STONECUTTERS CABLE-STAYED BRIDGE: FULL-SCALE TESTING OF DYNAMIC CONTROL DEVICES

G. P. Colato[1], R. Chiarotto[2], M. Fetti[3], S. Infanti[4], M. G. Castellano[5]

[1] *Director, FIP Industriale Technical Department, Selvazzano Dentro, Italy*
Email: gian.paolo.colato@fip-group.it
[2] *Senior Designer, FIP Industriale Technical Department, Selvazzano Dentro, Italy*
Email: renato.chiarotto@fip-group.it
[3] *Project Manager, FIP Industriale Overseas Department, Selvazzano Dentro, Italy*
Email: massimo.fetti@fip-group.it
[4] *Manager, FIP Industriale Research and Development Department, Selvazzano Dentro, Italy*
Email: samuele.infanti@fip-group.it
[5] *Senior Researcher, FIP Industriale Research and Development Department, Selvazzano Dentro, Italy*
Email: maria.gabriella.castellano@fip-group.it

ABSTRACT :

The Stonecutters cable-stayed bridge, now under construction in Hong Kong, is a crossing 1600 m long characterized by an 1018 m main span that sets it amongst the longest bridges of this type. It is designed to withstand extreme wind storms and earthquakes. Thus, the designer's foresight contemplated using a non-conventional restraint system to connect the deck to the pylons in both the longitudinal and transverse directions. At each pylon, a group of four 8000 kN capacity (800 mm stroke) Shock Transmission Units (STUs) are installed along the longitudinal direction, while two preloaded spherical bearings connect transversally the steel girder to the pylon - with a reaction that depends upon the dynamics of the imposed load. At the onset of any dynamic action, the longitudinally acting STUs are designed to temporary link the deck to the pylons providing for a very stiff connection. In order to avoid torque effects in the bridge structures, each group of units has a common hydraulic circuit that makes them react simultaneously during the dynamic event. Furthermore, said hydraulic circuit is designed to reduce to a minimum the reaction associated with slow movements induced by deck thermal expansions and prevent unexpected overloads. The special bearings reacting in the transverse direction are hydraulically preloaded and react as STUs only at the occurrence of a dynamically imposed load. This paper presents the technical description of the longitudinal STUs with particular emphasis on the full-scale testing program performed in accordance to contractual specifications.

KEY WORDS : cable-stayed bridges, shock transmission units, tests

1. INTRODUCTION

Stonecutters Bridge (Figure 1) is part of Hong Kong's ambitious plan to develop its infrastructure for the new millennium. It is a single span cable-stayed bridge with a main span of 1018m [Falbe-Hansen, 2004].

Large bridges such as the Stonecutters Bridge often need special structural devices to control their response to strong dynamic actions, both wind and earthquake. Sometimes, e.g. in the Storebaelt Bridge in Denmark [Infanti et al., 2000] the design choice was to use devices that allow slow movements but lock-up under dynamic actions; said devices are usually called Shock Transmission Units (STUs) or lock-up devices or hydraulic buffers or dynamic restraints. Other times, e.g. in the Rion Antirion Bridge in Greece [Infanti et al., 2003] the design choice was the combination of fluid viscous dampers with fuse restraints, designed as a rigid link intended to withstand the wind loads up to a pre-determined force and to fail under the specified earthquake, thus leaving the viscous dampers free to dissipate a big portion of the energy induced by the earthquake into the structure. Both STUs and fluid viscous dampers are piston/cylinder devices that utilize fluid flow through orifices to provide a reaction that is a function of the velocity applied to the aforesaid piston. So, the force generated by these devices is the result of a pressure differential across the piston head. The main difference between an STU and a fluid viscous damper is the hydraulic circuit (orificing), which makes them work very differently. STUs are not designed to dissipate energy. At the occurrence of a dynamic movement exceeding the so called “activation velocity”, they react as a very stiff link, whilst with very slow movements, such as those imposed by bridge thermal expansions, they do not provide any major reaction.

In the Stonecutters Bridge the design choice was to lock-up the deck to the pylons under dynamic actions through the use of special devices. At each pylon, a group of four 8000 kN capacity (800 mm stroke) STUs are installed along the longitudinal direction, while two special spherical bearings connect transversally the steel girder to the pylon. The lateral spherical bearings are hydraulically preloaded and react as STUs only at the occurrence of a dynamically imposed load [Colato et al, 2006]. The longitudinal STUs are described in the following.

