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Advances in materials applied in civil engineering

K. Flaga

Cracow University of Technology, ul. Warszawska 24, 31-155 Cracow, Poland

Abstract

This paper outlines the problems of the construction materials being used in civil engineering at the end of the 20th century and also of the construction materials of the future. The progress that have been made in the domain of basic construction materials such as steel and concrete over the 19th and 20th centuries is analysed. It is described how new materials such as carbon fibre reinforced polymer, high-strength concrete and high-performance concrete, create the possibilities of a further development. New opportunities for modern glued-timber structures are also presented. The limitations of the application of glass and plastics as construction materials are indicated.

Keywords: Steel; Concrete; High-strength concrete; High-performance concrete; Carbon fibres reinforced polymer; Bridges; Tall buildings; Offshore structures

1. Introduction

Civil engineering — the art of construction of all kinds of buildings — has been at man's service since the beginning of civilisation evolution. These buildings are dwelling as well as public buildings, industrial buildings, bridges, viaducts, tunnels, roads and railways, highways and airports, liquid reservoirs and loose-material containers, weirs, dams, offshore structures, TV towers, and a lot of other structures that form the environment that we live in.

Human activity in the field of civil engineering goes far back into the past, when man observing nature around him began to imitate and to improve it in order to create safer and better living conditions. Moreover, relatively early he noticed that his engineering "works" apart from reliability, durability and functionality had to have elements of harmony and beauty. The same opinion was expressed by Socrates when he said that everything created by man should be functional, durable and beautiful.

The development of civil engineering in the course of centuries meant a constant struggle with available materials, spans, or height, active loads and the forces of nature — water, fire, wind and earthquakes. Some of those elements have primary and the other secondary significance. Amongst those mentioned first, an essential role has always been attributed to the influence of the material on construction development.

First of all, ancient communities had at their disposal natural materials such as stone and timber. In the course of time, they learned how to use clay to form bricks, an artificial stones, which were first dried only in the sun and then baked. In the main civilisation centres (the Middle East, the Near East, and the Mediterranean region) the hot climate and inconsiderate economy led, in a short time, to the elimination of timber as a building material. It did not happen in the wood-abounding countries of Middle and Eastern Europe, Scandinavian and the Asiatic part of Russia.

Stone and brick — brittle materials — dominated civil engineering in the region of European civilisation for several centuries: from stone pyramids in Egypt 3000 years B.C. until the so-called First Industrial Revolution in England (the turn of the 18th and 19th centuries). They were suitable building materials for erecting walls and columns but at the same time, due to their low tensile bending strength, they caused a lot of problems in horizontal elements. Therefore a vaulted arch that was popular in ancient Rome, semicircular in its primary form, was the pattern that was to be employed for elements or structures of larger span.

The arch in the course of time became lighter and less massive. The ratio of span-to-width of piers carrying vertical and horizontal loads became increasingly greater. During the early Middle Ages no improvements were implemented. It was not until Gothic and the Renaissance that new forms and ideas were introduced. However, still they were always based on elements that were in the forms of arches, curvilinear vaults with more and more developed forms (e.g. cloister vault, cross vault, barrel vault, lierne vault). The arch changed from semicircular to segmental (e.g. Ponte Vecchio in Florence) and finally

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to elliptical (e.g. Ponte Santa Trinita in Florence). Stone and brick cupolas based on a circle or a polygon appeared as an alternative construction solution (e.g. Santa Maria del Fiore in Florence).

In the Baroque, Rococo and Neo-classicism the basic construction forms were not changed and only various ornaments and adornments were added. It was a complete change in the way of the perception of the world that has its roots in the Renaissance and then the Enlightenment that made civil engineering free from the enchanted circle of vertical pier and arch or double-curved roof.

2. Steel: basic construction material of the 19th and 20th centuries

Steel and cement are two relatively new building materials that were introduced at the turn of the 18th and 19th centuries. First cast iron, then puddled and cast steel and finally refined and high strength steel proved to be very good construction materials. They are so-called ductile materials that have high tensile and compressive strength. This strength enables the construction of steel bent elements with spans that some years ago were beyond consideration. The subsequent improvements of the production technology made it possible to obtain steel with increasingly better properties. This progress is most easily seen when considering the steel bridges [1]:

1. Ironbridge (Coalbrookdale), England, arch bridge with upper deck (1779), 30.5 m span;
2. Telford's Bonar Bridge, Scotland, arch bridge with upper deck (1815), 45.7 m span;
3. Menai Bridge, Wales, suspension-chain bridge (1826), 176.4 m span;
4. Britannia Railway Bridge, Wales, box girder bridge (1850), 144 m span;
5. Clifton Suspension Bridge, England, suspension-chain bridge (1860), 214 m span;
6. Brooklyn Bridge, USA, suspension bridge (1887), 486 m span;
7. Forth Rail Bridge, Scotland, truss cantilever bridge (1889), 521 m span;
8. Sidney Bridge, Australia, arch truss girder with middle drive (1932), 504 m span;
9. George Washington Bridge, USA, suspension bridge (1931), 1067 m span;
10. Golden Gate Bridge, USA, suspension bridge (1937), 1280 m span;
11. Verazzano Narrows Bridge, USA, suspension bridge (1964), 1298 m span;
12. Forth Road Bridge, Scotland, suspension bridge (1964), 1006 m span (Fig. 1);
13. Tagus Bridge, Portugal, suspension bridge (1966), 1013 m span;
14. Alex Fraser Bridge, Canada, cable-stayed bridge (1986), 465 m span;

