Maintenance System for Safe Operation of Out-dated Aerial Ropeways

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First aerial ropeway for personal transport in Slovenia was built in the year 1953. Until now, nearly 300 ropeways including ski lifts have been operating. Because of known political and economical reasons, there have practically been no investments into new facilities except in some rare cases, so that the average service life of ropeways in Slovenia amounts to over 20 years. The major part of vital load-bearing elements and assemblies on these ropeways exerts an essentially shorter service life from the ropeways themselves, which means that due to their worn-out state these elements should be renewed or replaced several times. For some of these elements such as ropes or rubber linings of wheels, precise criteria for the boundary values of serviceability are given in the regulations or standards already. For the vast majority of elements essential for the ropeway security as well, these criteria are not generally known but should be investigated and determined separately for each single facility with regard to its specific operating conditions. The required frequency of defectoscopic inspections is not specified by the regulations too except for new still undamaged ropes.

To assure the required safety of operation in spite of the age of facilities, regular maintenance works and a certain amount of defectoscopic inspections of vital load-bearing elements should be carried out. Under maintenance works, all those measures are understood, by which the service life of single parts of a facility is prolonged as much as possible. The objective of defectoscopis inspections is to detect in time those kinds of defects that would, after a certain period of operation, bring about a loss of load-carrying capacity or functionality of elements.

Maintenance of ropeways in the Republic of Slovenia is generally prescribed by national regulations which are ordering the extent of maintenance works and internal controls which are to be executed regularly as well as the evidence on the state of facilities in operation. Beside internal controls carried out by ropeway managers themselves, safety of ropeways is surveyed also by The Slovenian National Building and Civil Engineering Institute - an independent expert institution authorised by the Government to asses the ropeway operation ability. The institute's primary duties in this respect are: 1) Execution of temporary expert and technical surveys of operating and newly constructed ropeways by which the functionality of facilities and effectiveness of operation of safety signalling elements is tested and checked by measurements. A special attention is paid to the control of operation and survey of braking systems and mechanisms for stopping the ropeway in the case of a dangerous situation. 2) Carrying out defectoscopic inspections of ropes and other vital elements of mechanical and machinery equipment as well as of

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load-bearing steel structures. 3) Carrying out laboratory tests of materials and structural elements with the aim to evaluate their operating strengths or reduction of dynamical endurance in exploitation. On the basis of laboratory investigations, suitability of a given element can be established and its expected service life determined.

An estimation of risk is worked out preliminarily for each ropeway after respective time intervals of operation. The estimation is obtained by means of a method of analysis of possible consequences as a function of possible reasons for accident occurrence. This method enables the assessment of the required frequency of maintenance works and controls. The most frequent reasons for accidents can be divided into the following main groups: 1) failure of vital elements, 2) human factors 3) other reasons.

Possible reasons for failure of vital elements are going to be discussed in the further text.

Quality of material: deviations from quality as required by the project are especially hazardous in the case of high-strength materials or materials of high welding technical properties. All inhomogeneity defects and other defects which cannot be detected without laboratory tests are belonging to this group too.

Defects induced by the manufacturing process: besides defects originating from mechanical treatment, welding defects are especially dangerous, enhancing static breakage and first of all fatigue cracking and breakage.

Corrosion damages: the most frequent reason for critical reduction of static and dynamic load-bearing capacity is the effect of corrosion. The latter may occur due to poor or insufficient basic corrosion protection as well as inexpert or omitted maintenance works. Corrosion indentations may be the source of hazardous notch effects that are in most cases, beside wear of material, the main reason for rope or other load-bearing element rupture.

Other reasons: generally, wear of elements moving relatively to each other is leading only to disturbances of operation of single elements and assemblies. The exception are wire ropes which are prone to wear and thus to occurrence of wire breakage. Wire deformations brought about by the pressure among wires and wire strands may lead to rope rupture too. Modern regulations on design and maintenance are preventing unexpected rope ruptures to a great extent, but such events cannot be quite excluded in the case of corrosion attack.

The consequences of disasters may be people’s injuries and material damages. With regard to the extent of damage, the latter can de divided into small, medium and very heavy ones. Vital elements typical for the most of ropeways listed according to the estimation of degree of possible consequences in cases of loss of load-bearing capacity or functionality are presented in *Table 1*.

