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Structural Engineering in Arctic Regions

Structures de génie civil dans les régions arctiques

Konstruktiver Ingenieurbau in arktischen Regionen

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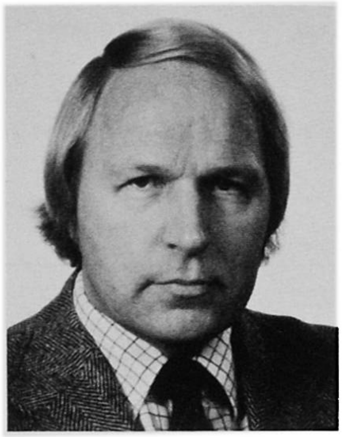

Pauli Jumppanen, born 1937, received his civil engineering degree in 1967 and his doctorate in structural mechanics in 1971 at the Helsinki University of Technology. First involved in bridge design and teaching, he came to the Technical Research Centre in 1978. He is now responsible for the research on structural engineering and design in arctic regions.

SUMMARY
The report outlines the most important features of structural engineering in arctic conditions. It discusses in general terms the influence of environmental factors on the selection of building materials and the design of load-bearing constructions. Durability problems with steel and concrete materials as well as in the corresponding structures are treated in more detail. Brief consideration is also given to structural systems and construction methods suitable for the arctic environment.

RESUME
Le rapport présente les caractéristiques essentielles des structures de génie civil dans les régions arctiques. Il passe en revue l'influence de facteurs environnants sur le choix des matériaux de construction et sur le projet des structures porteuses. Les problèmes de durabilité avec des matériaux en acier et en béton sont traités en détail de même que les structures correspondantes. Quelques considérations sont faites sur les systèmes structuraux et les méthodes de construction appropriées dans un environnement arctique.

ZUSAMMENFASSUNG
Die wichtigsten Merkmale des konstruktiven Ingenieurbaus in arktischen Regionen werden umrissen. Der Einfluss von Umweltsfaktoren auf die Wahl der Baustoffe und den Entwurf von Tragwerken wird generell erörtert. Anschliessend werden eingehender Probleme der Dauerhaftigkeit der Baustoffe Stahl und Beton sowie damit erstellter Bauwerke behandelt. Zum Schluss wird noch kurz auf die für arktische Regionen geeignetesten Tragwerkssysteme und Baumethoden eingegangen.

1. INTRODUCTION

Several definitions related to the scope of interest have been given to arctic regions around the North Pole. Definitions based on average temperature or the warmest month of the year as well as on the boundaries of the forest zone or the northern lights region have been used in natural sciences. Very convenient limits from the technological point of view are the boundary of the permafrost area on the land and the maximal extension of the ice cover on the sea. According to this definition, more than 60 % of Alaska, about the half of Canada and the Soviet Union, and some parts of Scandinavia and China are included in the arctic region (Fig. 1).