Figure 1. The Stonecutters Bridge under construction.

2. DYNAMIC CONTROL DEVICES

The proposed solution consists of a system composed by four STUs per pylon, installed along the longitudinal bridge axis, connecting the deck to the pylon (Figure 2). Each STU has 8000 kN SLS (24000kN at Static Breakdown) capacity and 800 mm stroke.

Each system is capable of accommodating the thermal contraction/expansion movements of the bridge as well as any other low velocity displacements without appreciable reaction, whilst at the same time ensuring an almost rigid connection between the box girder and the pylon in presence of forces of sudden onset, or when critical velocity movements are applied to the structure.

Each group of units is characterized by a hydraulic circuit where the flow control valve is in common. This requirement guarantees for a uniform STUs loading, thus eliminating any torque effect induced by differential reaction among the units.

To achieve the required low reaction for slow movements and, after a certain predetermined level of velocity, to develop a high level of resistance to any movements generated by dynamic inputs, the typical Force versus Velocity characteristic law is as described in Figure 3.

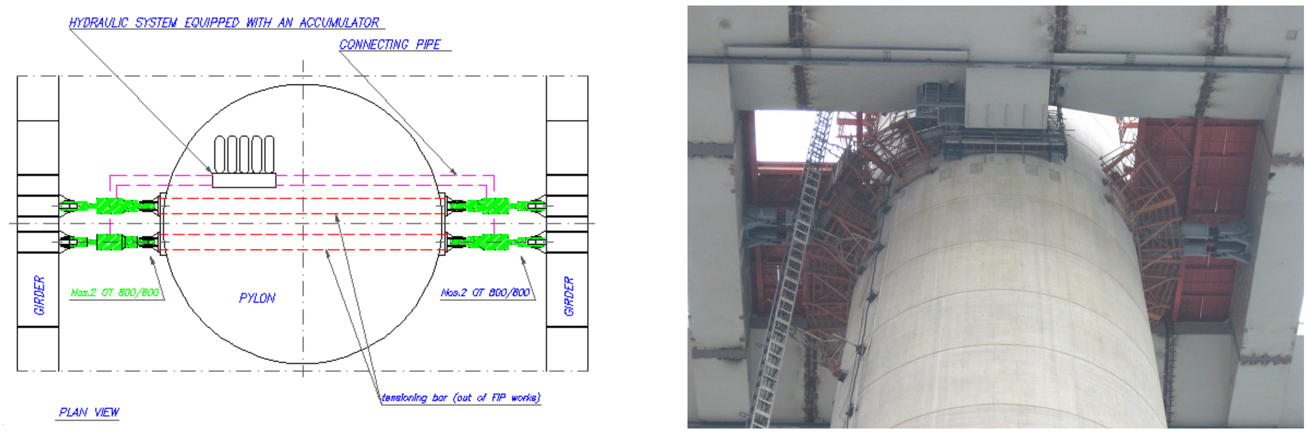
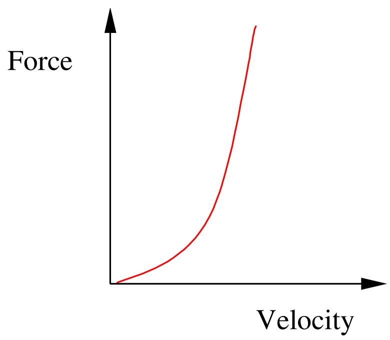


Figure 2. STUs arrangement.



$F = C \cdot v^n$, being n=2.
Where:
C=Damping Constant
V=Velocity
F=Force

Figure 3. Force versus Velocity constitutive law.

Since the objective of the design was to achieve a system that locks during dynamic actions, particular attention has been paid to its stiffness characteristics. A well-designed STU has to react like a very stiff spring, locking within a short piston stroke. So, particular attention has been paid to study the compressibility of the fluid so as to minimize the stroke needed to develop the design reaction.

Another very important parameter considered has been the STU behavior along an entire range of temperature variations. The specific design and the special oil used assure a constant behavior of the devices in the entire design range temperature (-5°C ÷ +70°C).

