The Testing Campaign on Seismic and Wind Protection Systems of the World´s Largest Cable Stayed Bridge: The Russkij Bridge at Vladivostok

Peter Huber, Dipl. Ing.
Maurer Söhne GmbH & Co. KG Munich, Germany

Oliver Benicke, Dipl. Ing. (FH)
Maurer Söhne GmbH & Co. KG Munich, Germany

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SUMMARY: TESTING COMPAIGN ON SEISMIC AND WIND PROTECTION
The Russkij Bridge will represent a landmark for the Asia-Pacific Economic Summit which will be held in 2012 at Russkij Island near Vladivostok. When completed, it will be world's largest cable stayed bridge with a main span of 1104 m and stay cables of 578 m. The environmental conditions at the bridge site are very severe. To prove the theoretical characteristics of the damping devices, testing was required. Considering the importance of the work and the extreme environmental and load conditions, the testing specs are particularly demanding.
The paper illustrates the testing procedures, some of which are innovative, and comments on the interesting results achieved. The above can provide a guide for those who will face future testing campaigns as demanding as this one, and may also provide inspiration for perfecting and integrating the present Norms.

Keywords: hydraulic, passive viscous linear and semi-active magneto-rheological dampers

1. GENERAL INSTRUCTIONS

It is a Monumental project. When completed, the Russkij Bridge will not only have the world´s largest main span for a cable stayed bridge – 1104 m – but with 578 m also the world´s longest stay cables.
The environmental conditions at the bridge site are very severe. The design wind speed is equal to 132 km/h and the wind gusts occur for an average of 10 min per day, which results in 7 million longitudinal impulses during the its expected 100 year service life. In addition, a seismic attack with a magnitude 8.1 shall be considered, with a probability of being exceeded once in 5000 years.
Even the local temperature range is quite wide (-40 ° to 70°C).
Considering the importance of the work and the extreme environmental and load conditions, the testing specs are particularly demanding.
The tests involved both, the anti-seismic protection system, consisting of six (6) hydraulic dampers 3000 kN axial load, and the wind protection system, consisting of No. 184 passive viscous linear dampers and No. 40 semi-active magneto-rheological dampers.
The seismic hydraulic dampers also carry out an important function in service condition, acting as very high stiffness lock-up devices to reduce the undesired strokes induced by wind, which may produce wearing in both the gaskets and the expansion joints. Similarly, the wind protection system mitigates the effects of a seismic attack on the cables. All the tests were carried up on full-scale devices.
Dynamic tests simulating the seismic input on 3000 kN hydraulic dampers were conducted at the SRMD facility of the University of California at San Diego. Particular difficulties arose with the tests at -40° C, given the considerable size of the device and the amount of heat produced by each trial.
The tests on the same dampers simulating the service conditions were carried out at Ruhr University at Bochum (Germany) and included the wearing and fatigue resistance tests for 7 million cycles induced by the wind gusts.
The tests on cable dampers (both passive and semi-active) were undertaken at EMPA in Dübendorf (Switzerland).

This paper highlights the testing procedures of the structural protection system for vibration, some of which are innovative, and comments on the interesting results achieved.
Structural protection system for vibration:

1. Hydraulic stay cable dampers to dampen the vibrations of the stay cables not only in their first mode, but including modes two to four, which may jeopardize the structural stability.
2. Hydraulic dampers as energy dissipators to mitigate a potential seismic attack, and in service stage have a lock up for wind impacts (7million impacts).

Figure 1. Computer simulation of the Russkij Bridge (under construction)

2. HYDRAULIC STAY CABLE DAMPERS

The mix of passive and semi-active hydraulic dampers was already implemented for the thus far largest cable stayed bridge in the world, which is the Sutong Bridge in China.
Within Russkij Bridge per each cable to be damped, two hydraulic dampers shall be provided for the steel pendulum lever arm system connecting the hydraulic dampers with the cable, which will be provided by FREYSSINET INTERNATIONAL. Finally the decision was for 184 nos. passive (for 92 nos. cables) and no. 40 semi-active hydraulic dampers (for the 20 nos. longest cables).

