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Aluminium as a material for modern structures

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Subject review

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Aluminium as a material for modern structures

The paper offers a systematic outline of aluminium alloys and places emphasis on their advantages by providing examples of aluminium use in modern structures. Rapid development of standards for this "new" material enables its wider utilization although all participants in the construction process, structural engineers in particular, should be additionally educated in this segment to enable a real increase in its use.

Key words:
aluminium alloys, structures, standards, design, application

Pregledni rad

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Aluminij kao materijal za suvremene konstrukcije

U radu se daje sustavan prikaz aluminijskih legura, te se na primjerima primjene aluminija u suvremenim građevinskim konstrukcijama naglašavaju njegove prednosti. Ubrzani razvoj normi za ovaj "novi" materijal omogućuje njegovu primjenu, no za stvarno povećanje te primjene nužno je o tome dodatno educirati sve sudionike gradnje, a posebno inženjere konstruktore.

Ključne riječi:
aluminijske legure, konstrukcije, norme, projektiranje, primjena

Übersichtsarbeit

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Aluminium als Material für moderne Tragkonstruktionen

Diese Arbeit gibt eine systematische Darstellung von Aluminiumlegierungen und weist an Beispielen der Anwendung von Aluminium in modernen Bauwerkskonstruktionen auf seine Vorteile hin. Die zügige Entwicklung von Normen für dieses "neue" Material ermöglicht seine Anwendung; dennoch erweist sich für eine weitere Ausdehnung die Edukation aller Teilnehmer des Bauprozesses und insbesondere der Tragwerksplaner als notwendig.

Schlüsselwörter:
Aluminiumlegierungen, Tragkonstruktionen, Normen, Entwurf, Anwendung

1. Introduction

Aluminium (Al) is the third most abundant element, subordinate only to oxygen and silicon, and it makes up 8 % of the Earth''s crust. It is also the only light metal to find its application in load-bearing structures in civil engineering. Nowadays, only steel is used more than aluminium in the field of civil engineering.

In nature, aluminium does not occur as a free metal but as an oxide mixed with steel, silicon, vanadium and titanium oxides. The ideas of isolating aluminium started to emerge at the beginning of the nineteenth century. A Danish scientist, Hans Oersted, managed to isolate the metal particle of aluminium in 1825, but the first significant result was achieved in 1827 by a German chemist Friedrich Wöhler after 20 years of research. In 1854, a French chemist Henri Sainte-Claire Deville, a professor at the Sorbonne in Paris, developed a reduction process using sodium. The process, with further refinements, enabled limited production of expensive aluminium. Siemens''s discovery of the dynamo machine in 1866 was an important stepping stone toward solving the principles of electrolysis, which was contemporaneously and independently patented by Paul Héroult in France, and Charles Martin Hall in the USA. After a long initial period of technological development, the time finally came for the use of aluminium alloys in structural design. However, it is only in the early 1950s that the first structures made of aluminium alloys were erected in form of prefabricated systems. At that time, development of such structural applications was hindered by inadequacy or even a complete absence of standards and recommendations, all of which made structural design difficult for engineers, consultant engineers, and supervisory boards.

Over the past several decades, structural behaviour of extruded and welded members has been in the focus of both theoretical inquiries and experimental research [1, 2]. Conclusions obtained so far present a solid basis for modern standardization and it may reasonably be argued that, at the European level, the limitations once imposed by the absence of standards and regulations have been successfully surpassed: starting with the first edition of the ECCS committee recommendations, published in 1978 by ECCS T2, presided by F. M. Mazzolani, up until publication of the final version of Eurocode EC 9 in 2007, by the Technical Committee CEN-TC 250/SC9, presided by F. M. Mazzolani. This committee is still active and new amendments and corrections are being continually presented and considered. Croatian standardization body, the Croatian Standards Institute, and more specifically its sub-committee HZN-TO 548/PO 9 (presided by D. Skejić) is also regularly involved in the discussions and amendments of the standards. Nevertheless, a lack of information on the potential of aluminium alloys in structural applications is evident, which is why their comparative advantages are quite seldom recognised by structural engineers.

Therefore, the main aim of this paper is to provide structural engineers with knowledge about possibilities offered by the utilisation of aluminium alloys in modern structural engineering. Basic properties of aluminium alloys are presented in the paper, and readers are introduced to a variety of related standards (HRN) EN 1999 and their applications, which provides an interesting introduction to a plethora of technical areas related to aluminium. Small weight, corrosion resistance, and a wide range of structural shapes, rightfully open the door to a more extensive use of aluminium in structural design. The authors hope that this paper will encourage structural engineers to delve into the series of standards (HRN) EN 1999, recognize positive properties of aluminium alloys, and start to use them more often in practice.

2. Aluminium alloys for structural applications

2.1. General

The success of aluminium alloys when used as a construction material, and their possibility of competing with steel, are based on assumptions related to their physical properties, production process, and technological features. Aluminium alloys are normally considered to be economical and, consequently, more competitive in applications where the following prerequisites are important, [1, 2]:

A. Low self-weight

Low specific weight of aluminium alloys, amounting to just a third of steel''s weight, enables and/or facilitates:
- simplification of construction phases;
- transport of fully prefabricated components;
- reduction of load transfer to foundations;
- energy savings either during construction or in subsequent use;
- reduced need for physical labour.

B. Corrosion resistance

The formation of a protective oxygen film on the surface enables:
- reduction of maintenance costs;
- good performance in corrosion-inducing aggressive environments.