The changes in volume of the hydraulic fluid was taken into account as an important effect related to temperature variations: this problem has been solved using suitable accumulators where nitrogen filled bags can expand or contract in order to accommodate the above described fluid volume variation, thus maintaining the required level of pressure.

The units are provided with anchor frames in contact with the steel cross girder diaphragms and the concrete towers. The fixing system to the concrete is obtained by means of tensioning bars, which connect the two adjacent STUs through the lower tower diaphragm. The central main body of the STUs is connected to the anchor frames by means of special spherical hinges, which allow the correct functioning of the devices also in presence of axial misalignment due to either construction/installation tolerances or service angular movements.

The above-mentioned units are characterized by the design data recapped in Table 1. Further details on the hydraulic circuit are given in [Colato et al, 2006].

Table 1 - Main Design Characteristics.

Force Vs Velocity constitutive law	$F = C \cdot v^n$, being n=2
Design Load	8000 kN
Static Breakdown	24000 kN
Service Design Stroke	± 400 mm
Maximum Rotation at Hinges	± 5°
Reaction Velocity (range)	Tunable from $1 \cdot 10^{-5}$ m/s to $200 \cdot 10^{-5}$ m/s

3. FULL SCALE TESTS

Full scale dynamic tests were carried out at FIP laboratory on one production STU in order to check its performances whilst static pressure test was performed on all the production units.

3.1 Test Equipment

Being the units under test of exceptional dimensions, the test equipment was especially built taking into consideration the load capacity and dimensions of the devices undergoing testing. It essentially comprises a support structure housing a servo-hydraulic actuator electronically governed by closed circuit feedback loop. The device under test was connected to the fixed portion of the aforesaid structure on one side, and to the actuating piston on the other one. Figures 4 shows both the testing equipment and the units during the course of the tests. Following is a descriptive summary of the various testing equipment components.

Figure 4. STUs under testing at FIP Industriale Laboratory.

3.1.1 Test Rig

The test rig is a steel frame comprising two end plates separated by four struts located on each plate corner. The test rig stiffness is provided by seven bars per each strut, tensioned to provide for a total compressive load of 16000kN. In order to ensure a proper lateral stability to the struts, such struts are laterally connected to each other at about half of their length. To one end plate, and externally to the frame, the actuator is fixed with its piston aligned with the center-line of the frame. The actuator capacity is 11000kN being its stroke equal to

±300mm. The STU clevis plates are connected respectively to the actuator piston on one side and to the end plate on the opposite side.

3.1.2 Test Configuration

The STU has been tested with its center line laid horizontally - as operating in the bridge – and pinned to the anchor frames in its centered condition. The off-centered condition tests were performed off-centering the unit by means of the actuator.

3.1.3 Closed-loop Actuating System and Instrumentation

Command and control functions are performed using an electronic MOOG unit to which the various measurement transducers are connected. A suitable 550 kW power hydraulic system provides the necessary oil flow. The applied load has been monitored by means of pressure transducers - to be used later on for in-situ monitoring – reading directly the pressure acting on the STU vessel chambers. So as to eliminate the effects of gaps and elasticity within the system, the imposed displacement was always measured by means of an SSI transducer (1000 mm total stroke) connected between the actuating rod and the STU cylinder. The load (pressure) measuring chain as well as the displacement measuring chain were calibrated by a HBM shunt calibration unit. The displacement measuring chain was calibrated using gauge blocks.

3.1.4 Data Acquisition System

All tests were conducted monitoring in real time load (pressure) and displacement and in some case the temperature on the block valve as well, using a Spider 8 (HBM) measuring amplifier connected to a PC equipped with a DIA-Dem data acquisition and processing software (National Instruments). Record sampling has been performed at a suitable frequency depending upon the test velocity (50 to 100Hz). Data concerning force, displacement and time were recorded and processed after testing, by the DIA-Dem software.

3.2 Test Program

As requested by the contract specification [Arup, 2003], the following tests have been performed:

- ***Resistance Tests***
  - Stiffness Test (TS)
  - Static Pressure Test (SPT)

- ***Performance Tests***
  - Static Loading Test (SLT)
  - Dynamic Loading Test (DLT) in centered and ±250mm off-centered condition

- ***Influence of Temperature***

3.2.1 Grouping

As said above, the four STUs installed in each pylon are all connected to a central hydraulic unit. In order to reproduce said layout during the tests, the hydraulic circuit has been set for testing as foreseen for its final configuration in the bridge.