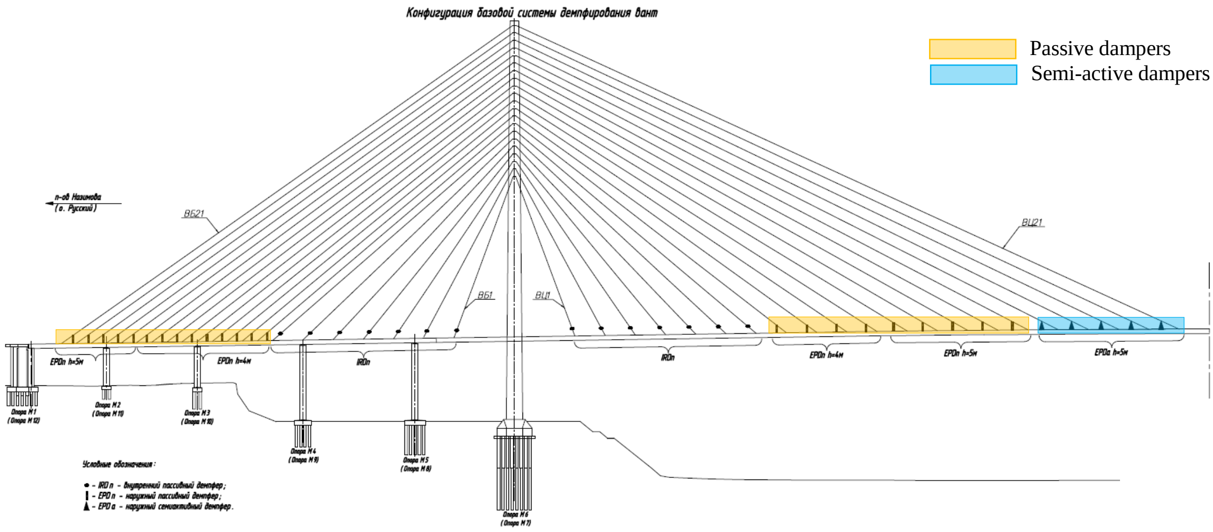

Figure 2. Location of Hydraulic stay cable dampers

The specification for the hydraulic stay cable dampers was a particularly strict one:

- Design wind speed of 36.68 m/s for the cables introduces max. 0.5 m/s piston velocity with 2 Mil. cycles for the hydraulic damper.
- Operation temperature range -40°C to +60°C. Facing such a large temperature difference, the variation in response force of the hydraulic damper has to be kept within a range of ±20%.
- A mix of passive and semi-active hydraulic dampers is anticipated. The back span, cables 8 to 21 and the main span, cables 8 to 16 will receive passive hydraulic dampers. The main span cables 17 to 21 will receive a semi-active hydraulic dampers.

- Logarithmic decrement of 4% shall be introduced into the stay cables no. 1 to 7, which is achieved by internal dampers of the cable supplier. In cables 8 to 15 the logarithmic decrement of 6% shall be achieved by external dampers. This shall even be increased to 8% for cables 16 to 21 – also by external dampers.
- The logarithmic decrement of 8% for the main span cables 16 to 21 shall be achieved for the eigenmodes 1 to 4 in the cable plane, which is required especially for the longest stay cables of 578 m length.