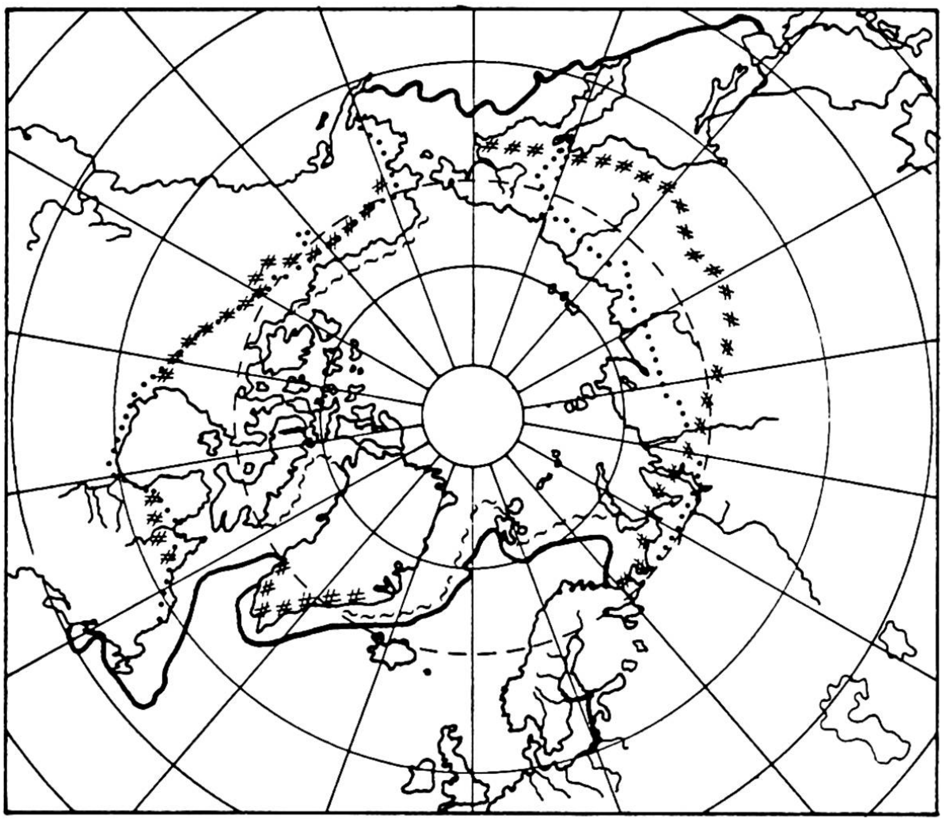

Fig. 1. Definitions of the arctic region from the technical viewpoint:
······· boundary of forest zone
boundary of permafrost area
~~~~~ boundary of arctic water region
⁓⁓ average maximal extension of sea ice.
~~~~~

In the so called subarctic regions, where the cold climate, frozen ground and the appearance of heavy snow cover cause difficulties for building and transportation activities, the problems and also the technical solutions are to a large extent similar to those in arctic conditions. As far as the antarctic region is concerned, the environmental factors are still more extreme than in the Arctic. The technology developed for arctic applications can form a starting point for the future utilization of natural resources in the Antarctic.

Traditionally, fishing and whaling have been major activities in arctic waters. In the nineteen fifties and sixties, the development of the forest products industry and the building of hydroelectric power plants gave an economic stimulus in arctic regions. In the mid-seventies, the dramatic increase in the price of oil changed the situation totally. The exploration for arctic oil and natural gas began on a large scale. More extensive mining of coal in northern Canada and the Soviet Union is also envisaged. Mining metals such as copper, gold, nickel, lead, silver, zinc, cadmium, titanium, etc. and other minerals and building materials such as asbestos, limestone, pyrophyllite, shale, gypsum etc. has been a traditional activity in certain parts of the Arctic. The importance of mining is increasing rapidly because of the industrial need for some important raw materials and a special need for certain strategic metals. Mineral resources both in the permafrost areas and on the continental shelf will be exploited on a large scale in future decades.

The exploration and the exploitation of arctic energy, mineral and material resources require many kinds of building operations on the land and in the sea, e.g. building of roads, bridges, factories, power stations and harbours as well as facilities for the exploration, production and transportation of oil, natural gas, coal and minerals. It is a challenging task to carry out building projects in the Arctic from the viewpoint of both technology and management. The problems orginate from the cold climate, the presence of ice, snow and permafrost, long distances and inadequate transportation network, lack of local labour and building materials, the fragility of the nature, and from many other of factors varying importance. Technological difficulties and strict safety requirements demand special care in the planning of building operations and in the design of structures.

The purpose of this paper is to give a short introduction to basic problems in the design of structures and the selection of materials to be used in an arctic environment. A brief mention is also given to environmental factors and their influence on construction methods in the Arctic.

2. ENVIRONMENTAL CONDITIONS

2.1 Cold climate

Cold climate influences materials and structures as well as practical construction work. In winter, the lowest temperatures in the continental regions and on the arctic islands can be below -60^{o}C. The temperature can stay below -50^{o}C for several weeks at a time. Since the summer temperature can reach values between +30^{o}and +40^{o}C, maximal temperature variation in some areas can be close to 100^{o}C.

On the coast and in sea areas, the climate is milder and the lowest temperatures in many places are between -30^{o}C and -40^{o}C. The working conditions are made difficult by strong winds and the combined effect of wind and low temperature. This effect is measured by the so-called windchill-factor. Values of the factor are given in several handbooks and publications. For instance, the temperature -40^{o}C and wind speed 0,5 m/s has the same effect as the temperature -7^{o}C with wind speed 20 m/s.