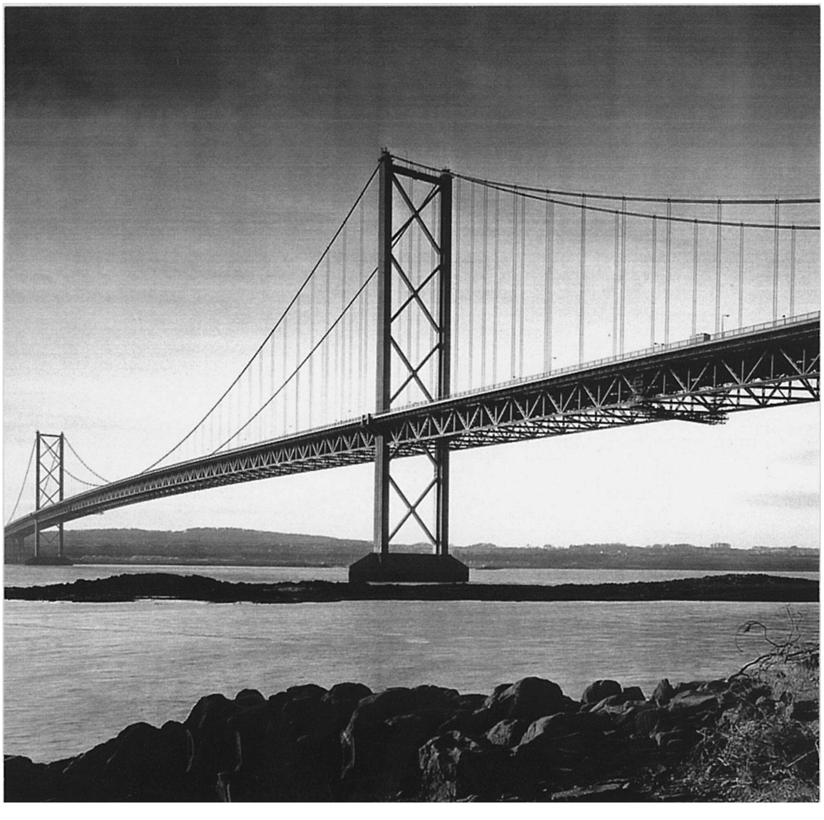

Fig. 1. Forth Road Bridge in Scotland.

Fig. 2. Pont de Normandie over the mouth of Seine River, cable-stayed, span 856 m.

15. Queen Elizabeth II Bridge, England, cable-stayed bridge (1991), 450 m span;
16. Bosporus Bridge II, Turkey, suspension bridge (1988), 1090 m span;
17. New River George Bridge, USA, arch truss girder with upper drive (1978), 518 m span;
18. Humber Bridge, England, suspension bridge (1981), 1410 m span;
19. Pont de Normandie, France, cable-stayed bridge (1994), 856 m span (Fig. 2).

Two suspension bridges have been constructed recently: the suspension Great Link Bridge with the span of 1624 m (finished in 1998) in Denmark and the Akashi Kaikyo Bridge with the record span of 1990 m (finished in 1998) in Japan. The Tatara Bridge, a cable-stayed bridge (finished in 1998) with the record span of 890 m in this class of bridges, has been constructed in Japan.

Despite such great progress, it seems that steel cable-stayed bridges and suspension bridges are reaching the limits of their possibilities. The studio project of the bridge over the Messina Straits established that at the main span of 3000 m two pairs of cables with a diameter of 1.2 m (a mass of about $4\times9.0=36$ t/m) would be loaded mainly by their dead weight and not by the suspended deck with car and railway traffic.

That is the reason for a challenge for the engineering of the 21st century: what can the high strength steel cables be replaced to make them much lighter but as strong as the steel cables? Space engineering achievements, transferred to civil engineering, can be helpful.

3. Carbon fibre reinforced polymer: a structural material of the future

Application of CFRP (carbon fibre reinforced polymer), the material that has been used until now in space and aviation techniques and professional sport, exemplifies this phenomena. EMPA — the Swiss Federal Laboratories for Materials Testing and Research in co-operation with the BBR, Stahlton and SIKA companies, are the pioneers in introducing this material to world engineering.

CFRP is composed of very thin carbon fibres with a diameter of 5–10 μm, embedded in polyester resin. The commercial carbon fibres have the tensile strength of 3500–7000 MPa, an elastic modulus of 230–650 GPa and an elongation at failure ranging from 0.6 to 2.4 %.