C. Functionality of structural shape

The extrusion process enables:
- improvement of geometrical characteristics of cross sections by design of minimum weight shapes presenting at the same time the highest level of structural efficiency;
- creation of stiff forms without using complex sections, thus avoiding welding or bolting;
- simple connecting systems between different components, thus improving joint details;
- combining different functions of structural components, which results in a more economical and rational cross section.

2.2. Aluminium

Regardless of the fact that aluminium is present on the Earth''s surface in inexhaustible amounts in the form of numerous oxide and silicon-based minerals, bauxite has remained, due to its solubility in alkaline media and high percentage of aluminium (20 % - 30 %), the main economically and technologically significant raw material for the production of alumina (Al_2O_3). Bauxite is a heterogeneous ore that mainly consists of one or more aluminium hydroxides, sometimes combined with silicon dioxide, steel oxide, and aluminosilicate (argentite). Aluminium oxide occurs in bauxite in form of three hydrated mineral types: hydrargillite, boehmite, and diaspore. Based on the data provided by the International Aluminium Institute [3], the world"s annual production of alumina and primary aluminium, expressed in 10^3 tonnes, is presented in Figure 1.

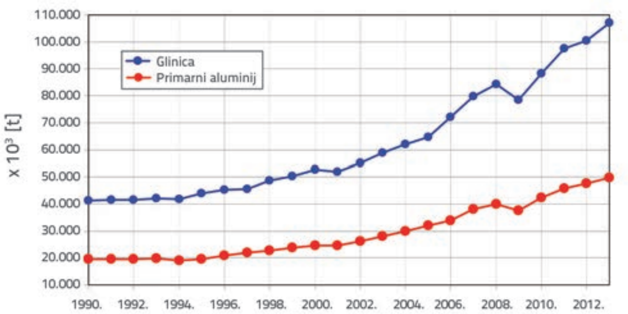

Figure 1. World"s annual production of alumina and primary aluminium expressed in 10^3 tonnes, [3]

Basic physical properties of aluminium and aluminium alloys are presented in Table 1. Other beneficial properties of aluminium and its alloys are:
- 2.9 times lighter than steel,
- shows good mechanical properties at low temperatures (including toughness),
- reflects well light and heat,
- non-toxic and without negative impacts on nature,
- good corrosion resistance due to its natural oxide layer,
- non-magnetic,
- no arcing during processing.

Table 1. Comparison of basic physical properties of pure aluminium and its alloys with steel

Physical properties / Metal	Aluminium/Aluminium alloys	Steel
Melting temperature	660 °C	1425 - 1540 °C
Density at 20°C	2700 kg/m³	7850 kg/m³
Thermal elongation	$23 \cdot 10^{-6}$ °C^{-1}	$12 \cdot 10^{-6}$ °C^{-1}
Specific heat	~ 920 J/kg°C	~ 440 J/kg°C
Thermal conductivity	~ 240 W/m°C	~ 54 W/m°C
Modulus of elasticity	70 000 N/mm²	210 000 N/mm²
Shear modulus	27 000 N/mm²	81 000 N/mm²
Poisson's ratio	0,3	0,3

However, in addition to its high production price, there are some other properties that negatively influence the choice of aluminium as a building material. The principal ones are its high deformability (modulus of elasticity is three times lower than that of steel), susceptibility to stability problems, significant reduction of load bearing capacity in heat affected zones during welding, and a relatively high sensitivity to fire.

2.3. Aluminium hardening

In its pure form, aluminium is a metal with a relatively low strength. The tensile strength of aluminium in its purest form is about 40 MPa, and a proof strength is about 10 MPa. These values are too low for the majority of technical applications. Therefore, aluminium alloys with mechanical properties that considerably surpass those of the original material have been developed. Hardening of aluminium can be achieved by alloying, work hardening, or precipitation. One of the most important properties of aluminium, and of the majority of its alloys, is their easy strain deformability and the possibility of achieving numerous thermal (metallurgical) stages, which consequently enable development of a wide variety of mechanical properties for structural applications.

2.3.1. Alloy hardening

Imperfections in the lattice structure can very efficiently be created by introducing foreign elements in the aluminium matrix. Up a certain point, their efficiency depends on the difference between the atomic radii of the foreign element and aluminium.
Magnesium ranks among the elements that are best suited for meeting strength improvement requirements. That is why a hundred years ago aluminium-magnesium alloys used to be the first choice materials for structural aluminium applications. High strength values have been obtained in alloys containing up to 10 % of magnesium. However, problems during the cold and hot working of these alloys, and the less than optimum corrosion behaviour of alloys with a very high magnesium level, led to a gradual adoption of alloys with a lower percentage of magnesium, but with an addition of manganese.

2.3.2. Work hardening

Plastic deformation creates imperfections in the lattice, generating a significant number of the so-called dislocations, especially along slip planes. New slip planes continually emerge with an increase in load and deformation. The mechanical strength of material increases with an increase in the density of dislocations. Simultaneously, the ductility decreases until, finally, the deformation process is stopped. During cold rolling, this work hardening is performed until cracks begin to occur in the material, usually at the edges of strips. However, this kind of hardening process can be reversed by heat treatment. Depending on temperature, and on the time of exposure to temperature, what has been gained in the hardening process can be reversed and returned to its original stage, i.e. the stage before cold working. Original ductility of material can also be restored. This heat process of obtaining the so-called "O temper" material is described as annealing. The cold working process can be restarted from this soft "O" stage. In industrial production, this process can be repeated several times to produce very thin materials from originally thick metal plates.