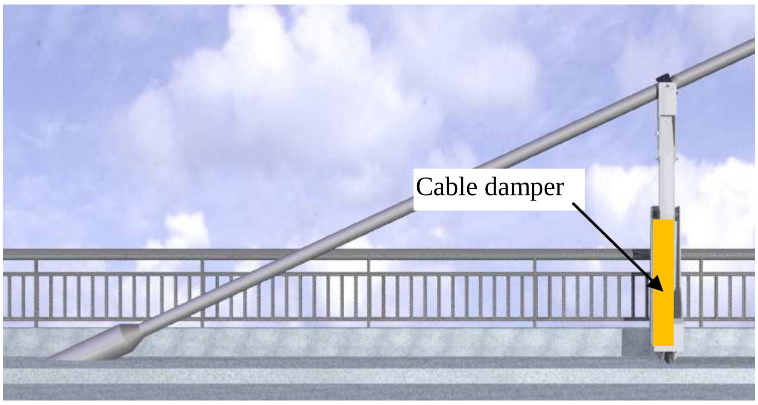

Figure 3. Installation situation of the cable dampers

Due to the importance of this structure and the demanding meteorological conditions, test must be done, for proving the characteristics of the passive and semi-active dampers. According to specification of FREYSSINET, qualification tests and production tests were prescribed.

Table 1. Physical properties

	Passive					Semi active	
Type (see §5)	EPD200-090	EPD 200-140	EPD200-220	EPD300-140	EPD 300-230	EPD 300-50/320	
Stroke	±100 mm	±100 mm	±100 mm	±150 mm	±150 mm	±150 mm	
Viscosity C (kN.s/m)	90	140	220	140	230	Min 50	Max 320
Maximum Service Force F_{max}(kN) = Blow-off Force (–0/+5kN)	20	40	65	50	70	65	
Maximum service speed V_{max} (m/s) = Minimum Blow-off speed	0.25	0.35	0.35	0.40	0.35	0.50	
Tolerance on viscosity (at production)	+/-10%						
Stiffness	≤ 10 kN/m						
Nominal speed V_{nom}	Vmax / 2						
Curve	Symmetrical (for both direction : tension and compression)						

2.1 Qualification Tests

Qualification tests were done by EMPA Laboratory at the Technical University of Bochum. According to the specification of FREYSSINET, the following tests must be performed:

2.1.1 Damping characterization at nominal temperature of 5°C:
- Samples: One piston of each type (5 passive, 1 semi-active).
- Parameters: Amplitudes and frequencies, see tables 2.1 and 2.2.
- Acceptance criteria: viscosity coefficient shall be within +/-10% of the specified.

2.1.2 Fatigue test at factory, according to following program:

- Samples: One passive piston, one semi-active piston.
- Parameters:
  - 2 million cycles at 1Hz with amplitudes of +/- 10mm.
  - A damping characterization test has to be performed at 100 000, 500 000, 1 million and 2million cycles.
  - Maximum force shall be recorded during the whole test.
- Acceptance criteria:
  - Variation of velocity due to combined endurance and temperature shall not be greater than +/-20%.
  - There shall be no evidence of oil drops forming.

2.1.3 Damping characterization under 2 extreme temperatures: -40°C and 60°C

- Samples: One passive piston, one semi-active piston.
- Parameters: Amplitudes and frequencies, see table below
- Acceptance criteria:
  - Variation of velocity due to combined endurance and temperature shall not be greater than +/-20%.
  - For low temperature at -40°C damper temperature, max. 60 cycles with max. 0,85Hz and max. +/- 20 mm amplitude before the 5 cycle measurement cycle are allowed.

2.1.4 Salt fog test. 500 hrs according to the following parameters (ISO 9227):

- Samples: One passive piston, one semi-active piston.
- Parameters:
  - Relative humidity: 20 to 100% humidity without condensation.
  - Salt corrosion: coastal region salty atmosphere.
- Acceptance criteria: Any pitting will be cause for rejection.
  - Painting: Rusted degree shall be RI0 according to ISO 4628/3.
  - Other Material: any pitting will be cause of rejection.

Table 2.1 Characterization test parameters, passive dampers

			Piston type			
A (+/- mm)	N (Hz)	V (m/s)	EPD xxx-090 C = 90kN.s/m	EPD xxx-140 C = 140kN.s/m	EPD xxx-220 C = 220kN.s/m	EPD xxx-230 C = 230kN.s/m
10,00	0,30	0,02	X	X	X	X
10,00	0,80	0,05	X	X	X	X
10,00	1,30	0,08	X	X	X	X
20,00	0,30	0,04	X	X	X	X
20,00	0,80	0,10	X	X	X	X
20,00	1,30	0,16	X	X	X	X
30,00	0,30	0,06	X	X	X	X
30,00	0,80	0,15	X	X	X	X
30,00	1,30	0,25		X	X	X

5 cycles minimum each test.

