CG.10.00-P-RG-D-P-GE-00-00-00-00-00-02.

Only permanent loads are included in the analysis. Therefore the results need to be combined with the remaining relevant loads given in the following load combinations:

- Primary structural components:

  - ULS: 6903

  - SLS1: 6913

  - SLS2: 6923

  - SILS: 6933

- Secondary structural components:

  - ULS: 6585

  - SLS characteristic: 6668

- SLS frequent: 6759

The damping coefficient is currently determined based on the important modes for the towers.

In the seismic analysis based on time-history analysis the buffers will operate in accordance with their characteristics.

The above described principles shall be applied with the contribution of a uniform temperature load case.

4.2.4 Seismic time-history analysis with preload

As the buffers arrangement at the towers provide different spring stiffness depending on the actual position of the buffer, the sequence of loads will have influence on the response from the buffers. To take this effect into account the buffers are preloaded before application of the time series and simulation of temperature and traffic conditions at the time of the seismic event. The traffic is placed at the most adverse position for a given structural element. For the buffers design the traffic can for example be placed in such way that the possible highest tension will be achieved due to traffic load.

4.2.5 Temperature

The contribution from temperature gradients is included in relevant envelopes in both static systems. The contribution from uniform temperature however is not included in any envelopes and can only be found as an individual load case, which is added manually to the envelopes.

The contribution from uniform temperature is taken from the "free-free" static system. The reason for this being is the fact that the nonlinear behaviour of the buffers can only be modelled correctly in the time-history analysis. The load from uniform temperature will exceed the threshold value of the buffers, requiring a change in the static system.

4.2.6 IBDAS output used in design of buffers and steel beams

The results base on an envelope of all load cases in the static, response and spectral analysis carried out in the "free-free" and "fixed-fixed" systems.

The seismic results base on time-history analysis with preload, used for determining movements in the longitudinal, transverse and vertical direction. The preload is based on the following components:

- Maximum uniform temperature,
- Fixation of the traffic loads such that there is maximum pulling out force in the longitudinal buffers at the towers.

5 Design Verifications

5.1 Design of Steel Beams and Connections.

The transverse and diagonal steel cross beams with connections are designed following Eurocode 3 requirements supplemented with rules in Part 1-1, 1-5, 1-8 and 1-9.

The effective area accounts for the effect of local buckling of the stiffened panels between cross-frames.

Table 5-1 and Table 5-2 represent the ratio of effective to gross area of the stiffened panels for the different plate thicknesses. The ratios are calculated for flat stiffeners of 15mm x 150mm and 20mm x 150mm used in transverse and diagonal beams, respectively. The stiffened panel length is 3.0m.

Transverse Beam - Stiffener 15 x 150						
Ratio χ: Effective area / Gross area						
						Stiffener spacing
Plate thickness	fy (MPa)	100	200	300	400	500
18	440	0.607	0.562	0.510	0.463	0.425
20	440	0.609	0.555	0.499	0.450	0.409
22	440	0.611	0.548	0.489	0.438	0.396
23	440	0.611	0.545	0.484	0.433	0.390
24	440	0.610	0.542	0.479	0.427	0.385
25	440	0.610	0.539	0.475	0.423	0.380
26	440	0.609	0.536	0.471	0.418	0.375
27	440	0.609	0.533	0.467	0.414	0.371
28	440	0.608	0.530	0.463	0.409	0.367
29	440	0.608	0.528	0.460	0.406	0.363
30	440	0.608	0.525	0.456	0.402	0.359

Table 5-1: Effective to gross area ratios - transverse beam

Diagonal Beam- Stiffener 20 x 150						
Ratio χ: Effective area / Gross area						
						Stiffener spacing
Plate thickness	fy (MPa)	100	200	300	400	500
24	440	0.619	0.576	0.525	0.479	0.439
25	440	0.620	0.574	0.522	0.475	0.435
26	440	0.622	0.573	0.518	0.471	0.430
27	440	0.623	0.571	0.515	0.467	0.426
28	440	0.624	0.569	0.512	0.463	0.422
29	440	0.625	0.567	0.509	0.460	0.418
30	440	0.627	0.565	0.506	0.456	0.414
31	440	0.627	0.564	0.504	0.453	0.411
32	440	0.627	0.562	0.501	0.450	0.408
33	440	0.628	0.561	0.499	0.447	0.405
34	440	0.628	0.559	0.496	0.444	0.402

Table 5-2: Effective to gross area ratios - diagonal beam

The gross section properties of diagonal and transverse beam are shown in Table 5-3:

	Flange THK [mm]	Web THK [mm]	fy [MPa]	Width [mm]	Height [mm]	Area [m^2]	Iy [m^4]	Iz [m^4]
Transverse Beam	24	20	440	1150	1300	0.13	0.03	0.03
Diagonal Beam	34	24	440	1150	1300	0.17	0.04	0.03

Table 5-3: Diagonal and transverse beam gross section properties

The cross sections of diagonal and transverse beam are presented in Figure 5-1 and Figure 5-2.