2.3.3. Precipitation hardening

Precipitation hardening, also called age hardening of metal, is a type of a heat treatment method consisting of an isolation of a finely dispersed phase in the base metal structure. The effect of precipitation hardening was first discovered and practically applied by Wilm in 1906. The precipitation hardening effects can be attributed to the fact that one or more suitable elements can form particles or the so-called intermetallic compounds, either among each other or together with the aluminium matrix. They also create lattice imperfections and, depending on the size of these particles and the uniformity of their distribution, they can cause a significant increase in strength. The entire process begins with the heat treatment of the solution, i.e. all alloying elements are in a solution (a solid solution) that is subsequently quenched to obtain a uniform distribution of all elements at ambient temperature. After that, all the elements start to move into the aluminium matrix. They form intermetallic compounds and grow. Although this happens at room temperature, the process is more efficient at elevated temperatures (natural and artificial ageing). It is important to note that the effects of precipitation hardening can be reduced if a material is exposed to high temperatures for short periods of time, or to more moderate temperatures over a longer period of time. It should also be noted that precipitation hardened alloys are nowadays dominant in many areas (e.g. in the production of extruded sections). During (hot) forming processes they have a low resistance to deformation and, in many cases, the extraordinary strength is reached afterwards thanks to the precipitation hardening process.

2.4. Aluminium alloys

Basic families of aluminium alloys with different chemical composition and mechanical properties are obtained by combining the primary aluminium with alloying elements. Aluminium alloys are usually classified according to their production procedure (cast and wrought alloys) and heat treatment (heat-treatable and non-heat-treatable), or on the basis of their chemical composition.

In practice, only several elements have proven to be fully effective as alloying elements for aluminium destined for structural applications. These are: magnesium (Mg), silicon (Si), manganese (Mn), copper (Cu), and zinc (Zn). They can be used either individually or in combinations. Aluminium alloys are classified based on their principal alloying element, i.e. according to the alloying element most represented in a particular alloy. The designation of wrought alloys according to [4 and 5] is presented in Table 2.

The 1xxx series designates pure aluminium with a minimum purity of 99.00 % and higher. The second number refers to the level of impurity. If the second number equals 0, the aluminium is not alloyed and the amount of impurities is within the limits of natural concentrations. On the other hand, if the second number is different from 0, it points to the need for conducting a special control of the level of one or more impurities, or the alloyed element itself. The last two numbers specify the lowest prescribed percentage of aluminium above 99.00 % (for instance, number 50 means that the minimum aluminium content is 99.50 %). Aluminium alloys are identified using a system in which the first numbers range from 2 to 8, as shown in Table 2. In the designation system for families of aluminium alloys, the second number specifies the modification of an alloy. If this number equals 0, it is an original alloy. If the number is different from 0, it is a modification of an alloy. The last two numbers have no particular meaning, i.e. they are used only to distinguish different aluminium alloys in a group.

Table 2. Major families of wrought aluminium alloys

Main alloying element	No. designation	Chem. designation
Aluminium (**Al**)	EN AW **1xxx**	EN AW **Al**
Copper (**Cu**)	EN AW **2xxx**	EN AW **AlCu**
Manganese (**Mn**)	EN AW **3xxx**	EN AW **AlMn**
Silicon (**Si**)	EN AW **4xxx**	EN AW **AlSi**
Magnesium (**Mg**)	EN AW **5xxx**	EN AW **AlMg**
Magnesium & silicon (**Mg** i **Si**)	EN AW **6xxx**	EN AW **AlMgSi**
Zinc (**Zn**)	EN AW **7xxx**	EN AW **AlZn**
Other elements (Iron **Fe**)	EN AW **8xxx**	EN AW **AlFe**

The designation of principal cast aluminium alloys is defined by standards [6-8]. An outline of the numerical designation system that is used for main groups of aluminium alloys is given in Table 3. Cast aluminium alloys have a designation starting with letters EN (the European numerical designation system) after which, separated by a space, there is a letter A (standing for aluminium). The letter A is followed by another letter (X) marking the form of the product, which can be one of the following:

- B: aluminium alloy ingot for remelting,
- C: castings,
- M: master alloys.

The first number in a cast alloy designates the main alloying element. The second number indicates the group the alloy belongs to, the third number can be any number, and the fourth number is always 0. The fifth number is also 0, except in cases when the alloy is meant for aeronautical applications.

Table 3. Designation system of the most common and main groups of cast aluminium alloys

Main alloying element	Numerical designation
Copper (**Cu**)	EN AX **2xxxx**
Silicon (**Si**)	EN AX **4xxxx**
Magnesium (**Mg**)	EN AX **5xxxx**
Zinc (**Zn**)	EN AX **7xxxx**

2.5 Choice of alloy

Many factors have to be taken into account when selecting an appropriate alloy for structural applications. For the design of load-bearing aluminium alloy structures, it is not only necessary to choose the corresponding alloy, but the designer also has to be familiar with physical properties of those alloys, which are listed in HR EN 1999-1-1 [9]. The choice of the most suitable alloys amongst those listed in [9] seems rather difficult. Except for strength values, which are the most important property for a structural engineer, alloys are distinguished according to many other aspects:

- availability in the form of a sheet or/and sections,
- purchase availability,
- decorative anodisable,
- filigreed/multihollow cross sections possible,
- exceptionally good or better welding strength,
- exceptionally good corrosion resistance (for special applications),
- price,
- bendability/formability (sections),
- foldability (sheets),
- high ductility,
- strength at and under influence of elevated temperatures.