The SPTs were performed on each group of 4 units connected through the hydraulic circuit.

The SLTs and DLTs were performed with only one unit installed in the test rig (Figure 4). Anyway, said unit is connected by means of hoses to the other three and to the central hydraulic unit to simulate the real configuration. It should be noted that the performance test carried out on only one device faithfully simulates actual loads, but the same does not hold for velocity. During the tests, the single unit was moved at four times the reference velocity in the effort to simulate the actual flow rate conditions through the flow control valve that takes place during use when the four buffer units move simultaneously. Thus, all the velocity values required in the contract specification for the STU system comprising four units (in the range from 0.01 to 2mm/s) were multiplied by four times during the tests.

3.2.2 Influence of Temperature

Some of the tests have been repeated simulating the working condition at –5°C and +70°C. The test simulating normal service conditions at extreme low temperature (-5°C) was performed by filling the buffer vessel with the same type of hydraulic oil recommended for the application, but with a viscosity corresponding to that of the used oil at such temperature. For the high temperature simulation, no same-type oil has been found fully compatible for testing at ambient temperature. So, the 70 °C test has been performed by conditioning the unit using thermo-resistances. The heating time lasted three full days.

4. FULL SCALE TEST RESULTS

Forces, displacement and time measurements were accurately obtained and recorded during the tests. The main test results are reported in the following paragraphs.

4.1 Stiffness Test

The test was carried out in order to measure the compressibility of the fluid into the STU cylinder loaded up to 8000kN, with the valves closed. It is worth to mention that the units are designed to withstand the above-mentioned load with a minimum safety coefficient of 3 over yielding. The measurement of force and deformation were read and recorded during the course of the test (see Figure 5).

4.2 Static pressure test

Such test has been performed in order to verify the capacity of the hydraulic system - including the piping system, cylinders, valves and other accessories – to withstand a 40 MPa internal pressure for 24 hours. The pressure was read during the test and a final examination of the hydraulic system was performed by the inspector.

4.3 Static Loading Test

The test determined the system resistance to thermal displacements. Normally temperature movements take place with girder velocities. Thus, the test was conduced applying a constant translation velocity to the STU in the order of 0.04 mm/sec (four times higher than the 0.01mm/s system velocity), and at the same time reading and recording the resulting reaction. The load was applied in both movement directions in order to verify the unit's behavior in both tension and compression (see graph of Figure 6).

4.4 Dynamic Loading Test

This test was aimed at verifying the design reaction at high velocities and with different valve settings. It was conducted by applying a 8000kN load thrust and verifying the corresponding activation velocity. Such thrust has been maintained constant for approximately 5 seconds. The test was repeated in the mid-stroke position and with a ±250mm piston stroke off-set. The load was applied in both directions in each test configuration. The measurement of the thrust and the displacement were recorded during the course of the test (see the graph of Figure 7).

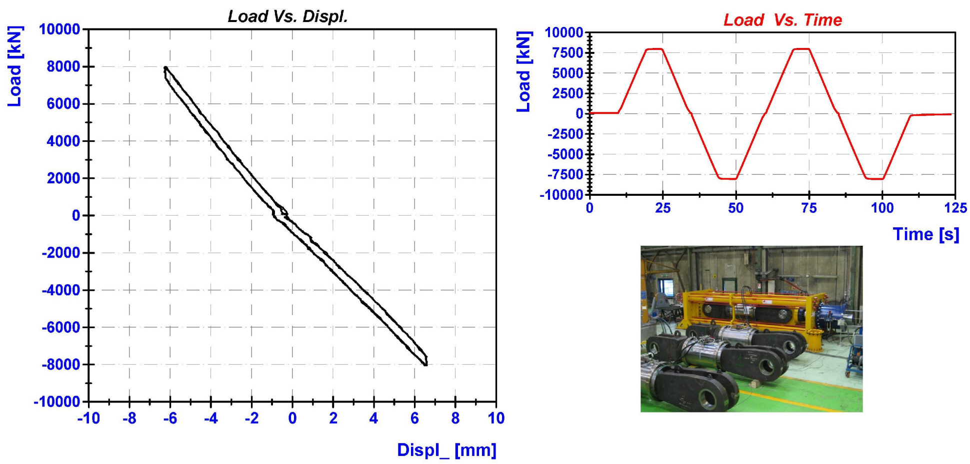


Figure 5. Results of stiffness test on STU No. 7 at -5°C.