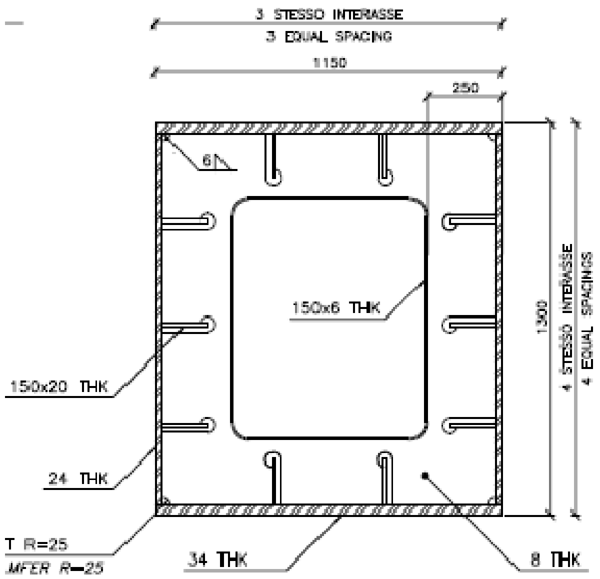

Figure 5-1: Cross section of diagonal beam

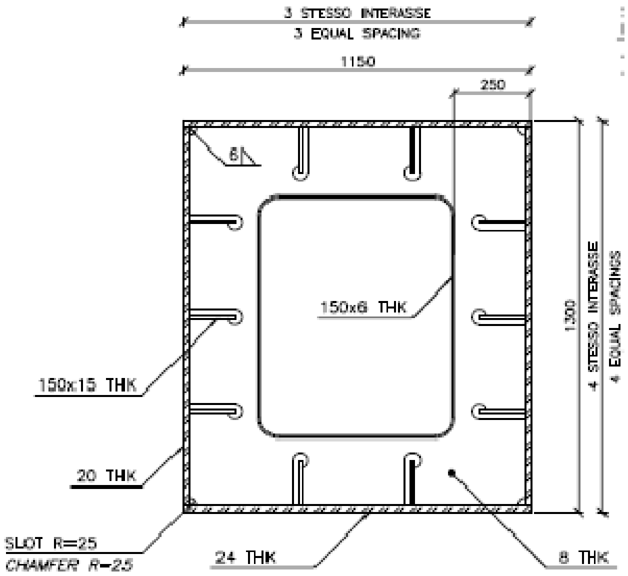

Figure 5-2: Cross section of transverse beam

Eurocode is used for assessment of axial, bending moments and shear capacities and utility ratios of each section:

$$UR = N_f / N_r + M_{f.y} / M_{r.y} + M_{f.z} / M_{r.z} \leq 1.0$$

$$UR = V_f / V_r \leq 1.0,$$

where:

N_f - the summation of the factored axial loads at a given section,

N_r - the factored axial capacity at the corresponding section,

$M_{f.y}$ - the summation of the factored moments around axis y-y,

$M_{r.y}$ - the factored bending capacity around axis y-y,

$M_{f.z}$ - the summation of the factored moments around axis z-z,

$M_{r.z}$ - the factored bending capacity around axis z-z,

V_f - the summation of the factored shear in one direction,

V_r - the factored shear capacity in corresponding direction.

The shear resistance in the form of utility ratio does not exceed 0.5, therefore the design resistance of bending and axial force doesn't need to be reduced, ref EN 1993-1-5, clause 7.1.

Three main combinations were considered in the design of the steel beams.

Load combination 1 contains ULS results based on envelopes and temperature effect. Load combination 2 includes most adverse effect of railway live load in the form of QL load case and uniform temperature. Load combination 3 consists of seismic time history analysis, uniform temperature effect and remaining permanent loads including partial live load (LL), which is comprising 20% of highway traffic and 30% of railway.

Table 5-4 to Table 5-9 present results in beams based on combinations and the corresponding utility ratios.

Load combination 1									
N_{ULS} [MN]	M_{ULS_y} [MNm]	M_{ULS_z} [MNm]	N_T [MN]	M_{T_y} [MNm]	M_{T_z} [MNm]	N_f [MN]	M_{f_y} [MNm]	M_{f_z} [MNm]	UR [-]
15.50	0.86	0.01	0.00	0.00	0.00	15.51	0.86	0.01	0.49
15.49	0.56	0.01	0.01	0.00	0.00	15.50	0.56	0.01	0.46

Table 5-4: Transverse beam - Combination 1, comprising ULS and uniform temperature

Load combination 1									
N_{ULS} [MN]	M_{ULS_y} [MNm]	M_{ULS_z} [MNm]	N_T [MN]	M_{T_y} [MNm]	M_{T_z} [MNm]	N_f [MN]	M_{f_y} [MNm]	M_{f_z} [MNm]	UR [-]
24.32	2.96	0.49	2.27	0.21	0.09	26.58	3.17	0.59	0.80
24.08	3.81	0.49	3.15	0.11	0.10	27.23	3.92	0.59	0.87

Table 5-5: Diagonal beam - Combination 1, comprising ULS and uniform temperature

Load combination 2									
N_T [MN]	M_{T_y} [MNm]	M_{T_z} [MNm]	N_{QL} [MN]	M_{QL_y} [MNm]	M_{QL_z} [MNm]	N_f [MN]	M_{f_y} [MNm]	M_{f_z} [MNm]	UR [-]
0.00	0.00	0.00	14.38	0.98	0.01	14.38	0.98	0.01	0.47
0.01	0.00	0.00	14.40	0.71	0.01	14.41	0.71	0.01	0.45

Table 5-6: Transverse beam - Combination 2, comprising uniform temperature and railway live load

Load combination 2									
N_T [MN]	M_{T_y} [MNm]	M_{T_z} [MNm]	N_{QL} [MN]	M_{QL_y} [MNm]	M_{QL_z} [MNm]	N_f [MN]	M_{f_y} [MNm]	M_{f_z} [MNm]	UR [-]
2.27	0.21	0.09	16.09	3.20	0.39	18.35	3.41	0.48	0.65
3.15	0.11	0.10	17.44	3.27	0.39	20.58	3.37	0.48	0.69

Table 5-7: Diagonal beam - Combination 2, comprising uniform temperature and railway live load

Load combination 3												
N_{TH} [MN]	M_{TH_y} [MNm]	M_{TH_z} [MNm]	N_T [MN]	M_{T_y} [MNm]	M_{T_z} [MNm]	N_{LL} [MN]	M_{LL_y} [MNm]	M_{LL_z} [MNm]	N_f [MN]	M_{f_y} [MNm]	M_{f_z} [MNm]	UR [-]
21.17	1.32	1.26	0.00	0.00	0.00	0.01	0.71	0.00	21.19	2.03	1.26	0.89
21.42	1.13	1.34	0.01	0.00	0.00	0.01	0.71	0.00	21.44	0.42	1.34	0.75

Table 5-8: Transverse beam - Combination 3, comprising time history analysis, uniform temperature, remaining permanent loads and partial live load

Load combination 3												
N_{TH} [MN]	M_{TH_y} [MNm]	M_{TH_z} [MNm]	N_T [MN]	M_{T_y} [MNm]	M_{T_z} [MNm]	N_{LL} [MN]	M_{LL_y} [MNm]	M_{LL_z} [MNm]	N_f [MN]	M_{f_y} [MNm]	M_{f_z} [MNm]	UR [-]
27.58	1.68	0.83	2.27	0.21	0.09	2.96	0.71	0.07	31.68	2.49	0.95	0.88
28.60	1.99	0.94	3.15	0.11	0.10	0.48	0.58	0.07	29.69	2.63	1.06	0.86

Table 5-9: Diagonal beam - Combination 3, comprising time history analysis, uniform temperature, remaining permanent loads and partial live load

5.2 Spherical bearings

At the central pin and at the connections with the towers spherical bearings will be used:

- INA GE 750-DW - connecting transverse beam with central pin and tower,
- INA GE 630-DW - connecting diagonal beams at central pin,
- INA GE 440-DW - connecting transverse buffers with wings welded to transverse beam,
- INA GE 440-DW - connecting longitudinal buffers with towers and deck diaphragm,
- SKF GE120 TXA-2LS - connecting vertical member with railway girder.