Several of the above-mentioned requirements must normally be met for each application but the purchase availability and low cost are always important. Therefore, in the majority of cases, the choice of an alloy and temper is practically given.

According to [9], aluminium alloys can be classified into three groups of durability: A, B and C, with each group having lower durability than the previous one. These classifications are used to define the need for and the level of required protection. In structures where more alloys are utilized, including electrodes in welds, the classification of durability must be in accordance with the lowest classification.

Wrought heat-treatable alloys, suitable for a base material for structures, belong to the 6xxx series (EN AW-6082, EN AW-6061, EN AW-6005A, EN AW-6063, and EN AW-6060) and fall into the durability class B. In the 7xxx series, the EN AW-7020 alloy is suitable for general construction applications and it falls into the durability class C.

The wrought non-heat-treatable alloys from the 3xxx, 5xxx, and 8xxx series (EN AW-3004, EN AW-3005, EN AW-3103, EN AW-5005, EN AW-5052, EN AW-5454, EN AW-5754, EN AW-5083, and EN AW-8011A) are recommended for structural elements. All alloys from the 3xxx and 5xxx series belong to the durability class A, whereas the EN AW-8011A alloy falls into the durability class B.

Six cast alloys, four heat-treatable alloys (EN AC-42100, EN AC-42200, EN AC-43000, and EN AC-43300) and two non-heat-treatable alloys (EN AC-44200, and EN AC-51300) are recommended for structural applications. All cast alloys from the 4xxxx series belong to the durability class B, whereas the cast alloys from the 5xxxx series are covered by the durability class A.

To sum up, the following alloys are most commonly used for structural applications:

- EN AW-6082 and EN AW-6061 for structures made of sheets and extruded profiles,
- EN AW-5083 and EN AW-5754 for structures made of sheets,
- EN AW-6060 and EN AW-6063 for structures made of extruded profiles.

To be able to select a suitable aluminium alloy, it is essential to be familiar with the designation system used for their characteristic stages or tempers. Aluminium stages can be:

F - rough stage of fabrication
O - annealed stage
H - work-hardened stage (e.g. cold-working)
W - tempered nonstabilized stage
T - heat-treated, i.e. temper stage

Other most commonly used temper designations (T) are:

T1 - cooled from hot working and naturally aged,
T2 - cooled from hot working, work-hardened and naturally aged,
T3 - solution heat-treated, work-hardened and naturally aged,
T4 - solution heat-treated and naturally aged,
T5 - cooled from hot working and artificially aged,
T6 - solution heat-treated and artificially aged,
T7 - solution heat-treated and artificially over-aged,
T8 - solution heat-treated, work-hardened, and artificially aged,
T9 - solution heat-treated, artificially aged, and work-hardened.

Additionally, for the design of aluminium structures, it is very important to be familiar with the designations of semi-finished products related to a particular aluminium alloy. Therefore, in HR EN 1999-1-1, [9], next to the reference to the corresponding norm, the following designations are also given:

SH - sheet (HRN EN 485)	EP/H - extruded hollow profile (HRN EN 755)
ST - strip (HRN EN 485)	EP/O - extruded open profile (HRN EN 755)
PL - plate (HRN EN 485)	ER/B - extruded bar (HRN EN 755)
DT - drawn tube (HRN EN 754)	ET - extruded tube (HRN EN 755)
EP - extruded profiles (HRN EN 755)	FO - forgings (HRN EN 586)

3. Application of aluminium alloys in civil engineering

3.1. Competitiveness

The best application of aluminium is related to some typical cases in which benefits are gained by at least one main property of aluminium: lightness, corrosion resistance, and functionality [10]. The following structural applications in the area of civil engineering, best related to the mentioned properties, are:

- Long-span roof structures where live loads are low compared to dead loads, i.e. reticular spatial structures and geodetic domes for covering long-span areas (e.g. halls and auditoriums).

- Structures located in hardly accessible places, away from fabrication shops, for which unhindered transport and easy erection are of crucial importance (e.g. transmission towers transportable by helicopters).
- Structures located in corrosion-inducing or humid environments (e.g. swimming pool roofs, river bridges, hydraulic structures, and off-shore superstructures).
- Structures with moving parts (e.g. sewage plant crane bridges and moving bridges), where lightness means efficient use of energy.
- Special-purpose structures for which maintenance operations are especially difficult and should be limited (e.g. masts, lighting towers, antenna towers, road sign gantries, etc.)

The mentioned applications belong mainly to the field of civil engineering. It should however be noted that the potential of aluminium application is much wider and is not limited to structural engineering only.

3.2. Lightweight structure

When the weight of a structure is crucial, the use of aluminium can present a valid alternative to steel. Besides, complete absence of maintenance increases its advantages, especially for those structures that are located in a humid environment.