This material was first applied in the strengthening of the Ibach Bridge near Lucerne in Switzerland in 1991 [2]. Laminated bands, size 150 mm×1.75 mm or 150 mm× 2.00 mm and 5000 mm long, glued to the reinforced zones were used there. The T3000 fibres that form 55% of the laminated content, have a tensile strength of 1900 MPa and a longitudinal elastic modulus of 129 GPa. Today this technique of the strengthening of building structures is increasingly more often used.

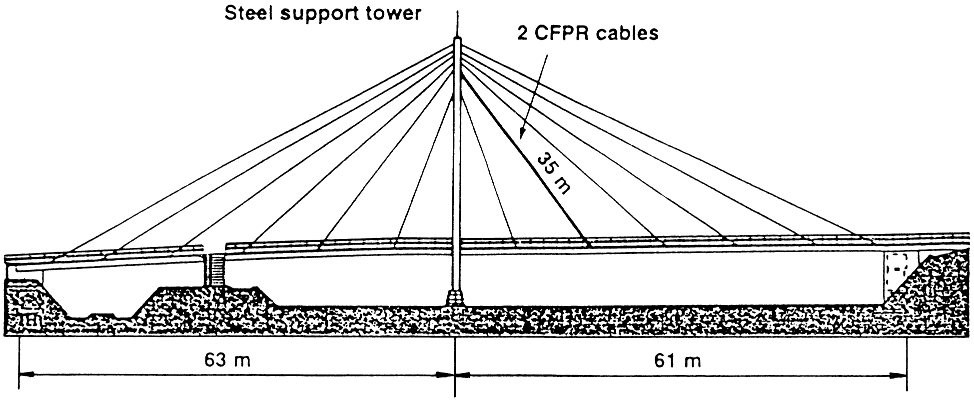

Fig. 3. A cable-stayed bridge with one pair of CFRP cables and 11 pairs of steel cables for support.

In 1996 in Winterthur, Switzerland, the Storchenbrücke [3], a cable-stayed single pylon bridge of 124 m length, was built. Here the CFRP stay cables were applied experimentally for the first time (Fig. 3).

Each of the stay cables, consisting of 241 wires with diameter of 5 mm, interacts with conventional steel stay cables. The appointment of this small bridge for applying CFRP for the first time was optimal as this material has practically zero thermal-expansion coefficient. At a length of about 35 m, it does not cause any problems when used in co-operation with cables composed of different materials.

The technical characteristics of the CFRP wires used in the stay cables mentioned above are as follows: T700 S fibres, material density in the wires 1.56 g/m^2, fibres content in the wires 68%, tensile strength 3300 MPa, longitudinal elastic modulus 165 GPa, thermal-expansion coefficient 0.2×10^{-6} K^{-1}.

From the above it follows that with very high resistance to axial tension exceeding even twice that of high tensile strength steel, the elastic modulus of CFRP stay cables is not much lower than that of the steel cables, whereas the mass density is about five times lower. Therefore CFRP is the material of the future especially as it is durable, fatigue resistant, and non-corrosive.

Before building in the CFRP stay cables used in Storchenbrücke, they were subjected to the test of 18.2 million load cycles at the stress amplitude of 220–270 MPa. The key problem that was faced was finding the method of anchoring the cables in the anchorage blocks. This was caused by the outstanding mechanical properties of CFRP being present in the longitudinal direction only.

The anchorage system worked out by EMPA laboratory solved the problem by the use of a truncated cone shaped locking block filled with casting material, the mechanical properties of which change in accordance with the length of anchorage (Fig. 4).

The main impediment to the widespread use of CFRP in civil engineering is the high price of carbon fibres, at about 25 Swiss Francs per 1 kg (however, they are 5.2 times lighter than steel). Considering the time of exploitation of the