The spherical bearings will not transfer bending moments and will allow for small rotations of transverse and diagonal beams.

6 Hydraulic buffers

The longitudinal and lateral restraints of the deck at the towers are provided by adaptation of hydraulic buffers, which under "normal" working conditions will remain closed and thus act as rigid connections. In the event of an earthquake the buffers will allow movements of the deck whilst hydraulically limiting the force transferred from the bridge girders to the towers and reducing the deck movements. The concept of the system is shown in Figure 4-1.

6.1 Characteristics

The characteristic of buffer D1 is shown in Figure 6-1.

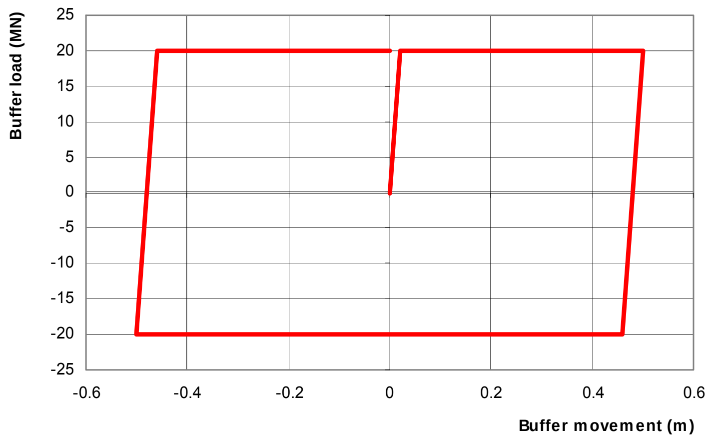

Figure 6-1: Characteristic of buffer D1

A total threshold value of 20MN is chosen for the hydraulic buffers. At lower magnitude of force practically no movements of the buffer will occur, covering effects due to wind loads. Installation of a hydraulic seismic isolator D1 results in a load reduction in the transverse direction from circa 60MN to 20MN in the case of ULS seismic events.

The characteristic of buffer D2 is shown in Figure 6-2.

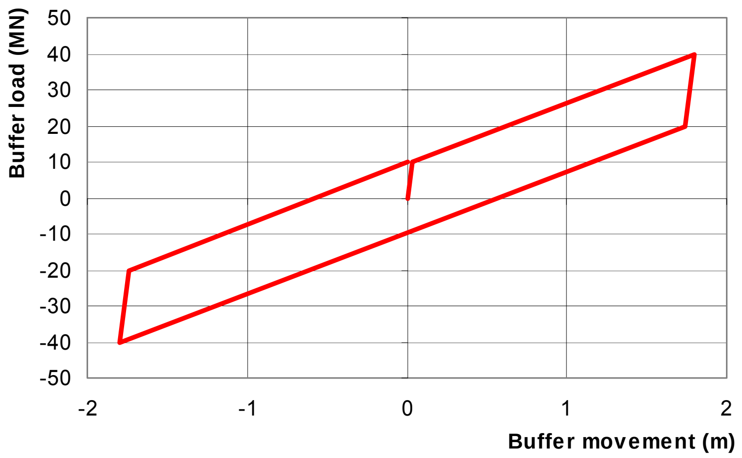

Figure 6-2: Characteristic of buffer D2.

The buffer acts as a damper combined with a spring. To limit the movements due to traffic, wind and temperature gradients the hydraulic system is installed with a threshold value. The threshold value will not be exceeded during the passage of trains. Subsequently the movements will be limited by relative displacements of the deck to the tower.

The buffers D2 comprise of 4 nos. hydraulic cylinders each in order to remain within acceptable and practical dimensions and to ensure a redundant system.

The threshold value is chosen to 10MN for each group of cylinders connected to each tower leg and the buffer system hence stops any longitudinal movements as long as the force in the buffers at each tower is less than 20MN. The 20MN load in the buffers will be exceeded in some load cases; e.g. when there is a temperature change for the bridge girder of $\pm 6^0$ C and during seismic event.

6.2 Conceptual design of the hydraulic systems

6.2.1 Buffer D1

The hydraulic system for buffer D1 is shown in the figure below. The buffer is locked for movements until the load exceeds the threshold value, controlled by the pressure relief valve. When the threshold value is exceeded the piston is allowed to move at constant pressures.

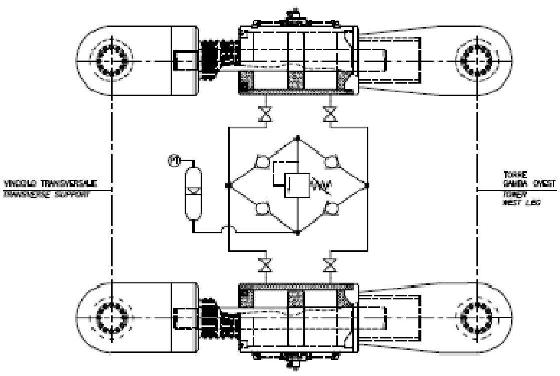

Figure 6-3: Hydraulic circuit, Buffer D1

6.2.2 Buffer D2

The buffer characteristic shown in Figure 6-2 is achieved by combining a damping system with a spring. When the bridge deck, and consequently the piston, moves the hydraulic pressure on one side of the piston will increase until it reaches the set pressure of the pressure relief valve, defining the threshold value. When reaching this pressure the pressure relief valve opens and the oil will flow into the accumulator tanks. As the upper part of the accumulator tank is filled with nitrogen compression of the nitrogen volumen will provide the spring action of the system, which will tend to return the piston to the middle position.

At the same time, as the oil pressure is increasing on one side of the piston, the oil pressure is decreasing on the other side due to the expanding nitrogen volumen in the accumulator tank located on the circuit connected to the this side of the piston. The resulting spring action will thus be the added action from the two accumulator tanks.

During seismic events the relative movements of the deck includes rotation of the deck relative to a vertical axis. From the global IBDAS model values for these rotations have been extracted through analysis of time-history series of the seismic events. Based on the relative movements form one side of the deck to the other of the buffers the oil volume and the flow rates can be calculated. The figure below shows the flow rates calculated during a seismic event.