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CONSEQUENCE	ELEMENTS
Very heavy damage	- carrying ropes or rope elements of bicable ropeways - hauling ropes of bicable ropeways and rope elements - hauling ropes of greater ropeways - load-bearing structures of bicable cabin lifts - supporting elements of hauling ropes - ropeway braking systems - ropeway safety signalling systems
Heavy or very heavy damage	- hauling ropes of smaller ropeways - wheel batteries of monocable ropeways - load-bearing structures of monocable cabin lifts - supporting elements of carrying ropes - tensioning mechanisms of hauling and carrying ropes - linings of ropeway driving wheels - carrying ropes of greater ski lifts - connecting systems of detachable vehicles
Medium damage	- ski lift hauling ropes - supporting and guiding elements of ski lift ropes - ski lift rope tensioning mechanisms
Small damage	- ski lift towing elements - entry and exit structures

Table 1

According to preliminary analytical judgements and laboratory investigations, the probability of breakage of new ropeway elements at normal operating loads is very low. The possibility of hidden failures is reduced to minimum by interphase controls during the manufacturing and assembling process. The probability of breakage of elements that have been in operation for several years is increased due to fatigue, wear and corrosion effects.

Ropeway cables represent a special kind of elements, which are highly loaded due to their functional operating conditions. Wire materials may reach tensile strengths of up to 2.200 MPa, but are submitted to notch effects and loss of dynamic load-bearing capacity because of operating conditions. Due to varying, i.e. dynamic loads, which they are withstanding and the said effects, the ropes shall be replaced after a certain period of operation. As it can be seen from *Table 1*, the rupture of ropes or rope fixings may have catastrophic consequences.

New and properly maintained ropes are dimensioned in a way to attain the so-called permanent strength. It means that they would have an unlimited service life if no changes of state occurred. During operation, however, there are circumstances under which their original state changes. These circumstances are especially: corrosion, wear of exterior wires, impressions of wires, and exceptional overloading (derailment, stroke of lightning). Because of all these changes induced by operating conditions, the ropes loose their permanent strength and pass over to the state of time-dependent strength.

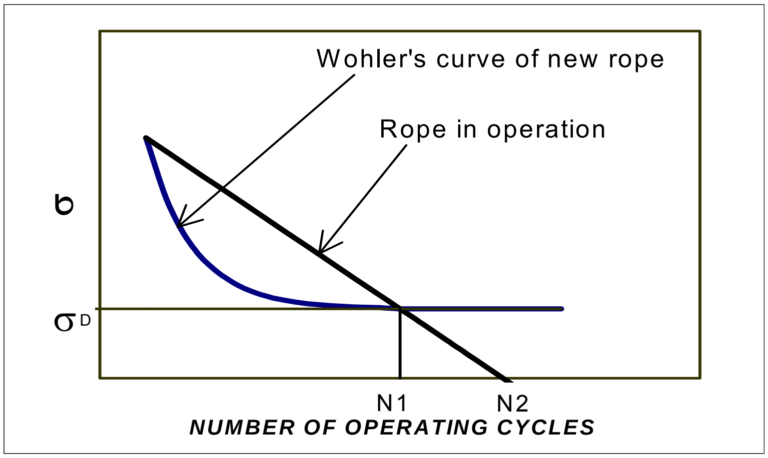

Diagram 1

It can be seen from *Diagram 1* that after a certain period of operation or a number of loading cycles N respectively, the dynamic strength of used ropes becomes too low and the ropes are not allowed to be in use any more. For that reason, procedures and terms of regular visual inspections of exterior rope wires as well as investigations of rope and connecting element interior by non-destructive methods are required by the regulations. The rope service life is limited and depends primarily on:

1) Rope loading which has been designed during the dimensioning phase of a ropeway project;
2) Rope homogeneity with regard to variable quality of single wires within the same cross-section;
3) Rope maintenance;
4) Maintenance of rope-guiding elements;
5) Climatic conditions.

A measure for rope wear during exploitation is a number of single wire ruptures by which the metallic load-bearing cross-section and consequently, the rope-breakage safety is reduced. For each single rope, the maximal allowed reduction of the load-bearing cross-section δ (%) is prescribed by the regulations. Reduction of the rope load-bearing cross-section with time is shown on *Diagram 2*.