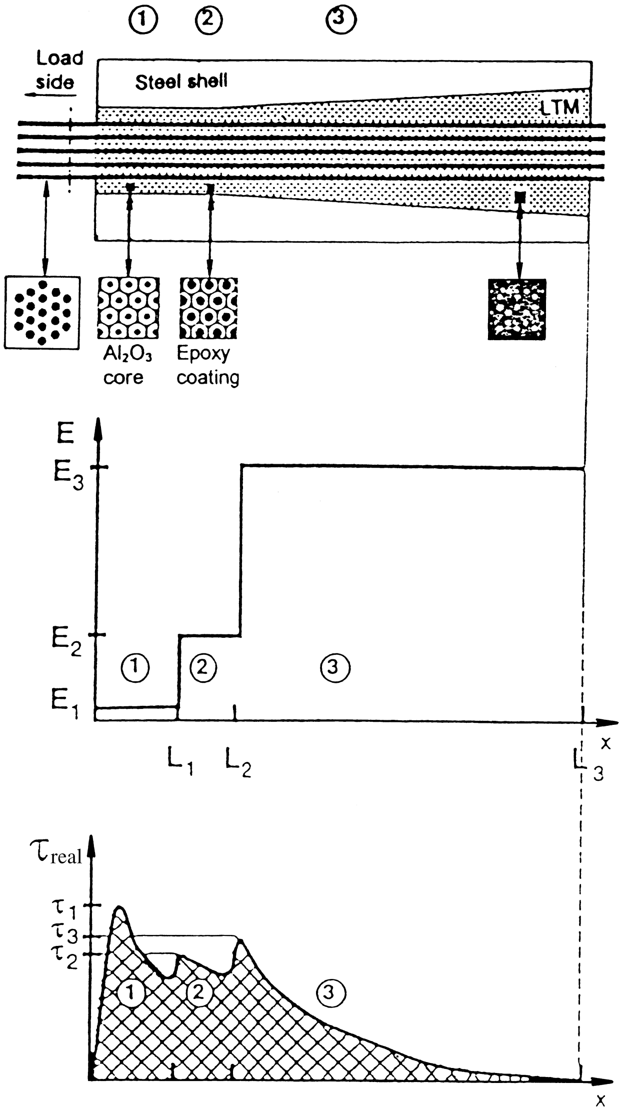

Fig. 4. Cone-shaped terminus of a 19-wire bundle encased in LTM (load transfer media). The inset shows the cross-sectional wire alignment (left) and the reduction in the epoxy coating thickness of the Al_2O_3 granules (right).

engineering object, the application of carbon fibres may appear more reasonable economically.

Finally, when referring to the question asked above, whether the CFRP stay cables may replace in the future the steel cables in suspension and cable-stayed bridges, it is worth quoting the data from paper [5]. The relative equivalent elastic modulus in steel cables decreases as their length increases from $E = 210$ GPa when $l = 0$, then $E = 163$ GPa when $l = 1000$ m to $E = 98$ GPa when $l = 2000$ m. The corresponding values for CRFP cables are 165, 163 and 162 GPa. These data and those above confirm that for $l > 2000$ m CFRP cables may become a much appreciated material of the future for large-span engineering structures.

4. Concrete: basic construction material of the 20th century

The other "invention" of the First Industrial Revolution that caused progress in civil engineering was cement. So-called "portland cement" that was patented in 1824 by J. Aspdin proved to be an excellent hydraulic binder that was used for the production of a new material — concrete. This material is relatively cheap and easy to produce. Based on aggregates and water present in nature and using the cement mentioned above, it was possible to "cast" various shapes of elements and structures. Soon concrete became the most popular building material of the 20th century. As "artificial stone" it has the same disadvantages as natural stone: low tensile strength and high brittleness. It is true that the quotient of strength $f_{\mathrm{ctm}}/f_{\mathrm{cm}}$ is $\frac{1}{10}$ for concrete (it is $\frac{1}{26}$ for natural stones, according to Bauschinger) but nevertheless this enables concrete to be used for bending elements, i.e. for the arch or vault form, similarly to brick or stone structures that were dominating in the first years of its application.

It was only due to the successful attempts by Monier and Hennebique in the 1870s and 1890s that a valuable new building material called reinforced concrete was created. The strengthening of the tensioned zone in concrete elements by means of flexible reinforcing bars and very good co-operation of both materials in the construction, made possible the covering of a span ranging between 30 and 40 m with bent reinforced concrete elements. For larger spans, the dead load of the structure itself became dominant, thus determining the upper limit of application of reinforced concrete. The situation was similar to the case of the so-called tall buildings where the upper limit was a height of 20 storeys determined by the load capacity of the vertical elements such as walls and columns.

Further progress was made possible owing to the introduction of active forces into concrete, i.e. prestressing of structure. Freyssinet's theoretical works and experiments (1926–1928) showed that for the prestressing procedure to be effective, high-strength concrete grades C30–C40 and prestressing steel with a strength of 1500–2500 MPa [6] must be used in the construction. Based on these assumptions, Dischinger built the first prestressed bridge in Aue (Saxonia) in the years 1937–1938 whilst in 1938, Hoyer patented the method of prestressing by means of thin tendons that were tensioned before casting, and transferring the forces to the concrete through adhesion. In 1939–1940, Freyssinet patented the method of prestressing the hardened concrete using cables anchored at the ends of the element, the method still being in wide use.

The introduction of prestressed concrete into civil engineering presented constructors with wonderful new opportunities (Fig. 5). There appeared new methods in the construction of bridges and public buildings (the cantilever and longitudinal sliding methods) as well as techniques (asymmetric shell structures, ribbon structures). The Varrod girder bridge in Kristiansand, Norway, was built in 1994

Fig. 5. Glen Jackson Bridge crossing the Columbia River in OR, USA.

using the cantilever method and its span was 260 m long. Tall buildings made of class C40 concrete are 30-storeys high.