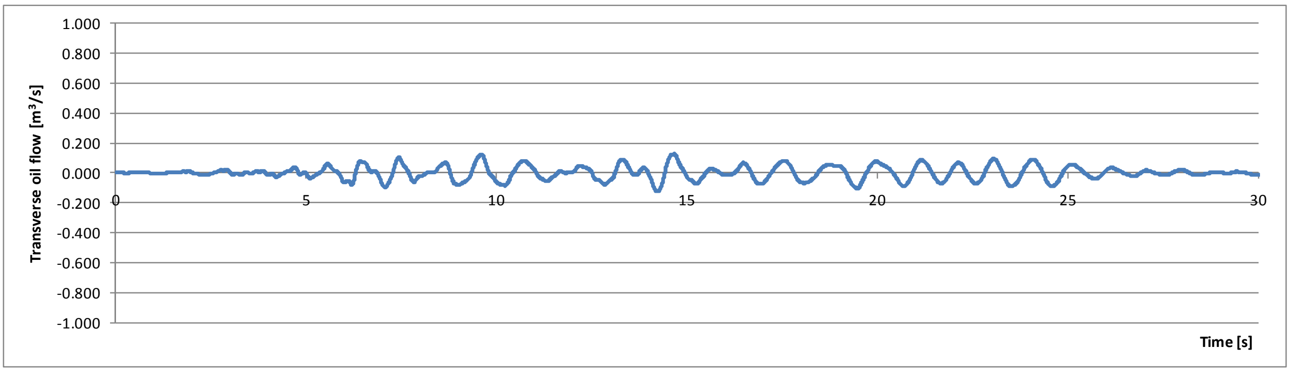

Figure 6-4: Simulation of transverse oil flow during seismic event

It is found that the peak volume of oil required to be moved from one side to the other during a seismic event will be in the order of 20-25l and that the peak flow rate will be app. 100-150l/s.

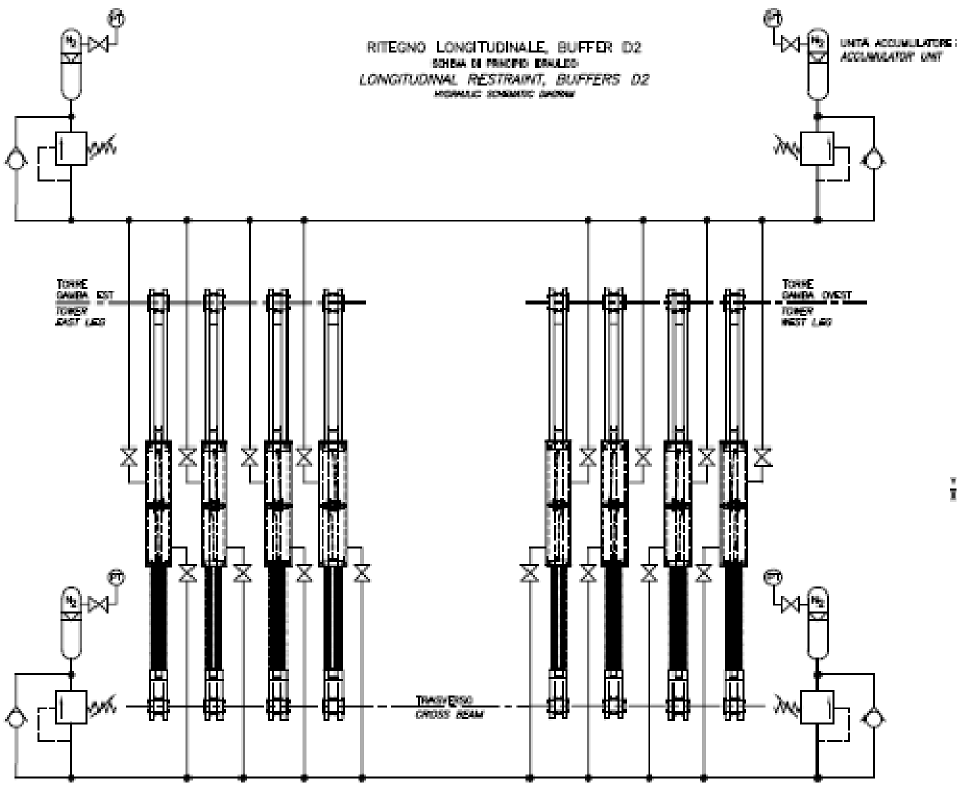

Figure 6-5: Hydraulic circuits, Buffer D2

A conceptual design for buffer arrangement D2 has been prepared by FIP Industriale, Italy. FIP is a possible supplier of the hydraulic buffer systems. The report includes confirmation that the required buffer characteristic can be obtained using pressure relief valves as damping devices and hydraulic accumulator tanks as springs in a hydraulic circuit linking the buffers at one tower leg to the buffers at the opposite leg. The report further included an assessment of the pipe dimension required in order The conceptual design report is attached in Appendix 2.

6.2.3 Failure of hydraulic link between the two tower legs

The function of the longitudinal restraint of the suspended deck - buffers D2 - will change in the case of accidental damage or malfunction of the link system between the buffers at each tower leg. In this case the two groups of cylinders are no longer connected and will act as individual supports.

At each cylinder valve blocks facilitates the possibility to block off the cylinders in case of loss of oil pressure. Further pressure relief valves are provided to avoid damage to the cylinders in case of excessive oil pressures. The principle however of the hydraulic connections at each cylinder are shown below:

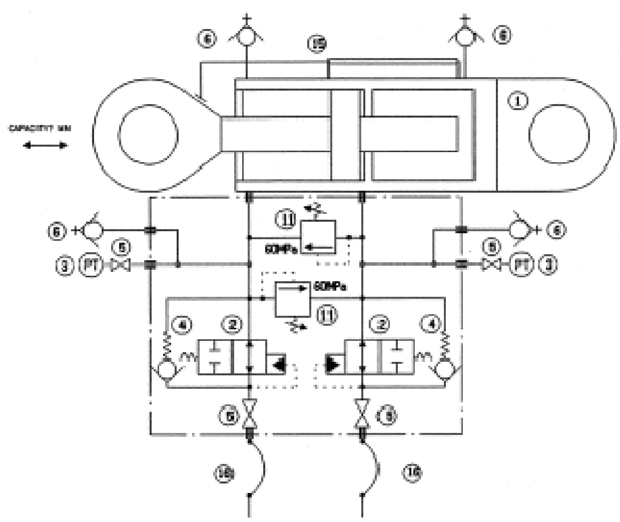

Figure 6-6: Typical valve arrangement at each cylinder

The following failure modes has been envisaged:

- Slow oil leakage from pipe joints, valves etc.
- Major loss of oil pressure due to hose or pipe burst

6.2.3.1 Slow oil leakage

In case of a decrease in the oil pressure an alarm will be sent to the control room, dispatching maintenance crew to activate the manually activated make-up pumps in order to maintain the pilot pressure.