Table 2.2 Characterization test parameters, semi-active dampers

			Tuning		
A (+/- mm)	N (Hz)	V (m/s)	C = 90kN.s/m	C = 190kN.s/m	C = 320kN.s/m
10,00	0,25	0,02	X	X	X
10,00	0,65	0,04	X	X	X
10,00	1,10	0,07	X	X	X
20,00	0,25	0,03	X	X	X
20,00	0,65	0,08	X	X	X
20,00	1,10	0,14	X	X	X
30,00	0,25	0,05	X	X	X
30,00	0,65	0,13	X	X	X
30,00	1,10	0,21	X	X	

5 cycles minimum each test.

Following two representative graphs show the testing results of one semi-active and one passive hydraulic damper, executed at Technical University Bochum and University of Armed Forces Munich/Germany.

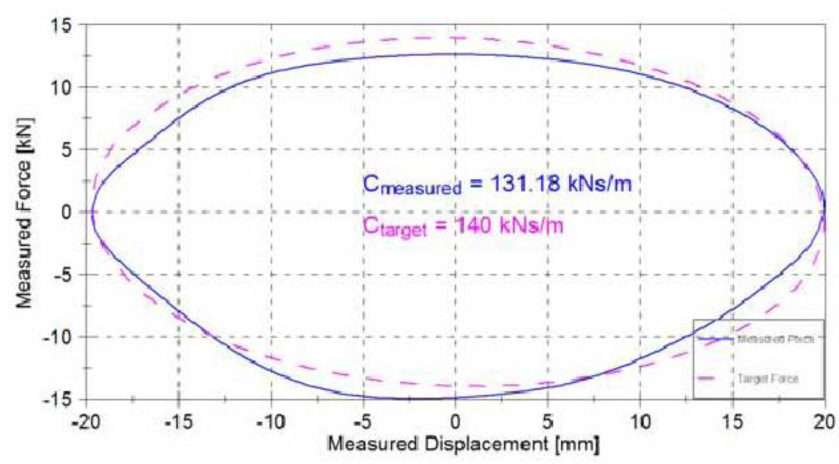

Figure 4. Test result of a passive damper, amplitude = 20mm, frequency = 0,8H

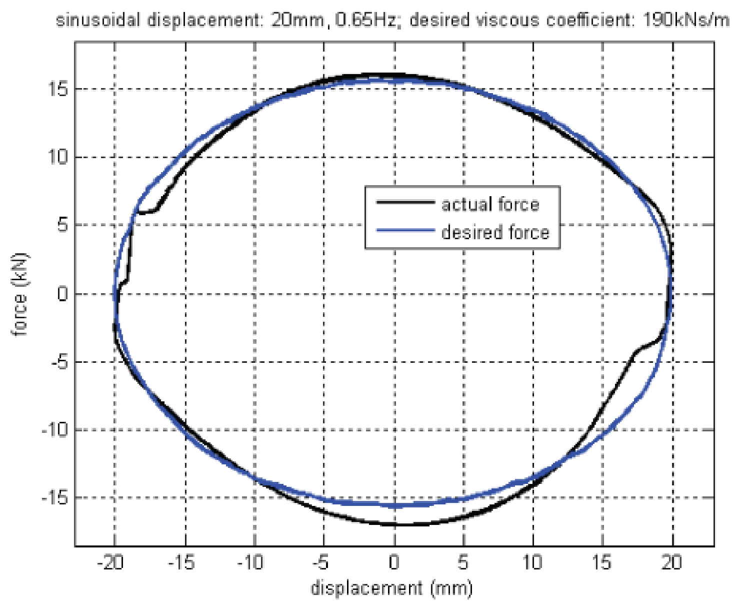

Figure 5. Test result of a semi-active damper

Within extensive type testing at EMPA Duebendorf/Switzerland and the University of Armed Forces Munich/Germany (Fig. 6) six hydraulic dampers finally proved that they fulfil the severe specifications.