Despite these successes, structures made of plain concrete seem to be doomed to misfortune, resulting from low resistance to corrosion and exposure to an increasingly more polluted environment. The thin coating of the reinforcement bar is subjected to carbonisation, generating the corrosion of the reinforcing steel. The untight covering and relatively high porosity of plain concrete cause the corrosion of the prestressing cables. The additional effect of chlorides (e.g. in traffic buildings) or sulphates (in industrial buildings) causes dangerous expansive corrosion of concrete. This applies, in particular, to constructions that are exposed directly to atmospheric factors (bridges, chimneys, reservoirs, cooling towers, etc.), their "service life" being reduced significantly. They require repairing and strengthening much earlier than planned. These procedures are time- and money-consuming. The assumed so-called service life of concrete bridges was 100 years in the 1950s, 75 years in the 1970s and nowadays it is only 50 years. Thus, at the end of the 20th century, durability has become a great barrier to plain concrete structures. In the 1980s, a new generation of concrete appeared in several countries in the world: high-strength concrete (HSC): class C60–C90 and high-performance concrete (HPC): class C90–C150.

5. High-performance concrete: a structural material of the future

The transition from high strength plain concrete (class up to C50) to HSC and HPC was possible due to some additives such as silica fume and superplasticisers, to plain concrete [7,8].

Silica fume, a by-product of the ferrosilicon production process, contains some 98% of pure SiO_2 and has a very large specific surface of 25 m^2/g, nearly 80 times greater than the specific surface of Portland cement. It has strong pozzolanic properties and, together with calcium hydrate $Ca(OH)_2$, forms stable calcium silicate hydrates. The hydrates appear mainly in the contact zones between the cement paste matrix and the aggregate grains, thus making the zones much stronger and less porous. Further, the additionally formed calcium silicate hydrates in the matrix cause the mortar to be more compact and stronger. As a result, the concrete structure becomes very homogenous.

Calcium hydrate CH, as a product of Portland cement hydration (some 17% of the mass) is the weakest element of the cement paste. It settles as large crystals on the surface of the aggregate grains, where together with the ettringite $\text{C-A-}\bar{\text{S}}\text{-H}$ and the water moistening the aggregate grains, it forms weak contact zones in plain concrete (Fig. 6).

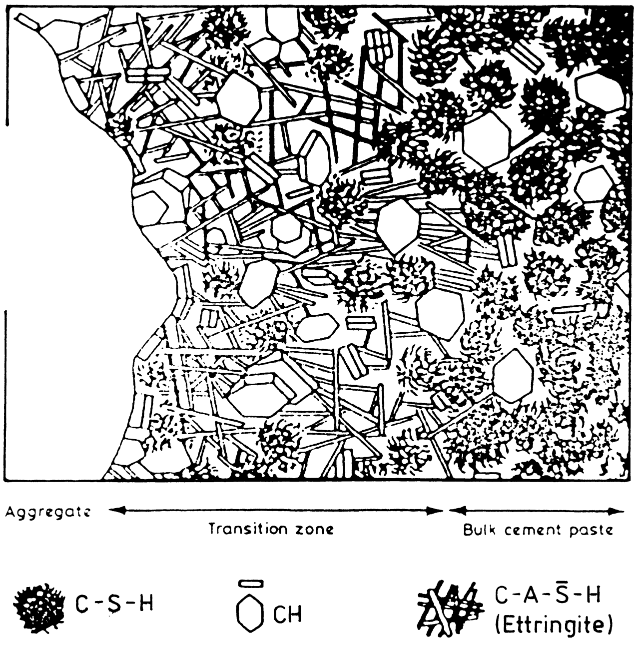

Fig. 6. Schematic description of the microstructure of cement paste in the bulk cement paste in concrete and at the transition zone adjacent to the aggregate [7].

To obtain high strength of concrete, it is necessary to use a very low coefficient *W/C* (ranging from 0.30 to 0.35). For HPC, the coefficient *W/C* should be even lower than 0.30. The obtaining of concrete mixes of the required consistence and workability would be impossible without the contemporary generation of superplasticisers. Superplasticisers, mainly melamine and naphthalene ones or their mixtures, affect, first of all, the contact layers of the cement paste and the aggregate grains making up the so-called double gliding layers. Adding 2–4% of plasticisers relative to the cement mass made possible the introduction of a new generation of concrete, HSC and HPC, into civil engineering.

HSC and HPC have the following characteristic features: (i) high compression strength; (ii) greater brittleness (and lower tensile strength in relation to compression strength); (iii) very low porosity and absorbability (about 3% by weight); (iv) high durability and freeze resistance due to high tightness; (v) adhesion to the reinforcement increased by 40%; (vi) shrinkage and creep reduced by 50%; being completed to 70% as soon as the 7th day of curing; (vii) increased heat of cement hydration and (viii) reduced fire resistance because of high tightness, which makes it impossible for the water contained in the hardened concrete to get out and causes its transformation into high-pressure steam during a fire.