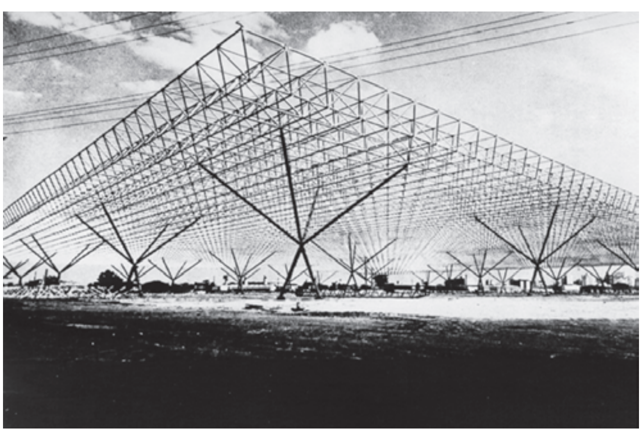

Figure 2. Roof structure for *Inter-American Exhibition Centre*, Sao Paolo, Brazil – under construction

There are several applications of reticular spatial structures in South America (Brasil, Colombia, Ecuador). A historical breakthrough in the area was a spectacular spatial structure built for the Inter-American Exhibition Centre in Sao Paolo, Brasil in 1969 (Figure 2). It covers an area of 67.600 m^2 with a 60x60m mesh. The height of the structure (layer) is 2.36 m. It was entirely bolted on the ground and was subsequently erected to its ultimate level of 14 m by means of 25 cranes located at the corners of the mesh, in the position of actual supports. The weight of the structure is 16 kg/m^2, it consists of 56820 elements, measuring 300 km in total length. The assembly time was extremely short: 27 hours; a total of 550,000 bolts were used for 13,724 nodes. The materials used for the structure are: aluminium alloys 6063 and 6351, T6 series for cylindrical bars, Al 99.5 for trapezoid sheets, and galvanized steel bolts for connections. A very similar case is the International Congress Centre of Rio de Janeiro, where the same type of mash was used (60 x 60 m). It covers a total area of 33000 m^2 (Figure 3).

Figure 3. International Congress Centre of Rio de Janeiro, Brazil (model)

Among many different applications of reticulated systems covered with aluminium sheeting, the most noteworthy are: the roofing of the sports hall *Coliseo General Rumiñahui*, Quito, Ecuador (Figure 4) and The Memorial Pyramid in La Baie, Quebec, Canada (Figure 5), commemorating a damage caused by a flood in the 1980s.

Figure 4. *Coliseo General Rumiñahui, Quito,* Ecuador

Figure 5. The Memorial Pyramid in La Baie, Quebec, Canada

Reticular domes present the most challenging application of aluminium alloys in structural engineering. This concept enables realization of large-scale facilities (sports arenas, exhibition centres, congress halls, auditoriums, etc.). These applications are highly interesting due to their short erection time, connecting systems used, and remarkable dimensions. The first applications are: "*Dome of Discovery*", built in London in 1951 for the South Bank Exhibition during the Festival of Britain (with directional reticulated arches, 110 m in diameter, and 24 kg/m^2 in weight), and a geodetic dome built in 1959 for covering the '*Palasport*" in Paris, using the Kaiser Aluminium system, 61 m in diameter and 20 m in height. Both structures were prototypes in their respective fields - the first and the largest.

Figure 6. *Spruce Goose* Dome, Long Beach, California, USA

Interesting structural systems for aluminium-made geodetic domes have recently been erected in the USA, where "ad hoc" systems for roofing industrial plants with ecological purposes, and for roofing large-span public buildings, were applied. A well-known example is the *Spruce Goose* Dome: the largest dome of this kind in the world, spanning more than 125 m in diameter (Figure 6). Many geodetic domes are used in industry, e.g. for coal storage plants (Figure 7).

3.3. Low maintenance requirements

Some special structures are used as a means to support fixed elements that are positioned at a certain level above the ground. They can be dominantly horizontal (e.g. gantries for traffic signs), or vertical (e.g. antennas, high voltange transmission lines and lightning towers). For structures of this type, it is of paramount importance to eliminate any sort of maintenance. At the same time, the extrusion process can enhance geometrical properties of cross sections, thus enabling a minimum weight and a maximum structural efficiency. In addition, the light weight of aluminium enables easy transport and fast assembly of prefabricated systems, thus offering competitive solutions when compared to other materials.

Figure 8. Aluminium towers, Naples, Italy

Many high voltage transmission lines have been built in Europe. Two important aluminium towers were erected in Naples. One of them is a tower supporting parabolic antennas of the Electrical Department of Naples, erected in 1986. The reason for choosing aluminium is, in essence, its light weight (the tower was erected at the top of an already existing concrete staircase) and its corrosion resistance property (no maintenance problems). It is 35 m high, from the top of the staircase, and its total height is 50 m. It consists of a cylinder with an internal diameter of 1800 mm and a 20 mm thick wall. It was fabricated by welding in workshop, and was separated along the height into three

Figure 7. Aluminium dome for coal storage plant

parts that were later field-bolted during erection (Figure 8, left). The second example is the "Information Tower" located near a football stadium in Naples and equipped with antennas and screens so that football matches can be viewed from outside of the stadium (Figure 8, right).

Aluminium properties play a crucial role in hydraulic applications (e.g. pipelines, tanks). Here aluminium is typically used in rotating crane bridges for large circular settling pools in wastewater treatment plants. Basically, its corrosion resistance property eliminates the need for maintenance of the structure even when it is placed in a corrosion-inducing environment, whereas its lightweight property permits energy savings during operation of the plant (Figure 9).

Figure 9. Wastewater treatment plant pool *Po-Sangone*, Turin, Italy

It should be emphasized that the main future trend in the application of aluminium alloys involves the use of such alloys on offshore structures, Here, aluminium alloys offer noteworthy benefits including cost reduction, ease of fabrication, and already proven efficiency under aggressive ambient conditions.