Figure 6. Dynamic testing of hydraulic damper for +60°C and -40°C

2.2 Production Test

Besides the qualification tests, also less comprehensive production tests were demanded, according to specification. These tests were performed as in-house tests at MAURER SÖHNE premises and included the following:

- Samples:	- 20% minimum of each piston type should be tested, - If acceptance criteria is not achieved for one tested piston, 60% of pistons shall be tested, - In case of failure of two or more pistons, 100% of pistons shall be tested.
- Parameters:	- Temperature: 5°C, - Amplitudes and frequencies: see tables 2.1 and 2.2,
- Acceptance criteria:	Viscosity coefficient shall be within +/-10% of the specified.

Differing from the specified test procedure, the permitted range of temperature was increased upon approval by client, from -5°C up to +20°C. Besides the in-house tests, for 10% of all manufactured dampers, FREYSINNET wanted additional tests at an independent approved testing laboratory, for verification of the in-house test results. The choice of dampers for additional tests was arbitrary and done by FREYSINETT. These additional tests were done by University of German Armed Forces Munich.
Furthermore MAURER SÖHNE tested 100% of the manufactured dampers in-house, to be sure, that every damper will react well.

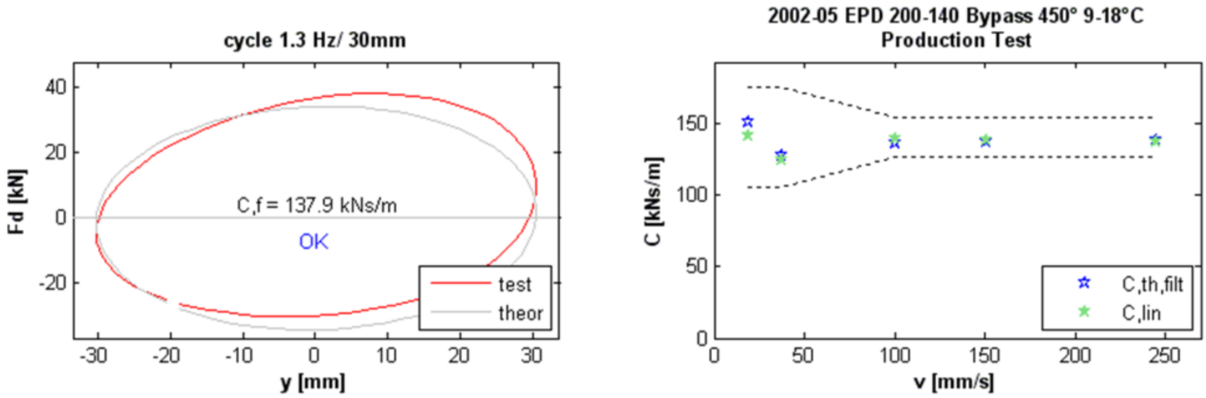

Figure 7. Test result of an in-house test of a passive damper

The semi-active hydraulic dampers (Fig. 8) adapt their response force depending on the occurring mode 1 to 4 of the stay cable in real time. The data input is comes from a displacement sensor. Its signal is being converted by a specially developed control algorithm in an output signal, which controls the viscosity of the special hydraulic fluid at the inner piston area or damper response force of max. 70 kN respectively.

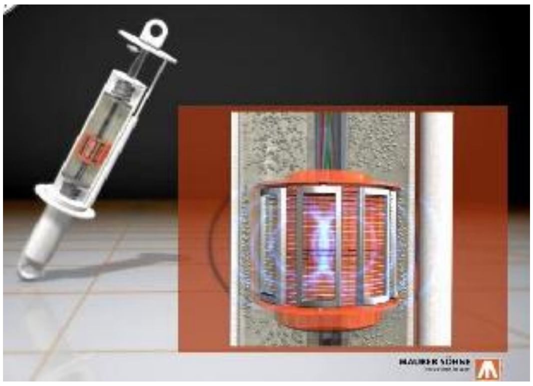

Figure 8. Semi-active hydraulic damper changes the viscosity of the fluid via magnetic field