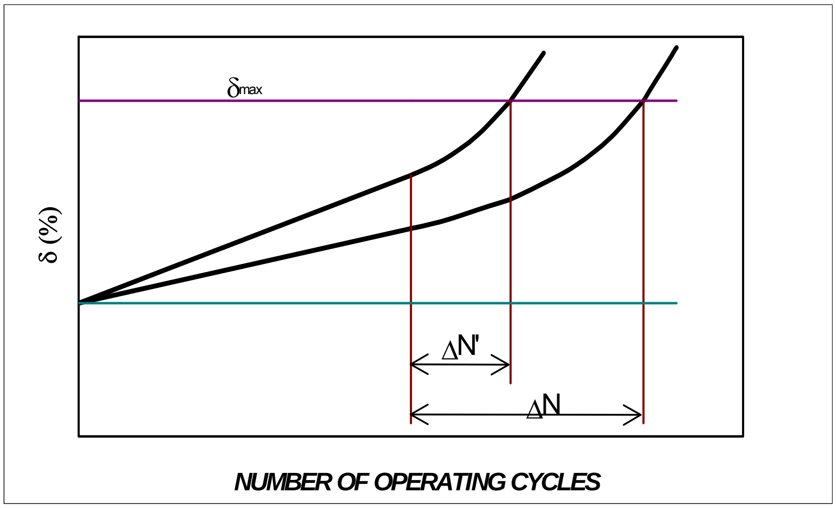

Diagram 2

In the case of the known curve δ – N, the period ΔN between single inspections of the total reduction of rope cross-section (including the rope interior) can be reliably determined. The period between two defectoscopic inspections of high-quality steel ropes, which are operating at normal climatic conditions and are regularly maintained, amounts usually to 4 years. Due to faster decaying, the period between two successive inspections must be correspondingly shorter (ΔN') in the case of low-quality and poorly maintained ropes as well as ropes with reduced resistance to dynamic breakage. The time interval (ΔN, ΔN') must be determined in such a way that the maximal allowed reduction of the load-bearing cross-section (ρ_{max}) is not reached in any case. The mentioned time intervals are provided for each rope in operation. To determine them, the amount of rope dynamic strength reduction must be known with regard to various degrees of rope wear. Corrosion tests and dynamic load tests of ropes taken out of operation and of the new ones, which had been artificially corroded in test chambers to simulate various degrees of wear, are carried out in the laboratory for that purpose. It has been found out namely that corrosion was one of the most important factors to affect the dynamic strength of ropes. Due to changes either on the wire surface or within material or its microstructure, the rope looses its permanent strength and passes over to the state of time-dependent strength. Material is exposed to fatigue, its toughness is reduced, and so are its static and primarily dynamic strengths. Corrosion pits acting as initiators for fatigue ruptures are leading thus to the reduction of dynamic strength, which is still further reduced by the appearance of stress corrosion. The latter is propagating among crystals as a combination of *corrosion and hydrogen brittleness*. The progress of the so-called corrosion fatigue of material is still further enhanced in the presence of dynamic loads. In the process of exploitation, ropeway cables are submitted to atmospheric corrosion substantially. Moisture is playing the role of corrosion medium (electrolyte) while oxygen or even hydrogen in a more aggressive atmosphere the role of depolarizators on the cathode. The maintenance of ropes is therefore an extremely important procedure. Unprotected surfaces are corroded persistently leading to higher wear of wires and thus to the reduction of the load-bearing cross-section.

The objective of corrosion tests and exposure in a salt corrosion chamber is to achieve a kind of corrosion, which would be similar to corrosion of rope wires after a certain period of operation concerning the depth and shape of corrosion pits. The corroded rope specimens are submitted to dynamic tests later.

The dynamic test method is a comparative one. Loads transmitted by a carrying rope during the passage of a clamping device around a driving or a return wheel are chosen for the dynamic test. The wheel diameter and the deflection angle of the rope to the clamping device are chosen to give the ratio of tensile to transversal force within the rope close to reality. To estimate the dynamic strength, Wohler's diagrams are drawn showing the relation of variable stress ratio magnitudes to the number of these variations. Load levels are chosen to obtain rope breakage in a real time. Two loads defined by the relation of various degrees of safety to the cumulative force of rupture of all the wires within a single rope cross-section are foreseen for each diagram. The tensile force within the rope is adjustable and constant during the test. The transversal force is a pulsating one and results in load oscillations between the lower stress limit, which represents the tensile force only, and the upper stress limit, which represents the sum of the tensile and the bending stress. Wohler's curves for three rope samples having various degrees of rope cross-section reduction or various degrees of corrosion respectively are shown in *Diagram 3*, in comparison with test results of the same specimens, yet the brand new ones without any damages.