The above data show HSC and HPC to be particularly fit for elements subject to axial and eccentric compression (the vertical parts of tall buildings, offshore platforms, prestressed structures) and exposed directly to atmospheric and environmental factors (polluted air, soil, sea salt, etc.). They let the dimensions of the cross-section of the elements become minimum and, in this way, increase the space for functional use. They are also applied widely in the construction of floors in tall buildings, greatly reducing their thickness. The application of HSC and HPC in civil engineering still requires some problems to be solved. Therefore international symposia are organised every 3 years in Stavanger (1987), Berkeley (1990), Lillehammer (1993) and Paris (1996). Some countries have already introduced codes authorising the use of HSC and HPC in building work (Norway, Finland, USA, Canada, Japan, Germany, Sweden, Holland). Other countries are working on such documents.

As regards the load capacity of columns made of these kinds of concrete and subject to axial and eccentric compression, the theoretical assumptions have been confirmed by test results. The brittle failure of concrete columns requires strong lateral reinforcement with stirrups. Similarly, in the case of bending elements, the proper use of the compressed zone of HSC is possible only for high degrees of beam reinforcement (Fig. 7). However, this is connected with the brittle character of the failure of that zone, which requires stronger reinforcement with stirrups [9].

Due to the cracking-limit state, the minimum reinforcement degree of tensile zones increases significantly and in bending elements are: (i) for C30 concrete and S400 steel, $\rho = 0.22\%$; (ii) for C60 concrete and S400 steel, $\rho = 0.32\%$ and (iii) for C90 concrete and S400 steel, $\rho = 0.40\%$.

The increase of the cracking resistance of the cross-section in prestressed structures grows proportionally in relation to the ratio $\kappa = 0.38 f_{ck}/f_{ctk0.05}$. The ratio is: (i) for C30 concrete, $\kappa = 6.0$; (ii) for C60 concrete, $\kappa = 8.4$ and (iii) for C90 concrete, $\kappa = 10.0$.

From the above specification it is seen clearly that towards the end of the 20th century there appeared a new generation of high quality concrete which will gradually replace plain concrete in civil engineering practice. The new type of concrete has already made it possible to build such structures as the following.

1. Offshore structures in Norway: Gullfaks C (1989, mean strength of concrete $f_{cm} = 75$ MPa, height of platform 262 m); Sleipner A (1993, $f_{cm} = 78$ MPa, water immersion 83 m); Troll Gravity Based Platform (1995, $f_{cm} = 82$ MPa, water immersion 303 m).
2. Cable-stayed bridges in Norway: Skarnsundet (1991, $f_{ck} = 60$ MPa, span of 530 m); Helgeland (1991, $f_{cm} = 73$ MPa, span of 425 m); in France: Perthuiset (1988, $f_{cm} = 80$ MPa, span of 110 m); Normandie (1995, $f_{ck} = 60$ MPa $- f_{cm} = 68$ MPa, span of 856 m).
3. Girder bridges in Norway Varrod: (1994, $f_{ck} = 65$ MPa $- f_{cm} = 73$ MPa, span of 260 m). Raftsundet (1998, $f_{ck} = 65$ MPa, span of 298 m); Joigny (1989, $f_{cm} = 78$ MPa, span of 40 m) and Sylans/Glacieres (1989, $f_{cm} = 68$ MPa, span of 60 m) in France (Fig. 8).
4. Tall buildings in the USA: Peachtree Centre in Atlanta (1991, $f_{cm} = 83$ MPa, height of 263 m); 311 South Wacker Drive in Chicago (1990, $f_{cm} = 84$ MPa, height 292 m); Union Square in Seattle (1989, $f_{cm} = 115$ MPa, height 220 m); in Germany: Trianon Hochhaus Deutsche Bank (1993, $f_{ck} = 85$ MPa, height 186 m) and Japan Centre in Frankfurt am Main (1994, $f_{ck} = 105$ MPa, height 115 m); or the Kuala Lumpur City Centre in Malaysia (1996, $f_{cm} = 100$ MPa, height 452 m), the highest building in the world at present (Fig. 9).

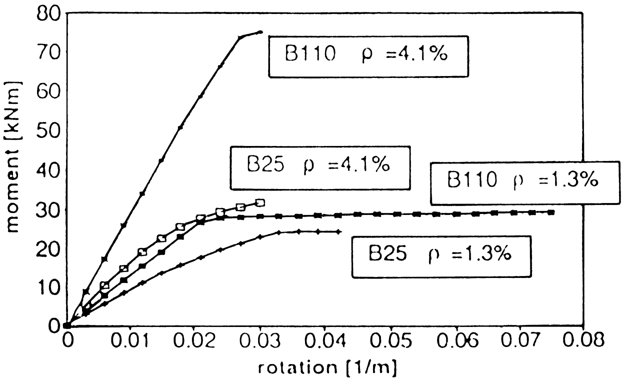

Fig. 7. The relationship "moment–curvature" in bending elements made of plain concrete (B25) and HPC (B110) [9].

The examples quoted above show that the HSC/HPC concretes have entered the building industry world-wide and enabled the construction of objects of unprecedented sizes.