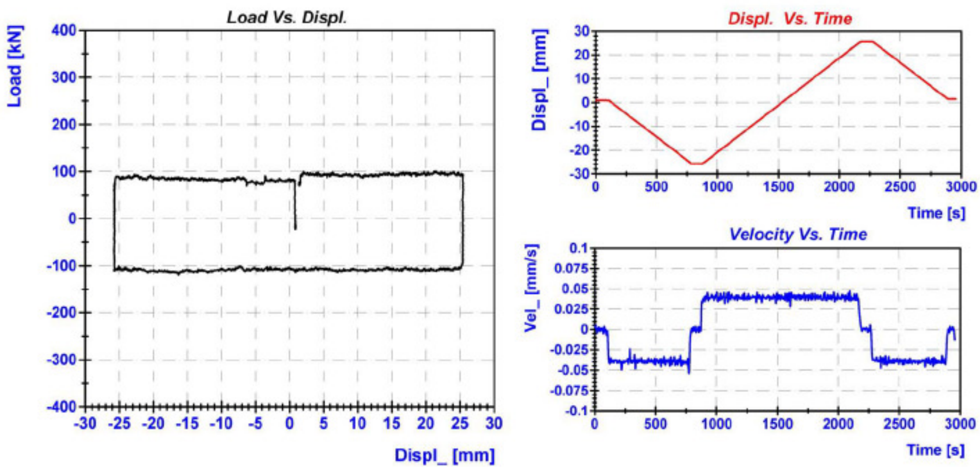


Figure 6. Results of static loading test on STU No. 7 at -5°C.

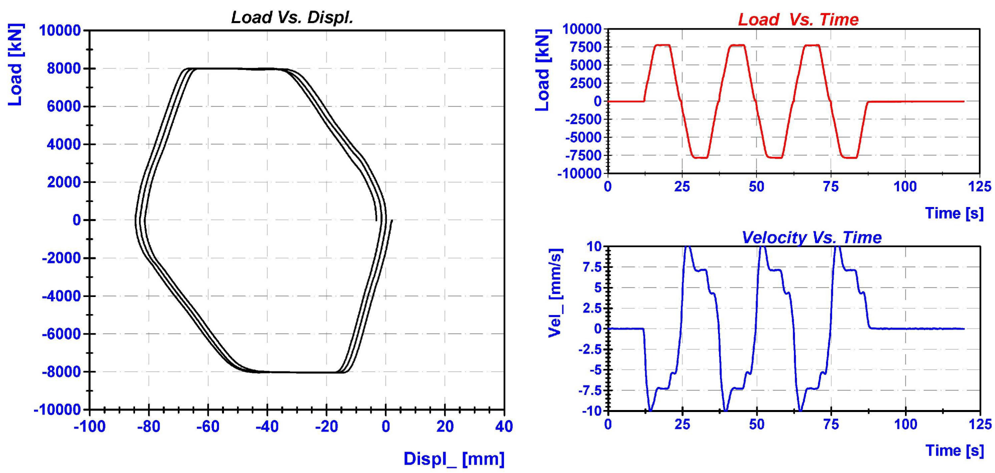


Figure 7. Results of Dynamic Loading Test on STU No. 7 at 70°C (velocity 7.3 mm/s).

5. CONCLUSIONS

The construction of strategically important large bridges requires design engineers to address new problems and thus their being open to devising advanced solutions.
Recent worldwide renowned projects, such as the Storebaelt Great Belt, the Rion-Antirion Bridge and now the Stonecutters Bridge, take advantage of the industrial latest advancements in designing and manufacturing large structural devices with very demanding design parameters.
Full-scale tests as those described in this paper, as well the operational life in already completed bridges, confirmed the reliability of said devices.
With the experience and the know-how of qualified companies even ever-dreamed projects may become true.