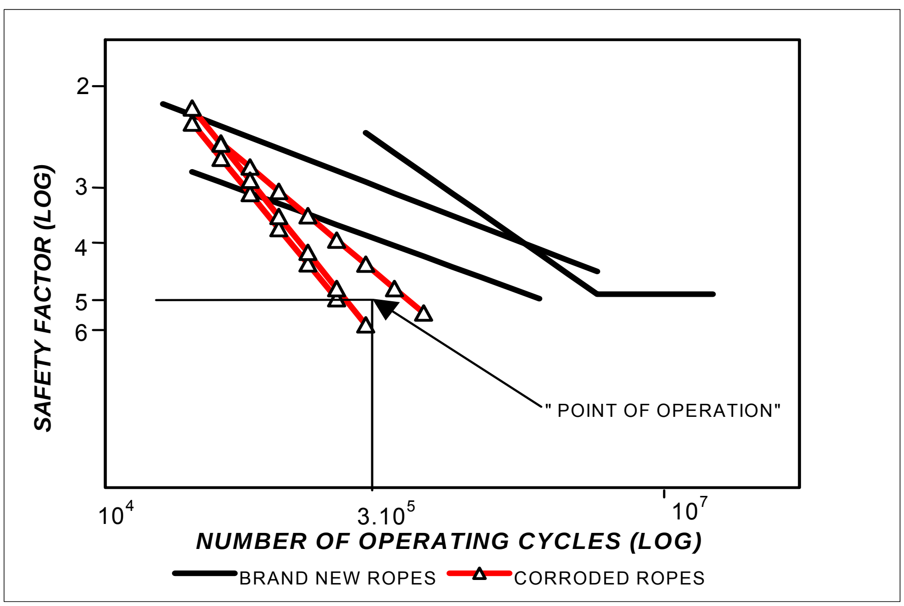

Diagram 3

A “point of operation”, i.e. a limit number of operating cycles at a required safety is marked in the diagram. Knowing this value for a given rope at given operating conditions and a given cross-section reduction, the required time interval between single defectoscopic inspections can be estimated.

Static laboratory tests are carried out on corroded rope specimens too. The following mechanical properties of ropes can be determined on the basis of these tests: nominal wire strength, wire toughness, static rope breaking force and estimation of dynamic rope strength. The advantage of the mentioned tests is first of all in that they can be performed on a wire specimen sampled from a rope in operation. The specimen is usually taken on the point where the rope has been damaged already, so there is no additional weakening. Actual reduction of load-bearing cross-section due to wear and corrosion of the sampled wire can be determined by means of the static tensile test. Wire toughness and indirect estimation of the rope dynamic strength reduction can be deduced from the number of bendings and torsion swingings.

Some of regularly maintained and surveyed carrying ropes of Slovenian ropeways have attained the age of over 25 years already.

The control method of investigation of ropes, main vital ropeway elements, was described into detail above. Beside ropes, defectoscopic inspections are being carried out for all other vital ropeway elements, which are submitted to fatigue, wear and corrosion at similar time intervals depending on the degree of wear.

A comprehensive group of such parts are machined elements from mechanical equipment and wheel batteries, such as axles, shafts and bolts. Fatigue cracks and wear-induced defects are being detected by means of non-destructive tests, for example ultrasound, by means of penetrants, magnetoflux and visual methods. Experiences gathered by these inspections have shown that the wear-induced defects, as a rule, appear prior to fatigue cracks indicating that the elements should be replaced because of loss of functionality (e.g. increased air) and not because of risk of breakage. The exceptions to this rule are reduction gear exit shafts with directly mounted driving wheels, which transmit considerable combined variable loads. As no preliminary wear indicating the worn-out state could be detected on these shafts after 15 years of operation, they have been inspected defectoscopically regularly each year since then. Another big group of elements is steel structures to which welded driving wheels, casings of wheel batteries and vehicle load-bearing structures are belonging. According to regulations, a half-year visual inspection by the ropeway manager is ordered for all these elements. Intention must be paid primarily to cracks (first of all along welds), corrosion, excessive deformations, state of screwed joints and state of corrosion protection. Most critical locations, which should be inspected as carefully as possible, are determined for each ropeway facility. In case any change of state or suspicion of defect is detected, a detailed inspection using a non-destructive defectoscopic method is to be carried out, and that on all the remaining parts of the same structure. With regard to the age of a structure, measurements of the load-bearing steel sheet thickness of closed supporting elements are to be performed too.