3. HYDRAULIC DAMPERS

At both deck ends three hydraulic dampers will be installed while these will be fixed with a slope of approximately 13° in damper mid position, which was considered by the designer for the force calculations. The hydraulic dampers (Fig. 9) with a mass of the 5200 kg (without any brackets) serve a double function. Originally they were designed to dissipate the energy from a seismic attack with a response force of 3000 kN and a seismic movement of ± 350 mm at 200 mm/s . The additional function is to act like very stiff shock transmitters for the load case “wind impact”. The wind itself creates only a response force of 1000 kN to max. 2000kN. This load was calculated to occur 7 million times in the period of the design life of the bridge (100 years). Thus the hydraulic deck dampers had to be designed for fatigue caused by wind loads, which ultimately turned out to be the deciding factor for their design.

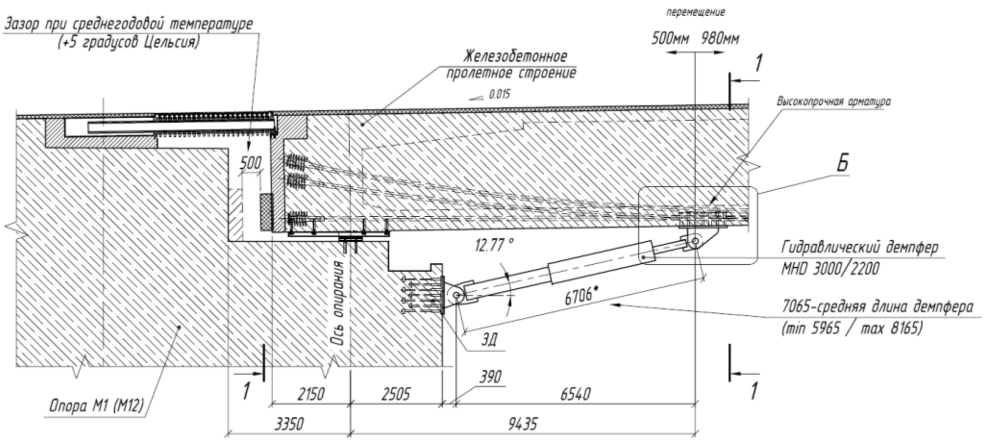

Figure 9. Arrangement of the viscous damper between bridge deck and abutment

It was further required that the damper – specifically the shock transmitter function of the damper in service stage - only display a very low compressibility of between 1.0% and 1.5% (of displacement capacity in one certain direction) for service impacts, such that the desired response force is immediately activated as soon as the wind loads occur, to protect the stay cables, the expansion joints and the bridge bearings from excessive movements and fatigue caused by wind.

In reality the maximum displacement that due to wind loads allowed by the damper until full wind force transmission will be around 7-15 mm per impact. But even these 7-15 mm, which by design occur 7 million times in the course of 100 years, add to a total accumulated sliding displacement of 98-210 km.
One condition for such a fairly stiff damper respectively STU for service conditions that immediately activates the response force is a very low exponent α, which constitutes the law of viscous dampers:

$$F = C \bullet v^{\alpha}$$

Whereas F being the response force of the damper, C being a damper specific constant, v representing the movement velocity, and α representing the exponent of this equation.
In order to be practically independent from the movement velocity v, a very low exponent α is mandatory (Fig. 10). In this case α was selected to be 0.04, and the damper constant C to be 3148 kNs/m.
A second condition for immediate force response is a rather low compressibility of the damper in force acting direction. This requires that the damper operate under a relatively low pressure of 85 bar for the load case “wind” with 7 Mil. load cycles, and then with max. 250 bar for the load case “earthquake or extreme wind” with 200 load cycles. The hydraulic damper has to perform in a temperature range of -40°C to +60°C while a force tolerance of only +/-10% together with the fabrication tolerance is acceptable.
The ULS load is 3000kN, and the regular frequent SLS load is 1000kN. The maximum movement velocity at a seismic attack is 200 mm/s, and it shall lock-up for displacements caused by wind starting from of 1-1.5 mm/s.