The function of the longitudinal restraint is not affected.

The cause for the alarm shall be found and repaired.

6.2.3.2 Major pressure loss

The hydraulic cylinders are equipped with hose-burst valves which will close immediately in case of loss of pilot pressure. Each cylinder is then sealed off maintaining the oil in the chambers.

The longitudinal restraint will now work as a rigid connection between the deck and the tower. The pressure relief valves, however, will allow movement of the piston as the oil will flow between the two chambers when the relief pressure is reached and ensure that the hydraulic pressure does not damage the cylinders.

The load acting on the tower leg will in this case be determined by the relief pressure set on the pressure relief valve.

It shall be noted that a full operating longitudinal restraint will be active on the opposite tower during the repair period.

An alarm will be sent to the control room in case of loss of oil pressure and maintenance crew shall be dispatched to locate the leakage. Spare parts shall be brought from the storage to replace the damaged parts.

6.2.3.3 Effects on structures

In the event that loss of oil pressure will occure the valves at the cylinders will close and the connection between the tower and the deck will become rigid. As loss of oil pressure is considered only to occur at one tower, the buffer arrangement at the opposite tower will thus be in normal operation.

Loss of oil pressure is considered to be an accidental load case and SILS load cases 1-3 should be considered. In the Design Basis, however, there is no specific load case defined covering malfunction of the buffer system. Due to the short period of time, in which the buffer arrangement is out of normal operation due to loss of oil pressure, the following SLS1 load combinations have been applied:

Load case 6.4 (SLS1): 1.0PP + 1.0PN + 1.0QR + 1.0VV + 1.0VT

Load case 6.5 (SLS1): 1.0PP + 1.0PN + 1.0QR + 1.0VS + 1.0VT

These load case shall be combined with the load case comprising uniform temperature of the structure.

The buffers in both sides of one tower are fixed links while the buffer arrangement at the opposite tower is in normal operation.

To simulate the rigid buffers at one tower two additional elements have been included in the global IBDAS model and forces in these element have been calculated for the load cases above. The results are:

Load case	Nmax (MN)	Nmin (MN)
SLS 6.4	33.3	-33.1
SLS 6.5	37.5	-37,5
VT uniform (ΔT=20°C)	12.9	-12.8

Table 6-1: Forces in rigid links between tower leg and suspended deck

By combining the contribution from uniform temperature with either load case 6.4 (incl. wind loads) or with load case 6.5 (incl. seismic loads) the calculated force in the fixed connection will exceed the design loads for the buffers, which is 40MN (total of 4 buffers).

In this case the the force in the connection will be limited by the safety relief valve located on the buffers allowing oil to flow from one chamber on the cylinder to the opposite chamber. The relief pressure should be set to a pressure corresponding to the max. design pressure of the cylinder limiting the load on the structures to 40MN/side.

The detailed effects on the bridge structures in the accidental loadcases above are assessed in doc. no. CG1000-P-CL-D-P-SV-I3-00-00-00-00-01 Design Report - Roadway, Railway and Cross Girder.

6.3 Buffers behavior

Verification of the implemented buffer characteristics is carried out in the seismic analysis based on time-history analysis in order to simulate correctly the non-linear behaviour of the buffers. The ULS limit state is used as basis.

6.3.1 Buffer D1

The force in the buffer D1 is plotted as a function of movement for time series E8 in Figure 6-7. The dominant transversal component can be seen.

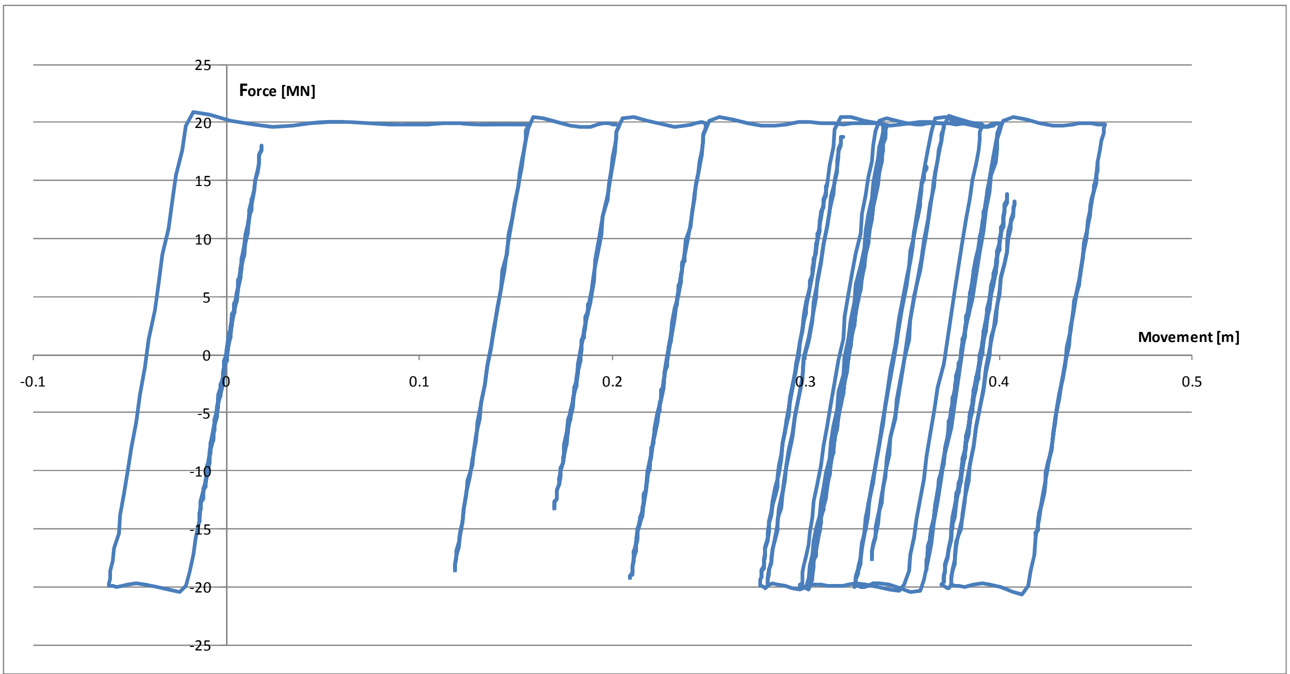

Figure 6-7: Buffer D1 at Sicilia tower for 0.8s+1.0y+0.75z, time series E8. Force plotted against movement.