Based on experiences gathered by the Slovenian National Building and Civil Engineering Institute during the inspections of ropeways, it can be stated that even facilities having a considerably longer average service life than the similar ones in other countries, may nevertheless ensure a high degree of safety of transportation. This statement has been confirmed by the fact that since the construction of the first ropeway in our country, there have been practically no heavier accidents due to the facilities themselves. The knowledge gained during the survey of state of ropeways is going to be applied to new facilities, where hidden defects or other unexpected deficiencies are not excluded as well.

ZAG Ljubljana has been authorized by the Ministry of Science and Technology to carry out the attestation of conformity of all construction products and works for which certificates of conformity are required. This includes all the products and works that will be needed for the new motorways which are presently under construction in the Republic of Slovenia. For other construction products, certificates proving their compliance with the currently valid technical regulations and standards are issued.

ORGANIZATION

ZAG Ljubljana carries out its work in the following fields:

- materials,
- building physics,
- structures,
- geotechnics and the traffic infrastructure,
- metrology.

The 180 employees, including more than 70 experts with university qualifications and in some cases academic titles, perform their work in one of five departments, corresponding to the above-mentioned fields of work. Each department has its own laboratories, and three departments have a number of specialized sections. There is also a library, which is one of Slovenia's best in the field of technical literature, and a centre for informatics.

A special group has been formed for the carrying out of tasks within the scope of Slovenia's new motorway construction projects.

MATERIALS

The *Laboratory for Mineral Binders and Mortars* researches and tests cements, limes, naturally-occurring silicates, some anorganic materials, waste materials (fly-ash and slag), traditional and special mortars for masonry work, plastering and repair works, special mineral binders, and chemical and mineral additives for mortars and concretes.

The *Laboratory for Stone and Aggregates* investigates and tests the mechanical and physical properties of stone and rocks, as well as those of secondary raw materials to be processed into aggregates. It also carries out the petrographic and mineralogical analysis of raw materials and products in the construction industry.

The *Laboratory for Concrete* performs standard tests on concretes and prefabricates, and, as an independent third party, carries out surveillance and confirms the adequacy of quality control procedures used by concrete producers, as well as on site, particularly on motorways. It also researches new kinds of concretes, and investigates concrete durability.

The *Laboratory for Metals, Corrosion and Anti-Corrosion Protection* performs standard tests on and carries out the attestation of conformity of metals in the construction industry and of general-purpose metallic products. It also investigates corrosion, and advises and carries out control tests in the field of anti-corrosion protection.

The *Laboratory for Ceramics and Refractory Materials* researches and tests raw materials for ceramics, as well as building, technical and decorative ceramic products, and refractory materials.

The *Laboratory for Polymers* investigates the chemical and physical properties of all polymeric materials, as well as researching and testing polymeric products. Advice about the use of polymer-based products in building repair works is also given.

The *Laboratory for the Physical-Mechanical Testing of Hardened Concrete and Prefabricates* carries out non-destructive and material-structural tests of hardened concrete, in the laboratory and in situ. It also investigates the parameters of concrete quality in existing structures.

BUILDING PHYSICS

The *Laboratory for Acoustics* carries out standard and non-standard laboratory and in situ acoustic tests, and also prepares technical documentation in the fields of building and room acoustics, and protection against noise.

The *Laboratory for the Efficient Use of Energy and Renewables* carries out research, standard and non-standard laboratory and in situ tests of the thermal properties of materials and structures, as well as calculations in the field of thermal insulation. It also carries out tests and advises in the field of protection of the internal environment from the effects of radon.

The *Fire Laboratory* performs standard and non-standard fire tests. The standard methods of testing include tests of the basic materials, tests of burning characteristics, and the simulation of standard and real fires. Non-standard tests include the testing of protective clothing for firemen, of the efficiency of extinguishing of new fire extinguishing products, and fire testing at prototype scale.

The Section for Fire Engineering carries out research into the behaviour of all kinds of structures under fire loadings. It also establishes criteria for the fire safety design of buildings.

STRUCTURES

The Department for Structures has six sections, specializing in different types of structures and loading conditions, and also a large, well-equipped laboratory for structural testing and research. All kinds of building and civil engineering structures (of the latter, particularly bridges and dams) can therefore be treated. The behaviour of structures and their foundations is investigated and analysed for both static and dynamic loadings, as well as for seismic actions, and appropriate certificates of conformity are issued. Apart from structures made from the more traditional building materials, such as stone and brick, reinforced and prestressed concrete, timber (including gluelam timber), and metals (steel and aluminium), structures made from artificial, mainly polymer materials are also investigated.