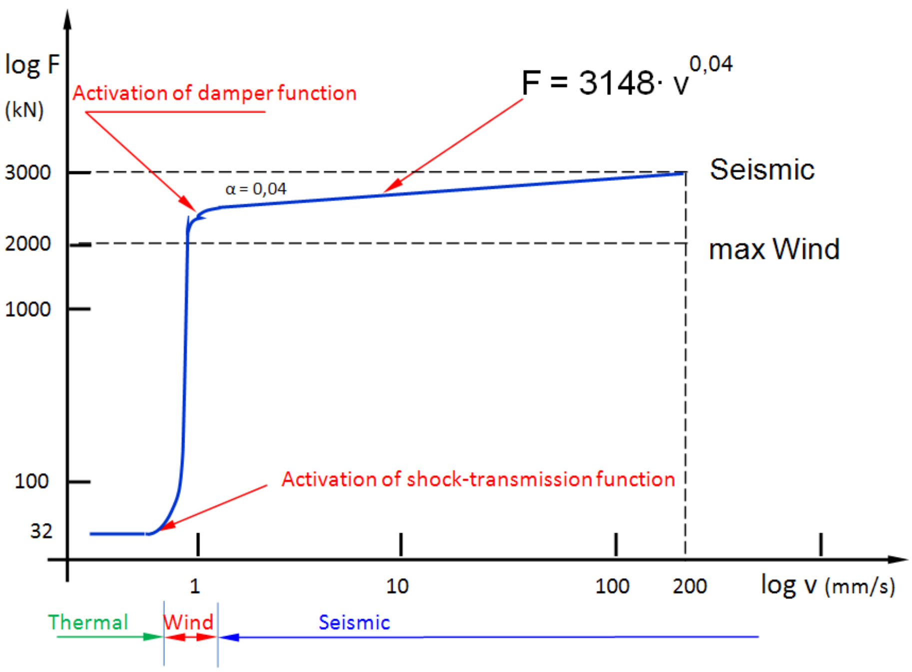

Figure 10. Damper characteristics

The design must be according EN15129, which means, among others, that a certain “over velocity” has to be considered which increases the response force by a safety parameter.
Testing was carried out in August 2011 in the CALTRANS Testing Rig (Fig. 14) at the University of California in San Diego according to EN15129 and the specific client´s requirements with regard to lock-up velocity, temperatures down to -40°C and lock-up displacement for service wind loads.

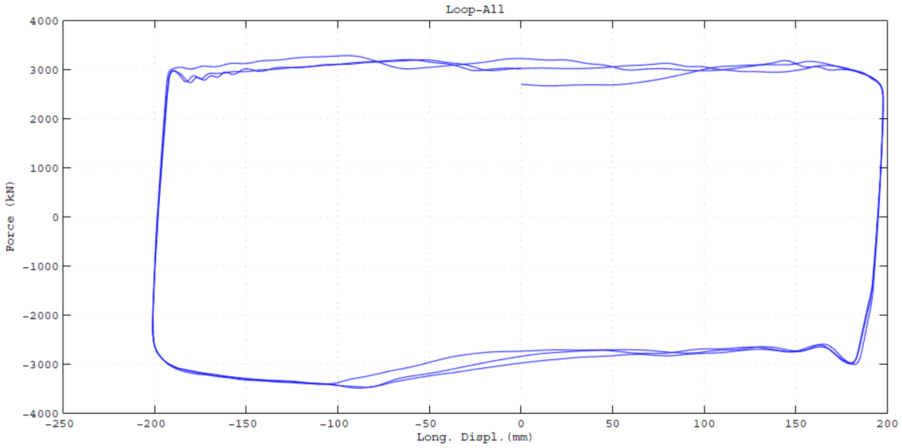

Figure 11. Test result of University of California in San Diego.

The production testing for stiffness with lock-up (after 7-15mm) and slow movement resistance (30-100kN for 0,1mm/s and +60°C to -40) where carried out the Ruhr University in Bochum (Fig. 12).