Staircases, mezzanine flooring, access platforms, walkways, gangways, bridges, towers, and cable ladder systems, can all be constructed in form of prefabricated units for simple assembly offshore or at a fabrication yard. Helidecks are also fabricated from aluminium alloys since the early 1970s, and they are now completely tested for use in heavy duty conditions, Figure 10. Moreover, they are designed in modules and with bolt connections, thus enabling easy and quick erection, and simple handling and shipping. In addition, their use enables up to 70 % reduction in weight with respect to steel, not to mention compliance with the most stringent safety criteria, and up to 12 % cost reduction.

An entire array of modules for crew quarters and utilities has recently been developed: from large purpose-built modules to flexible ones. The modules can be used individually or assembled in a group to form multi-storey complexes, connected with central, transverse corridors and staircases.

3.4. Bridges

All types of bridges have so far been constructed using aluminium alloys. The Arvida Bridge in Quebec, Canada, built

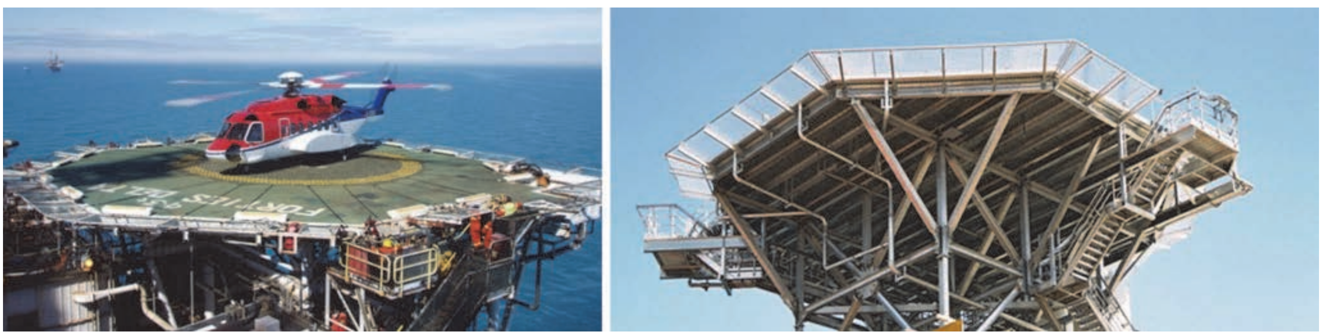

Figure 10. Helidecks

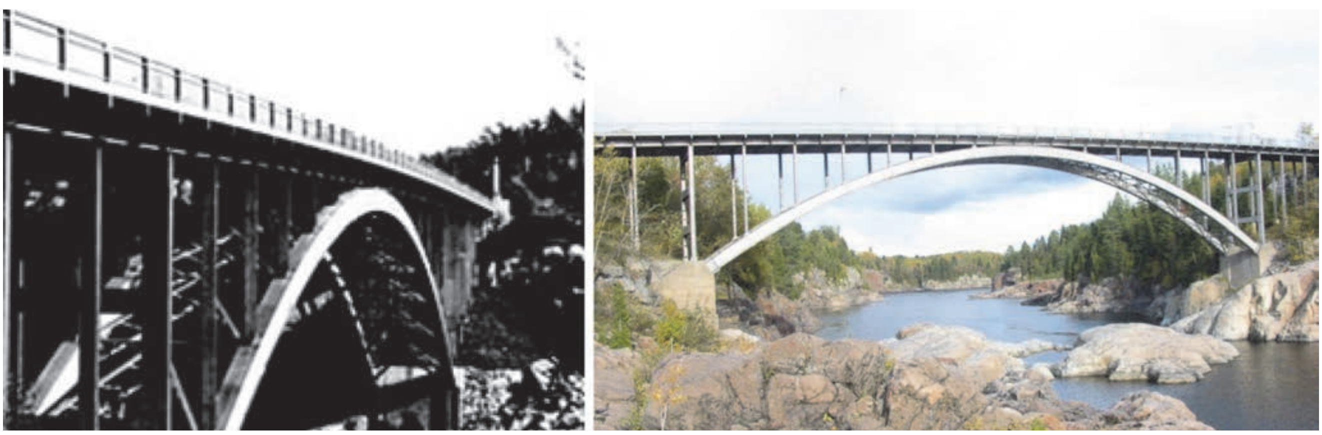

Figure 11. The Arvida Bridge in Quebec, Canada

in 1950, was one of challenging motorway-bridge prototypes made of aluminium alloys. It was built according to a Maillart"s scheme. It has a total span of 150 m, an 87 m arch, and its total weight amounts to 200 tonnes (Figure 11).

A technology of composite structures made of aluminium beams and concrete decks has also been developed. Concrete-aluminium composite systems were used for some bridges erected in the 1960s in the USA and later on in France.

A new, important field of application is that of military bridges where lightness and corrosion resistance play a fundamental role. Currently it is possible to cross a 40 m span using prefabricated elements as they are easily transportable and easy to erect. The main applications of this kind were realized in Great Britain, Germany, and Sweden, Figure 12. In Germany, military bridges are fabricated in form of pre-fabricated units characterized by simple transport and assembly (Figure 13).