On the basis of the results of measurements carried out by the staff of the *Section for Metal Structures and Transport Devices*, the Department is authorized to issue certificates of conformity for aerial ropeways and ski-lifts of all kinds. Within this section various elements and the assembled parts of vehicles and other means of transport are also tested.

In the *Laboratory for Structures*, static and dynamic tests of structural elements and assemblages can be carried out at both prototype and reduced scale. The main testing equipment consists of a spacious strong testing floor, a shaking-table and numerous programmable hydraulic actuators and testing-machines with a capacity of up to 5000 kN, as well as reliable data acquisition and processing systems. All kinds of structural tests can be carried out reliably and efficiently, either in the laboratory or on site.

GEOTECHNICS AND TRAFFIC INFRASTRUCTURE

The *Section for Geomechanics and Environmental Geotechnics* performs research, studies and testing in the fields of geotechnics, geomechanics and environmental protection. The *Section for Road Maintenance and Management* carries out all measurements needed to monitor the surface and structural characteristics of road pavements at both project and network level. The *Section for Geotechnical Monitoring* carries out long-term observations of hydro-electric power-station structures and of earth structures, and also investigates areas subject to landslides and settlement.

The *Section for Engineering Geology and Rock Mechanics* carries out geological-geotechnical investigations for all stages of the design of tunnels and other underground structures, as well as performing geotechnical monitoring of these structures during construction and exploitation, including stability measurements.

The *Laboratory for Soil Mechanics* performs all standard tests, as well as some special tests, of soils and crushed rock. It also investigates the quality of earthworks under construction.

The *Laboratory for Asphalts, Bitumens and Bitumen-Based Products* carries out tests of asphalt mixes as produced and asphalt layers as placed. It also performs tests of bitumen-based waterproofing materials for use in buildings and road construction.

METROLOGY

The *Laboratory for Metrology* is specialized for the carrying out of measurements of forces, torques, and hardness. It also carries out measurements of mass, toughness, r.p.m. and pressure. By the authorization of the Ministry of Science and Technology, the Laboratory verifies officially prescribed and other measures. It also investigates the conformity of devices and machines with the requirements of the ISO 9000 and EN 45000 standards.

INTERNATIONAL CO-OPERATION

ZAG Ljubljana participates in numerous international research projects, such as ARROWS, COPERNICUS, COST, COURAGE, EUREKA and FILTER, as well as in various bilateral projects with universities and research institutes in other countries. ZAG Ljubljana is also a member of numerous international organisations such as RILEM, FEHRL, CEN, CERLABS, EGOLF, NFPA, OITAF and TAC.

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Laboratory for Concrete	Fire Laboratory	Metal Structures and Transport Devices	Geotechnical Monitoring	
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ZAG Ljubljana (Zavod za gradbeništvo Slovenije) is the Slovenian National Building and Civil Engineering Institute. It was founded by a decree, which was promulgated by the Government of the Republic of Slovenia on April 21st, 1994, about the reorganization of part of ZRMK Ljubljana (the Institute for Testing and Research in Materials and Structures) into a governmental research and testing institute. ZAG Ljubljana was entered into Slovenia's official List of Companies on March 17th, 1995.

STATUS AND ACTIVITIES

ZAG Ljubljana is an independent, impartial and non-profit organization, which fulfils all the requirements of the EEC Council Directive No. 89/106 regarding approval bodies which carry out the testing and attestation of conformity of construction products. It performs the following work:

- fundamental and applied research in the fields of building materials and structures,
- attestation of conformity and certification of building materials, products and executed works,
- pre-competitive development in the fields of building materials and structures,
- development of new methods of testing and measurement,
- studies, tests, measurements, surveys, monitoring, analyses, and technical consultancy in the fields of structures, transport devices, traffic infrastructure, the external and internal building environment,
- studies, tests, measurements, surveys, monitoring, analyses, and technical consultancy in the field of the efficient use of energy and renewables,
- calibration and attestation of measures, standards and reference materials,
- control, calibration and attestation of the conformity of measuring devices, apparatus, testing machines and the individual elements of industrial systems,
- training of research and technical staff in particular technical fields,
- preparation of technical codes and standards.