Figure 12. Production test at Ruhr University Bochum with slow resistance & lock-up test.

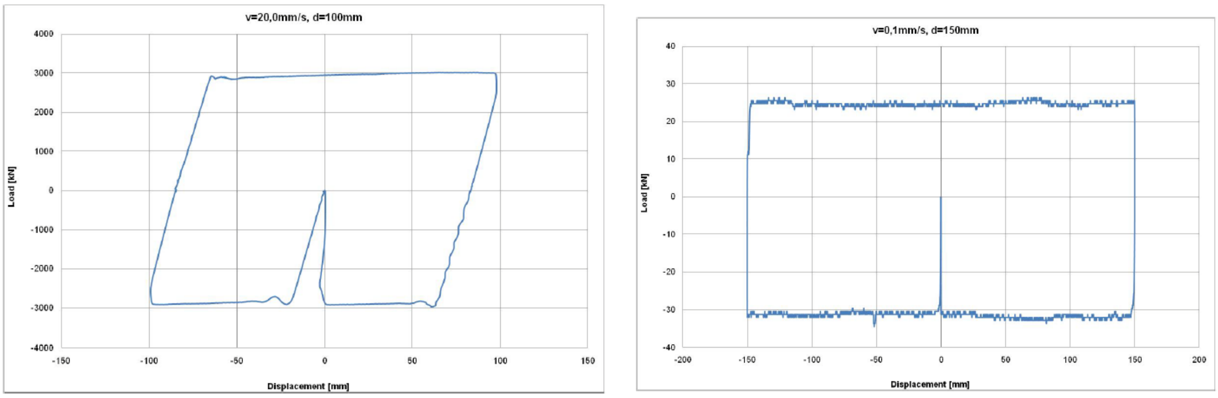

Figure 13. Test results of Ruhr University Bochum

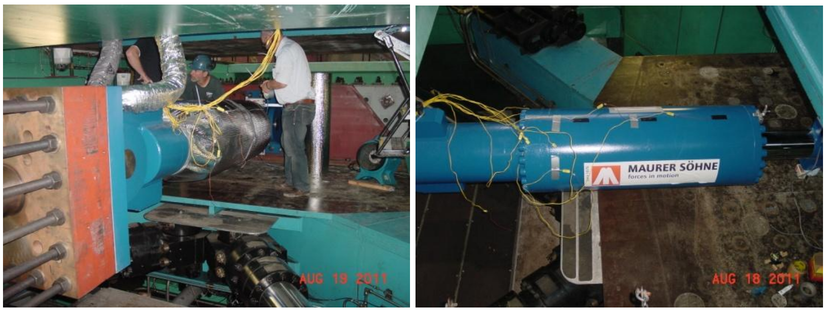

Figure 14. Type test of hydraulic damper at University of California San Diego

3. CONCLUSIONS

The system for the damping of the Russkij Bridge provides the required damping and energy dissipation respectively for various load cases like earthquake and wind.

For the service load cases like wind & rain-wind phenomena the hydraulic cable dampers stabilize the cables by adding significant amounts of damping. Especially the 20 nos. longest cables were fitted with semi-active dampers constantly providing the optimum damping to the first four eigenmodes depending in which mode the cables are vibrating. These semi-active dampers change their damper response force in real time depending on the active cable mode.

The three hydraulic deck dampers at each bridge end react with up to 3000 kN each and provide extreme stability for service wind impacts with only 7 mm to 15 mm displacement. For the seismic load case these will move +/-350mm and dissipate huge amounts of energy while the response force is kept constantly at a force level of 3000kN for a velocity range of up to 300mm/s. However the requirement for fatigue resistance for 7 Mil. wind impacts with 1000 kN is the dimensioning criteria for the single damper parts.

All devices have been excessively and successfully tested according to clients requirements (tight force tolerances+/-10% to +/-20%; temperature range -40°C to +60°C; great stiffness, fatigue cycles, etc.) and relevant standards like EN15129.

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