Figure 12. Swedish military bridge

Figure 13. German military bridge set-up

Due to a slow moving load, foot-bridges also rank among structures where aluminium alloys are successfully utilized. Additional advantages due to aluminium"s lightness are rather obvious in the case of moving bridges. Examples of aluminium foot bridges can be found in France, Germany, the Netherlands, Italy, and Canada.

3.5. Refurbishment of bridges

A lightweight system for the replacement of damaged concrete deck structures of bridges has been developed and employed in Sweden. It is based on an orthotropic plate made of hollow aluminium extrusions. This solution can in many cases prove to be very competitive as an alternative to more conventional solutions. Weight reduction has enabled the use of existing foundations and supports.

4. Eurocodes and aluminium

The unavoidable complexity of standards for aluminium structures is essentially caused by the nature of the material itself, which is considered to be much more "critical" and less known than steel, thus requiring more complex analyses and solutions to more sophisticated problems. This is why the related standard should be educative and informative as well as normative. The ENV issue of Eurocode 9 "Design of aluminium structures" (1998) is made of three documents (Part 1.1 "General structural rules", Part 1.2 "Structural fire design", and Part 2 "Structures susceptible to fatigue"). Upon an explicit request made by EAA (European Aluminium Association), and due to a great interest in new fields of application as expressed by representatives of the aluminium industry, two new issues were added in the transition phase: "Cold-formed structural sheeting" and "Shell structures". On the basis of suggestions collected in the meantime, the transformation from ENV to EN began in 2001. This phase was concluded in 2005 and the final version of Eurocode 9 consists of the following five documents:

- Part 1.1: *General structural rules*
- Part 1.2: *Structural fire design*
- Part 1.3: *Structures susceptible to fatigue*
- Part 1.4: *Cold-formed structural sheeting*
- Part 1.5: *Shell structures*

Unlike other Eurocodes, Eurocode 9 consists only of one part that is divided into: one fundamental document, "General structural rules", and four other individual documents all related to the fundamental one. Specific types of structures (e.g. bridges, towers, silos, etc.) are not mentioned, as it is the case for the steel. Only general topics are given, i.e. topics that are applicable not only to structural engineering, but also to broader civil engineering areas, transport industry included.

The preparation of Eurocode 9 was based on the most significant results achieved in the field of aluminium alloy structures, without ignoring previous activities conducted within ECCS, and those related to the revision of outstanding codes, like BS 8118. The ECCS method for column buckling was, with some minor editions, also utilised in EC 9. The method is based on the use of two buckling curves (a and b) which cover extruded profiles made of heat-treated and work-hardened alloys, respectively [11]. Generally, the design of beam, column and beam-column members is performed taking into account specificities of aluminium alloys. For welded profiles, the reduction effects of the heat-treated zone are accounted for via the corresponding reduction factors. This method is based on experimental evidence, which enabled the characterization of aluminium alloy members as "industrial bars".

The novelty of Eurocode 9, Part 1.1 "General structural rules", lies in the fact that, for the first time in an aluminium structural standard, the analysis of inelastic behaviour begins from the cross section up to the structure as a whole. A classification of cross-sections was made on the basis of experimental results, all of which had been gathered from an "ad hoc" research project supported by the main representatives of the European aluminium industry, who provided the material for specimens. The result was a specification of behavioural classes based on the slenderness ratio (b/t), according to an approach qualitatively similar to the one applied to steel, but with a different range of behaviour, which was based on experimental evidence and verified through numerical simulations [12].

An evaluation of resistance of cross sections has been introduced in a unique manner, with a special reference to ultimate-limit states related to the four classes. For the members belonging to class 4 (slender sections), the check of the local buckling effect is performed using a new calculation method based on the effective thickness concept. Three new buckling curves for slender cross sections are assessed, including heat-treated and work-hardened alloys, together with welded and non-welded shapes [2]. This method presents a starting point for a detailed treatment of the cold-formed sheeting, as given in Part 1.4 "Cold-formed structural sheeting".

The problem of evaluation of internal forces and moments is considered by taking into account several models for material constitutive law, from the simplest ones to the most sophisticated ones that lead to different levels of approximation. A global analysis of structural systems in the inelastic range (plastic, strain hardening) relies on a simple method similar to the well-known method of plastic hinge, but considers typical parameters of aluminium alloys such as: absence of yielding plateau, continuous strain-hardening, and limited ductility of some alloys [2].

The importance of ductility with regard to the local and global behaviour of aluminium structures has been highlighted, due to sometimes poor values of ultimate elongation, and a new "ad hoc" method for the evaluation of the rotation capacity for members in bending has been set up [13].

A new classification system for the resistance, stiffness and ductility of joints has been proposed. A new method for the resistance assessment of T-stubs has been established and introduced in Part 1.1 on the basis of experimental evidence about the monotonic and cyclical testing.

The new Part, 1.5, addressing shell structures, has been compiled following the same format of the similar document in EC 3. However, the method relies on the corresponding buckling curves obtained from empirical evidence on aluminium shells [14].

Structural fire design is a transversal topic for all Eurocodes dealing with structural materials, and it is comprised in Part 1.2. For aluminium structures, it has been standardized for the first time according to general structural rules, in which fire resistance is assessed on the basis of three criteria: resistance (R), insulation (I) and integrity (E). It is generally known that aluminium alloys are normally less resistant to high temperatures compared to steel and reinforced concrete. Nevertheless, by introducing rational risk assessment methods, fire scenario analyses can in some cases lead to a more favourable time-temperature relation. This may give rise to a more competitive status of aluminium, and thermal properties of its alloys may have a beneficial effect on temperature development in structural components [1].