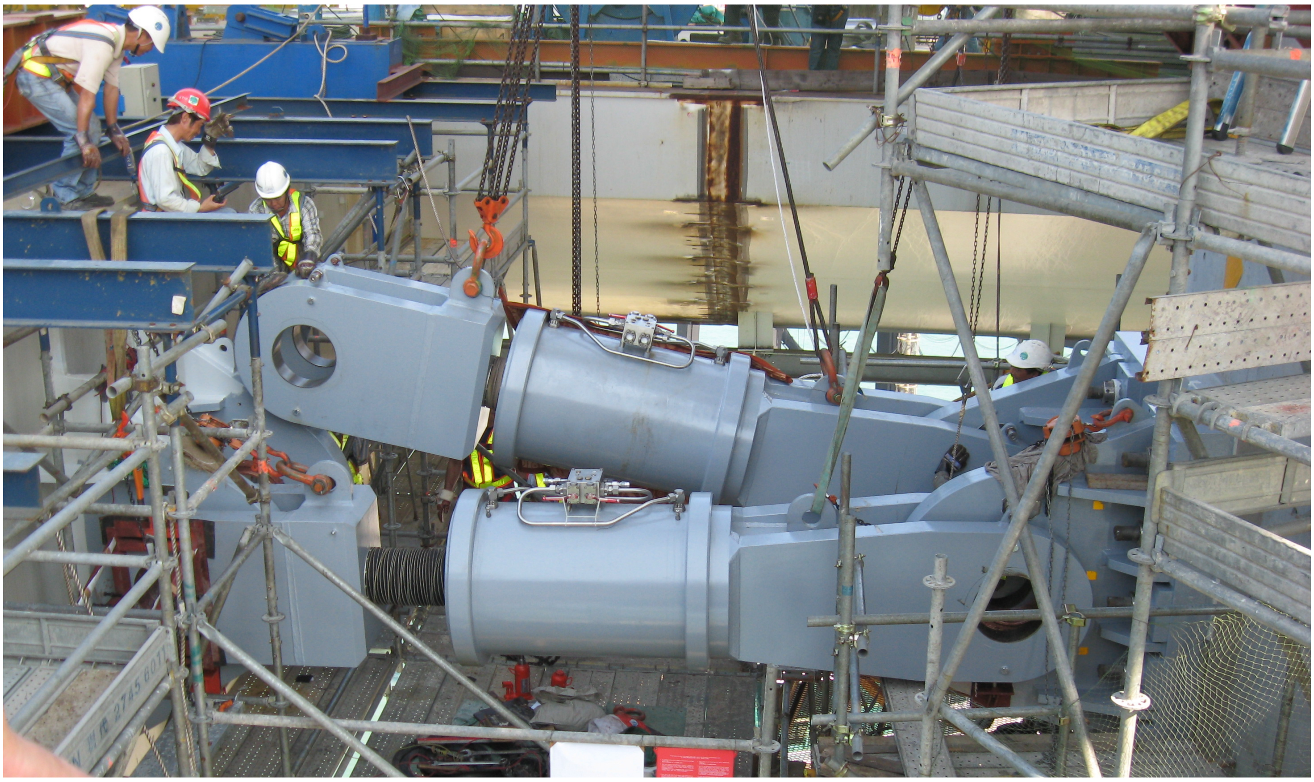


Figure 8. Two units under installation.

ACKNOWLEDGMENTS

The authors wish to express their sincere gratitude for the active and fruitful contribution to the project rendered by Mr. Pierluigi Galeazzo, Manager of the FIP Industriale Testing Laboratory, and all his team.

REFERENCES

ARUP (2003). Particular Specification HY/2002/26. Hong Kong.
Colato, G.P., Chiarotto R., Infanti S. (2006). Dynamic control devices for the Stonecutters cable-stayed bridge. Proceedings of 100th Anniversary Earthquake Conference, 8th US National Conference on Earthquake Engineering (8NCEE), San Francisco, California, USA.
Falbe-Hansen, Klaus (2004). Stonecutter Bridge: Detailed Design. Proceedings of fib Symposium 2004, 26-28 April 2004, Avignon.
Infanti S., Colato, G.P., Castellano, M.G. (2000). Structural devices for bridge engineering: the challenge goes on. Proceedings of Bridge engineering conference 2000, Sharm El-Sheikh, Egypt.
Infanti S., Papanikolas P. and M.G. Castellano (2003). Seismic protection of the Rion-Antirion Bridge. Proceedings of the 8th World Seminar on Seismic Isolation, Energy Dissipation and Active Vibration Control, Yerevan, Armenia.