It is presented that the initial stiffness of the buffer is correctly modelled. The threshold value of 20 MN is achieved and after exceeding the force the stiffness of the buffer changes. The buffer is moving between -0.061m and 0.458m in a total distance of 0.519m.

6.3.2 Buffer D2

The force in the buffer D2 at the Sicilia tower is plotted as a function of movement for time series E1 and presented in Figure 6-8 with a dominant longitudinal component.

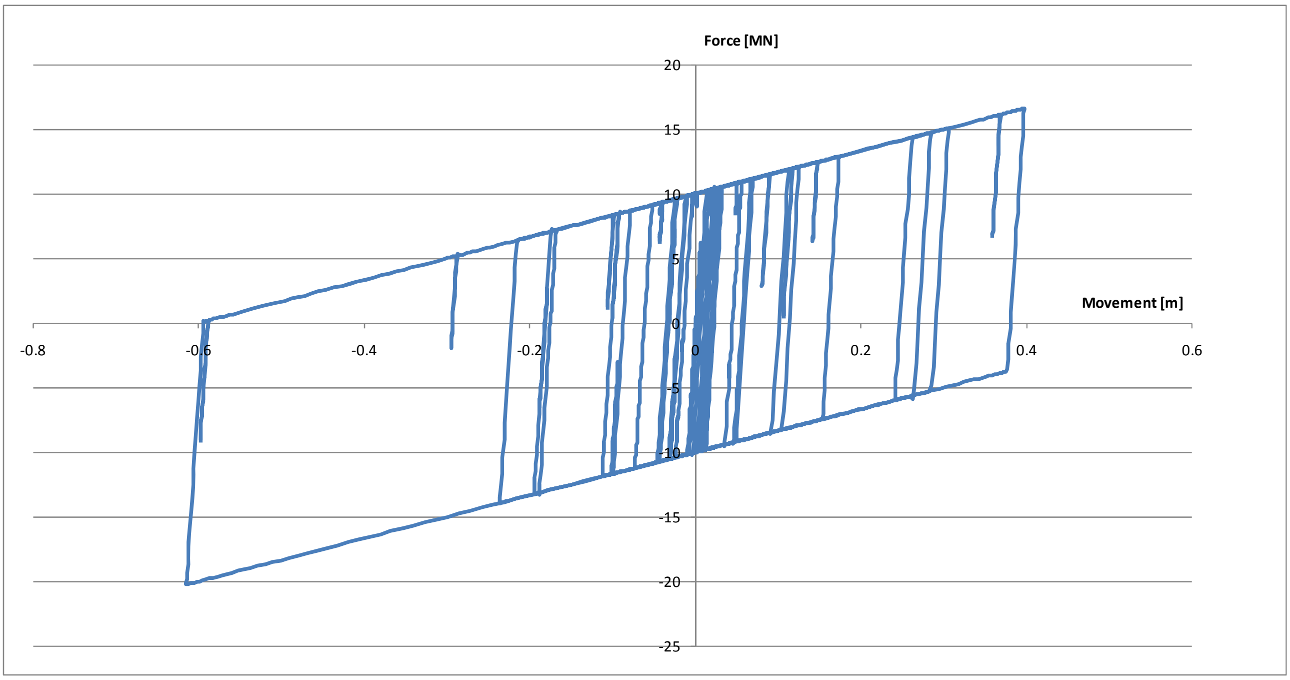

Figure 6-8: Buffer D2 at Sicilia tower for 1.0s+0.8y+0.75z, time series E1. Force plotted against movement.

The behaviour is as expected, however without preloading the force and movements are not as big as shown in the characteristic in Figure 6-2.

The preloading condition is added based on the following components:

- Maximum uniform temperature;
- Fixation of the traffic loads such that there is maximum pulling out force in the longitudinal buffers at the Calabria tower.

The force in buffer D2 at the Sicilia tower is plotted as a function of movement for time series E1 with a dominant longitudinal component with preloading on Figure 6-9. The movement is shown as a function of time in Figure 6-10.

The development in buffer D2 at the Calabria tower is platted for the same setup in Figure 6-11 and Figure 6-12.

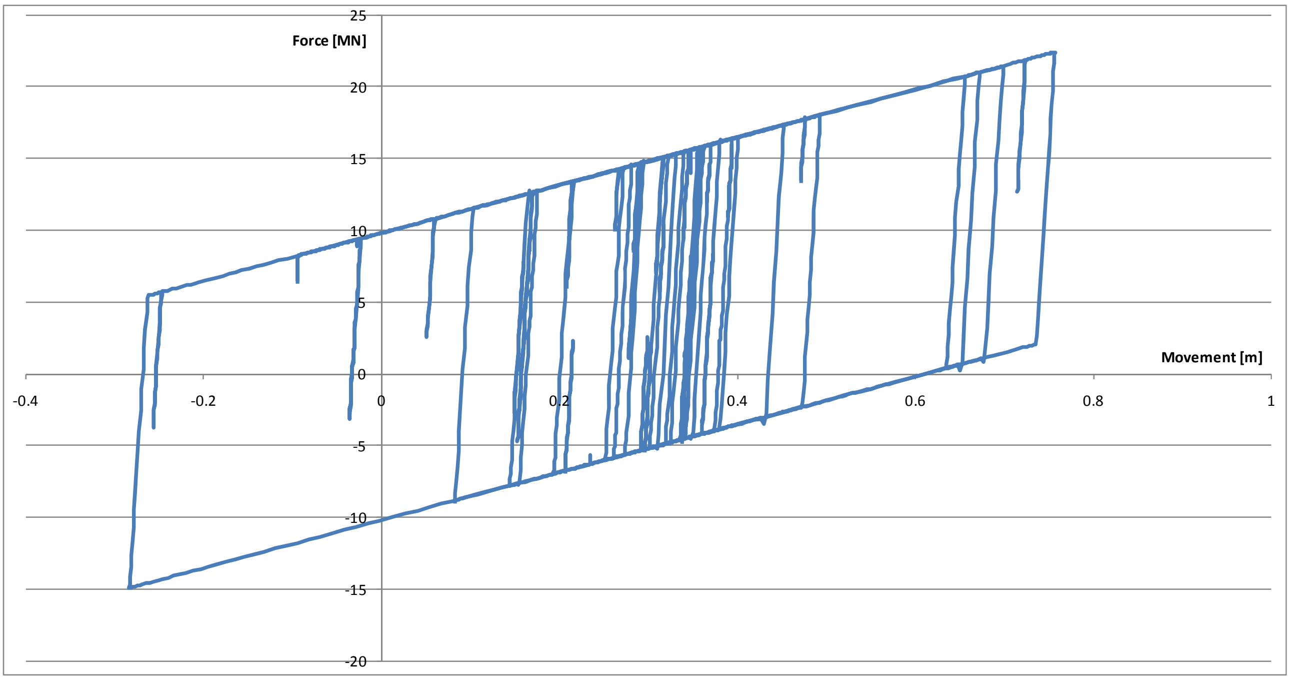

Figure 6-9: Buffer D2 at Sicilia tower for 1.0s+0.8y+0.75z, time series E1, with preload consisting of temperature and traffic. Force plotted against movement.