Knowledge about fatigue behaviour of aluminium joints has been consolidated over the past 30 years [1]. The ECCS recommendations for the fatigue design of aluminium structures were published already in 1992. They represented the fundamental bases for the development of Eurocode 9. It was decided to develop Part 1.3 in EC 9, *Structures susceptible to fatigue*, in a general manner, by giving general rules applicable to all types of structures exposed to fatiguing loading with respect to the limit state of fatigue-induced fractures. This part does not correspond to the similar part for the steel Eurocode, where only bridges are addressed. Three design methods have been introduced:

- Safe life design (SLD)
- Damage tolerant design (DTD)
- Design assisted by testing

The following basic groups of detail categories have been considered:

- non-welded details in wrought and cast alloys,
- members with transverse welded attachments,
- members with longitudinal welded attachments,
- welded joints between members,
- crossing welds/built-up beams,
- mechanically fastened joints,
- adhesively bonded joints.

The use of finite elements and guidance on the assessment by fracture mechanism was suggested for the stress analysis.

Finally, it should be noted that the importance of the quality assurance on welding was highlighted with specific reference to the standards belonging to the group of HRN EN 1090 "Execution of steel and aluminium structures".

5. Conclusion

Although a high price of aluminium alloys remains the main obstacle to their wider use in construction, the utilisation of aluminium alloys in structural engineering is undoubtedly justified. This paper addresses only some cases in which the use of aluminium alloys in structural engineering constitutes a practical, advantageous, and often the only practical solution. Examples of the structures where the priority is given to the lowest possible weight (large spans, transport, installation) and the longest durability (corrosion resistance) are presented. Reasons for using aluminium are usually based on the properties of its alloys: light weight, easy workability, toughness at low temperatures, low maintenance costs, durability, and recyclability. However, the stability and fire resistance of aluminium structures have not been sufficiently investigated, and a varied behaviour of a great number of aluminium alloys in use does not allow simple comparison with steel. A considerable attention is given to these issues in the most recent first phase of development of the second generation of European standards. Despite the current situation with standards, this paper offers fundaments for an introduction to specific issues for the design of these still somewhat neglected metal structures, by outlining basic properties of aluminium alloys and the development of their respective Eurocodes.

REFERENCES

[1] Mazzolani, F. M.: Aluminium Alloy Structures (second edition), E & FN SPON, an imprint of Chapman & Hall, London, 1994.

[2] Mazzolani, F. M. (editor): Aluminium Structural Design, International Centre for Mechanical Sciences - Courses and Lectures Vol. 443, Springer Vienna, 2003.

[3] Web stranica International Aluminium Institute (www.world-aluminium.org) - pristupljeno 24.04.2014.

[4] HRN EN 573-1:2008, Aluminij i aluminijeve legure - Kemijski sastav i oblici gnječenih proizvoda - 1. dio: Sustav brojčanog označivanja (EN 573-1:2004).

[5] HRN EN 573-2: 2008, Aluminij i aluminijeve legure - Kemijski sastav i oblik gnječenih proizvoda - 2. dio: Sustav označivanja na temelju kemijskih simbola (EN 573-2:1994).

[6] HRN EN 1780-1: 2008 - Aluminij i aluminijeve legure - Označivanje legiranih aluminijevih ingota za pretaljivanje, predlegure i odljevke - 1. dio: Sustav brojčanog označivanja (EN 1780-1:2002).

[7] HRN EN 1780-2: 2008 - Aluminij i aluminijeve legure - Označivanje legiranih aluminijevih ingota za pretaljivanje, predlegure i odljevke - 2. dio: Sustav označivanja kemijskim simbolima (EN 1780-2:2002).

[8] HRN EN 1780-3: 2008 - Aluminij i aluminijeve legure - Označivanje legiranih aluminijevih ingota za pretaljivanje, predlegure i odljevke - 3. dio: Pravila pisanja kemijskog sastava (EN 1780-3:2002).

[9] HRN EN 1999-1-1:2008, Eurokod 9: Projektiranje aluminijskih konstrukcija - Dio 1-1: Opća pravila (EN 1999-1-1:2007).

[10] Mazzolani, F. M.: Structural Applications of Aluminium in Civil Engineering, Structural Engineering International (SEI), Journal of the IABSE, Vol. 16, No. 4, 2006, pp. 280-285.

[11] Mazzolani, F. M.: Stability problems of aluminium alloy members: the ECCS methodology, in Structural Stability and Design (edited by S. Kitipornchai, G.J. Hancock & M.A. Bradford), Balkema, Rotterdam, 1995

[12] Landolfo, R., Mazzolani, F.M.: The Background of EC9 design curves for slender sections (invited paper), Volume "FESTSCHRFT" (in honour of Prof. Joachim Lindner), 1998.

[13] De Matteis, G., Landolfo, R., Manganiello, M., Mazzolani, F.M.: Inelastic Behaviour of I-Shaped Aluminium Beams, Proceedings of the Sixth International Conference on Computational Structures Technology, B.H.V. Topping and Z. Bittnar (editors), Civil-Comp Press, Stirling, Scotland, 2002., http://dx.doi.org/10.4203/ccp.75.27

[14] Mazzolani, F.M., Mandara, A.: Buckling of aluminium shells: proposal for European curves, Proceedings of the ICTWS 2004, 4th International Conference on Thin-Walled Structures, Loughborough Leicestershire, 2004.