It could also be mentioned here that due to higher hydration temperature, in massive elements made of these concretes the strength drops by 10–15% when compared with 28 day hardened concrete at ambient temperature $t_a = 20°C$. This should be taken into account when defining the characteristic strength of these concretes using a factor reducing χ by the value [9]: $\chi = 0.95(1 - f_{ck}/600)$.

The resistance to fire of HSC/HPC concretes can be improved by the addition of polypropylene fibres. At high temperatures the fibres melt, leaving in the concrete structure tube-like hollows in which the water of hardened concrete expands. The steam can then evaporate outside through the side surfaces without damaging spalling of the concrete, which later reduces the load carrying capacity of the structure.

6. Other advanced elements in concrete structural materials

From amongst many, two may be mentioned.

1. The introduction of glass (GF), carbon (CF) and aramid (AF) fibres as tendons to prestressed structures [4]. These tendons are usually used as either wires or wire strands with about 60–65% epoxy resin matrix fibres, modified appropriately. Their main advantage is lightness (density about five times lower than that of steel), and similar strength, lower modulus of elasticity and lower failure elongation than those of steel (see Table 1, [12]). The σ–ε characteristics for these tendons are close to linear, hence their brittle failure.

Fig. 8. Viaduc de Sylans on the A40 Motorway in France.

2. The common use of fibre concrete most often reinforced with steel fibres (such as "Harex", "Dramix", etc.) for shotcretes used in tunnel shell, repair and reconstruction work of bridges or cooling towers, wear resistant heavy loaded floors of storehouses. The main advantage of concrete reinforced with steel fibres is not only two times higher than its tensile strength, but also several times higher its ductility, measured by increase of the fracture energy G_F or the so-called toughness index calculated as the ratio of the areas F_1/F_2 (Fig. 10).

Fig. 9. Kuala Lumpur City Centre, the world's tallest building [10].

In the author's experience [13] the fracture energy increases (as compared with that of non-reinforced concrete) in the case of fibre addition $v_f = 0.5\%$ (by weight) was found to be 207%, for v_f=1.0–457% and for v_f=1.5–678%. This is an essential problem in members under repeated variable loads, impact loads, etc.

To reduce the splash loses in the case of fibre shotcrete, silica fume is frequently added.

Finally, the SIFCON method should be mentioned, which was worked out in Germany to reinforce the damaged concrete pavements of roads and airport lanes as well as in the ceiling of buildings. In this method mild steel bars were completely substituted for steel fibres to a quantity in excess of 10% by volume. The fibres are scattered on the cleaned surface, slurred with high quality cement base mortar and consolidated with a float vibrator.

This material has a compressive strength of about 90–105 MPa and a tensile strength in bending of 35–45 MPa. It well interacts with the base, and does not need expansion gaps or demolition of the existing pavement. The composition of the high quality mortar can be as follows [11]: cement PZ55, 1000 kg/m^3; sand 0/0.7 mm, 860 kg/m^3; water, 330 kg/m^3; silicasuspender, 13 kg/m^3 and superplasticiser, 35 kg/m^3.

7. The renaissance of wood

Wood has always been one of the basic building materials. However, considering its limited life (15–25 years) and lack of moisture resistance and fire resistance, wooden buildings

Table 1
The tendon types and its details

Lp.	Tendon type	Fibre content (%)	Diameter (mm)	CS area (mm^2)	f_{py} (MPa)	E_p (GPa)	ε_u (%)
1	CF-strand	64	12.5	76.0	1885	138	1.6
2	CF-bar	65	8	49.0	1550	148	1.2
3	GF-bar	62	8	50.0	1480	44	2.6
4	AF-bar	65	6	28.3	1777	53	3.3
5	Steel-strand 7Ø5	100	15.2	138.7	1629	197	3.5
6	Steel-bar	100	9.3	51.6	1086	197	3.5

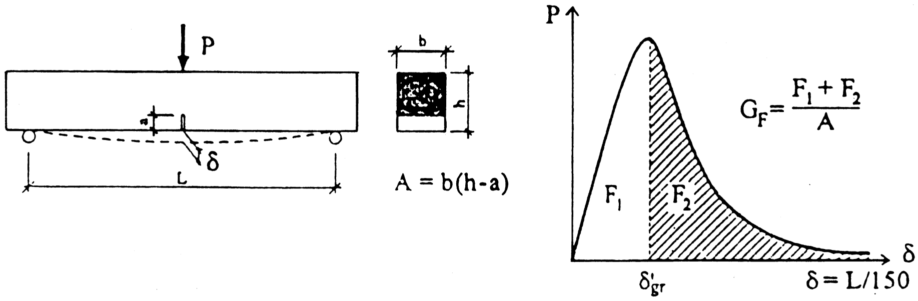

Fig. 10. The relationship P–δ for a beam of fibre concrete. G_F: fracture energy; F_1/F_2: toughness index [13].

have always been only temporary. That is why only few such buildings have survived (e.g. Kappelbrücke bridge in Lucerne, from 1333).