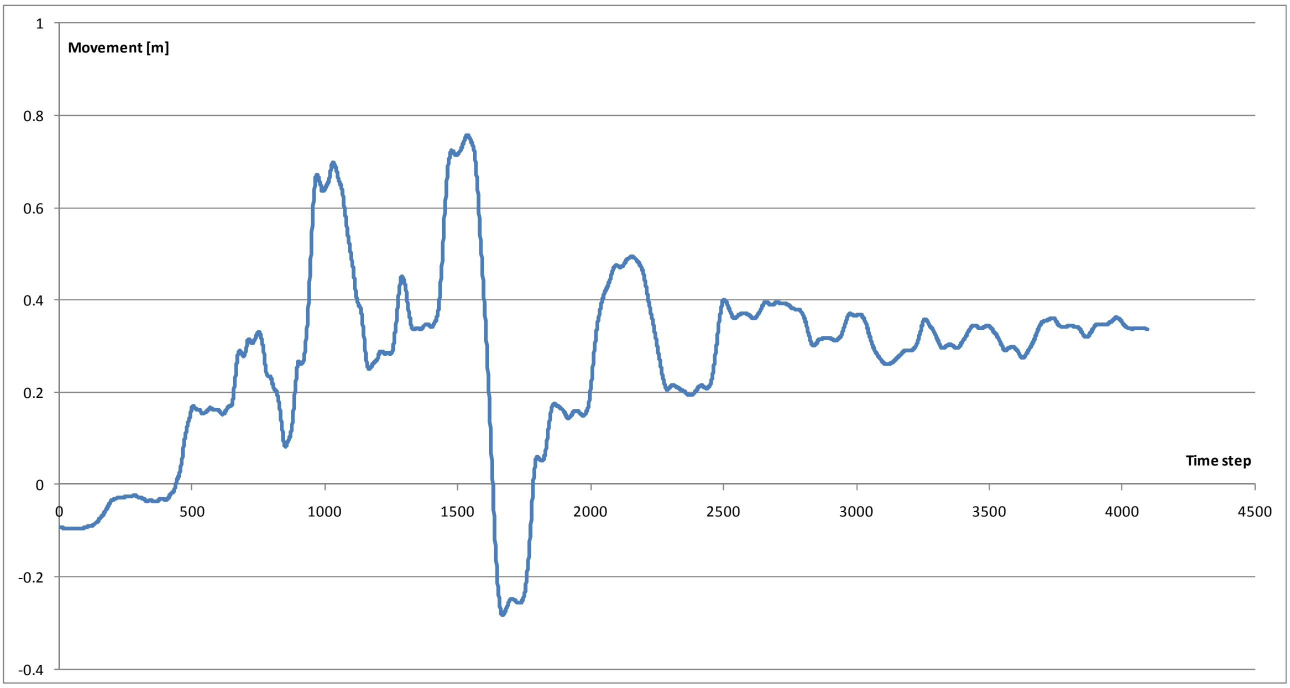

Figure 6-10: Buffer D2 at Sicilia tower for 1.0s+0.8y+0.75z, time series E1, with preloading consisting of temperature and traffic. Movement plotted against time

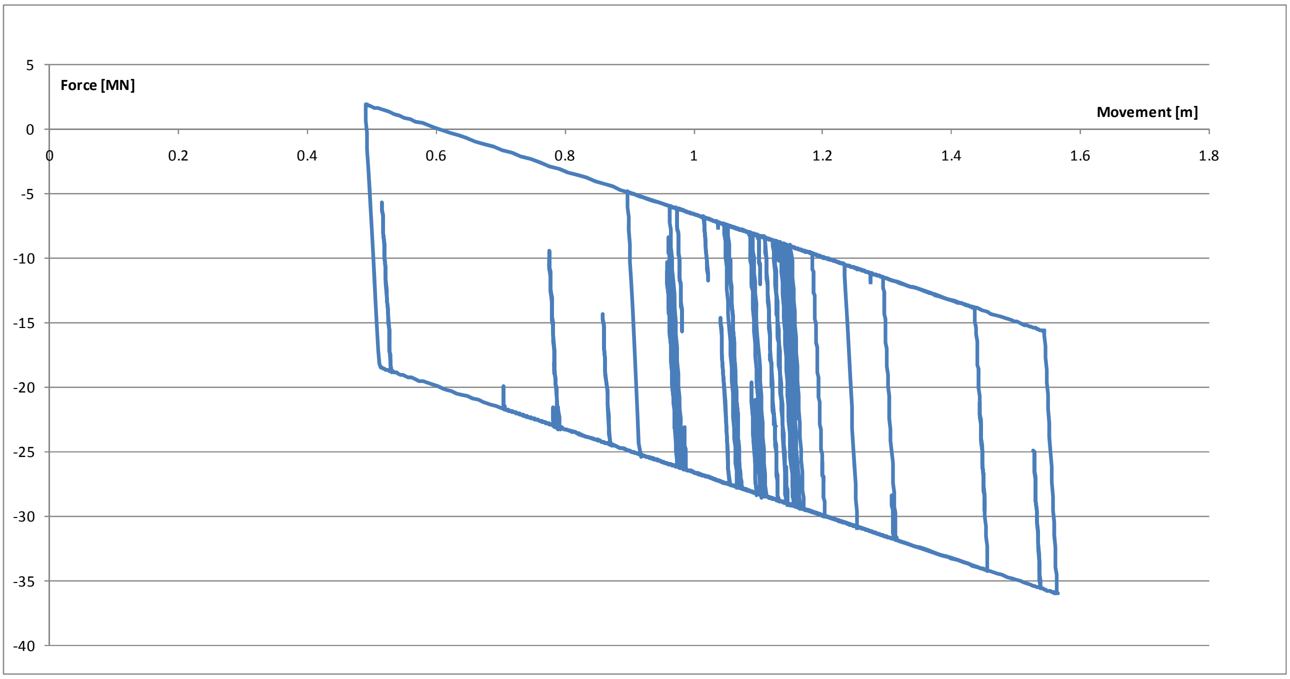

Figure 6-11: Buffer D2 at Calabria tower for 1.0s+0.8y+0.75z, time series E1, with preloading consisting of temperature and traffic. Force plotted against movement

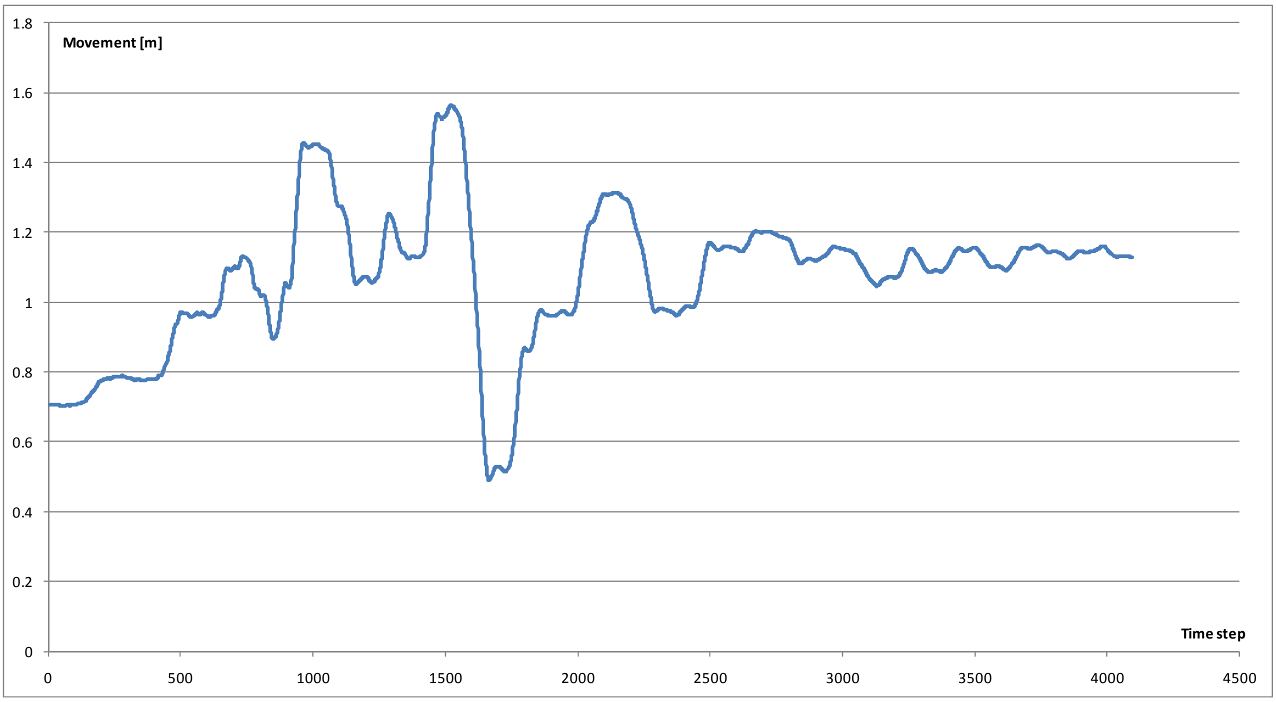

Figure 6-12: Buffer D2 at Calabria tower for 1.0s+0.8y+0.75z, time series E1, with preloading consisting of temperature and traffic. Movement plotted against time

The force range in the buffers at the Calabria tower is between 1.9 MN and -36.0 MN. The preload initially stimulates the buffers to shift 0.71m before the earthquake is initiated. The buffers are moving between 0.49m and 1.565m in a total distance of 1.565m.

Comparing the two plots in Figure 6-9 and Figure 6-11 it is seen that the buffers at Sicilia and Calabria towers respectively are operating opposite of each other. It was expected by the application of the buffers.

When the earthquake is initiated the buffers at the Sicilia tower have similar movements to the buffers at the Calabria tower. The initial movements however are not identical. At the Sicily side the initial shift is -0.093m, where at the Calabria side is 0.71m. This is due to the fact of fixation of the traffic loads which are determined to provide maximum pulling force in the longitudinal buffers at the Calabria tower. At the Sicilia tower, however, this position of traffic loads will have the opposite effect, thus counteracting the effect of the uniform temperature.

6.4 Movement

The seismic time-history analysis is used with preloading of the buffer arrangements to determine the peak forces, movements and rotations in buffer D1 and D2. The preload condition is based on the following components:

- Maximum uniform temperature,
- Fixation of the traffic loads to obtain maximum pulling out force in the longitudinal buffers at the towers.

The movement of the buffers can be found in CG1000-P-BX-D-P-SS-A0-00-00-00-00-01 (Articulation system - Longitudinal supports) and CG1000-P-AX-D-P-SS-A0-00-00-00-00-03 (Articulation system - Suspended deck supports at terminal structures).

7 Railway girder at the terminal structure

At both ends of the suspended structure the railway girder is protruding into the terminal structure over a distance of 38.8 m. The last 14.1 m is the spline girder for the railway expansion joint E4. It is supported on bearings A9, A10 and A11 where A9 and A10 are free sliding bearings and A11 a guided sliding bearing.

The reason for this arrangement is to limit the vertical movement and the rotations generally in the railway expansion joint.

Appendix 1 - Detailed calculations for structural elements

1 Transverse Connection

1.1 Connection to central node

- Pad eyes
- Pins
- Spherical bearings

1.2 Buffer arrangement

- Pad eyes
- Pins
- Spherical bearings

1.3 Connection to tower

- Pad eyes
- Pins
- Spherical bearings

1.4 Telescopic device

2 Longitudinal Connections

2.1 Connection to central node

- Bolted connection
- Pad eyes
- Pins

- Spherical bearings

2.2 Connections to cross girders / suspended deck

- Bolted connections

3 Vertical connection to railway deck

3.1 Main structural element

3.2 Pad eyes

3.3 Pins

3.4 Bearings

Appendix 2 - Longitudinal Hydraulic Buffer System, Conceptual design