In the 20th century, despite such competitive materials as steel and concrete, wood retained its significant role in building in many developed countries (USA, Canada, Russia). It was possible due to the progress in woodworking and processing technology in the last 40 years which resulted in the following [14]: (i) the durability of modern wooden structures, owing to proper preservation, matches that of structures from steel and concrete and (ii) the wooden structures built at present are almost exclusively made by means of industrial methods of producing elements or whole objects, which significantly reduces labour consumption.

Natterer [15] from Lausanne, one of the greatest advocate of wooden structures, says that if we want to save the forests we should build of wood. In most countries forests are sick and the timber from these forests can be used to make girders from several layers of boards glued together. This gives in effect a very good and relatively cheap structural material (as compared with concrete and steel).

In modern structures wood is used in the form of: (i) traditional solutions in which solid timber, of local sort or imported, is used and (ii) solutions based on the technology

Fig. 11. A pedestrian timber ribbon bridge in Essing (Germany), span of 73 m.

Fig. 12. Timber roof structure of the Olympic hall in Hamar (Norway), span of 250 m.

of laminated timber, which makes it possible to produce large size structural elements or whole spans.

In both cases progress has been made due to: (i) new industrial technologies of production, preservation and chemical modification of wooden structures; (ii) the application of high strength timber and (iii) new construction solutions adapted to modern technologies.

Wood was the material of which were made the beautiful pedestrian bridge in Essing over the Rhine–Main–Danube Channel (Fig. 11) [16] and roofs of the Olympic halls in Hamar and Lillehammer for the Winter Olympic Games in 1994 (Fig. 12).

In the 21st century this material, easily available in nature, workable and light in weight, will undoubtedly serve as a supplement for concrete and steel structures, with all the modifications described above.

8. Other construction materials

Materials such as glass or plastic must not be neglected in this account. So far both have been used to produce finishing details of buildings. However, there is already on the Polish market [17]: armoured glass (flameproof Pyroshield, fire-protecting and fireproof Pyrostop and Pyrodur), and multilayer laminated glass (called multifloat: Standard — safety glass, Atak stop — breaking-proof, Supreme — bullet-proof, Hartfloat — hardened, structural glass).

Many of these types of glass have high mechanical strength, three to six times greater than that of plain glass, high thermal resistance and resistance to temperature changes (up to 150 K) and do not cause injury when broken. They can carry heavy loads in building facades, glazed roofs and skylights, screens and windows in sports objects, hospitals and schools, and noise shields in streets and highways.

As far as plastics are concerned it has to be said that progress in the field of chemistry of plastics goes forward much quicker than in the domain of other construction materials. Therefore it should be assumed that in the coming years new construction materials based on high-molecular weight polymers will compete successfully with traditional materials.

Plastics are very suitable for use in building structures, especially because of their lightness (mass density $\rho = 1000-1400\,\mathrm{kg/m^3}$), high chemical resistance, high light transmittance, dyeability in the cake, ease of forming. The most important disadvantages of plastics are: low coefficient of elasticity, high rheological deformability, low thermal resistance and ageing caused by UV radiation. The tensile strength of plastics without reinforcement is 10–80 MPa, but an efficient reinforcement with glass fibres enables an increase of this value to 130–600 MPa (in the direction parallel to the fibres) [18]. The modulus of elasticity of plastics is relatively low (2 GPa), but plastics reinforced with glass fibres can achieve values comparable with that for steel (55 GPa).

Modern chemistry tries to neutralise the disadvantages of plastics by adding compounds that are able to absorb UV energy and re-emit it as waves of greater length, which have no destructive influence. The flammability of plastics is being limited by the application of additives, which stop fire after the removal of a flame. The introduction of the reinforcement causes not only significant increase of the tensile strength and the modulus of elasticity, but also considerably prevents plastics from creeping.

The above limitations have resulted in plastics being applicable only as secondary construction materials in civil engineering [19]: (i) in laminar elements (“sandwich” type); (ii) in translucent elements and structures such as skylights, roofs and walls and (iii) in 3D structures.

Amongst the 3D structures in which plastics are used are: folded plate structures, membrane structures made of reinforced resins, rigid cellular plastics, film and fabric, spherical domes and pneumatic structures. In the most cases the above-mentioned structures act together with steel tendons.

There are also well-known and still-being-developed applications of construction plastics as polymer–concrete (PC), polymer–cement–concrete (PCC), neoprene (chloroprene rubber) bridge bearings and plastic chimneys with an outer steel body (used in the case of the high corrosive power of fumes). Plastics play a very important part as glues, used as wood adhesive (in laminar girders), and as concrete adhesive (in the free cantilever method of bridge assembly for joining prefabricated elements). Resins are also useful in repair works for injecting cracks in concrete and masonry structures and in the fastening of steel or CFRP band elements used for the strengthening of concrete and steel structures.

From the foregoing it is clear that the area of applications of plastics in civil engineering is very wide. It serves not only as a complement, but often is responsible for the proper work of the traditional construction materials: steel, concrete, ceramics and wood.

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