2.2 Snow and ice

Amounts of rain in the Arctic, especially in the tundra region, are quite small. Similarly, the snow cover is in general thin and the snow loads on roofs and horizontal structures somewhat less than in the subarctic region, in most areas 70 kg/m^2 or less.

The main problems are caused by moving snow and the accumulation and packing of snow against buildings or in other special places. The transportation of snow starts when the wind speed is more than 10 m/s and increases rapidly after the speed 15 m/s. The density of pack ice can reach the value 300...500 kg/m^3, and in multiyear snow fields the value 700...900 kg/m^3 which is close to the density of ice.

On the sea, ice loads and their effects raise the most serious problems for structures and building operations. Ice loads are caused by the movement of ice cover (thermal, wind, currents), first-year or multiyear pack ice layers and ice ridges, and floating icebergs. The maximal thickness of ice cover on arctic seas varies from one to three metres, the thickness of pack ice from 3 to 5 or more metres, and the thickness of ridges up to 50...70 metres.

Although ice conditions and ice loads on structures have been studied by numerous researchers and institutes in recent years, many unsolved problems remain, such as loads caused by multiyear ice, ice loads on large scale structures (harbours, artificial islands), and problems resulting from ice jams and break-up of ice in arctic rivers.

The development of ice and snow control, management systems for building sites, and large field operations are also needed. This is necessitated by differences in local conditions and possible rapid changes in weather. The systems can be based on weather forecasts or on special satellite, flight and field observations. The local control can be based on field measurements, special geometry of buildings, protective structures etc.

2.3 Permafrost

The most dominating phenomenon when building on land in the Arctic is the permafrost. The thickness of the frozen layer varies from a few metres to as much as 1500 metres. The permafrost can be continuous, discontinuous or composed of several types of local formations, such as of pingos and palsas.

The soils on the surface melt annually to a depth which can be evaluated from the formula (z in cm)

$$z = k \cdot \sqrt{\sum_i h_i T_i}$$

where h is the time (in hours) and T the temperature (in ^{o}C). $\sum h \cdot T$ is then the time-temperature amount of the warm period of the year and k the coefficient depending on the soil type and surface vegetation. k varies from 0.5 to 1.5. The depth of the melted layer, the so-called active layer, is between 0.5 and 2.0 m in a continuous permafrost and between 0.7 and 5.0 m in a discontinuous permafrost.

The appreciable strength of frozen soils can be utilized in many ways in building operations in the permafrost area. The problems are basically caused by the melting of frozen soils. The active layer is typically very moist and has a very low load-bearing capacity. Also a more extensive melting of permafrost can take place during a warm period e.g. in the case of flooding. The harmful effects of soils produced by melting are the thermokarst process, which maintains a continuous melting process in the permafrost, thermoerosion and material transportation with running water, and local or even larger earth-slips in the ground.

2.4 Other environmental factors

In addition to the factors mentioned above, arctic regions have many other special features which need to be taken into account in the design of structures and the planning of construction works. Such features include:

- Low visibility and darkness caused by the long winter period, fog, seedust, and moving snow.

- Restricted variety of local building materials available.

- Erosion and transportation of soil materials due to rivers, floods and sea currents.

3. BUILDING MATERIALS

3.1 Local materials

In arctic construction building materials are often used on a large scale. Examples of very large constructions are platforms and artificial islands used in the exploration and the production of oil and natural gas, pipelines, industrial plants, roads and bridges for large loads, power plants etc. The need to utilize local materials wherever possible is therefore obvious.

Ice cover in seas and rivers can be used for transportation, and also some building works can be carried out using the bearing capacity of ice. The thickness of the ice cover can be increased e.g. by pumping water onto the ice or by using cooling machines. Ice can also be reinforced by timber products, steel bars or cables, plastic fibres etc. Also for road and foundation construction the use of ice as the natural or reinforced material appears to have some potential.

Sand and gravel are generally obtainable from river banks and the sea bed. These materials are needed especially for roads, foundations, harbour structures and artificial islands. Their use both in a non-frozen and a frozen condition is possible. Sand and gravel can also be used for making concrete in the Arctic, and local aggregate materials often give very good durability in concrete structures.

The availability of mining slacks as well as crushed stones and rocks will increase as mining activities increase. Materials of this kind can also be used for concrete aggregates and road construction.

There are extensive timber resources at low latitudes of the permafrost areas. Several kinds of raw materials for the building industry can be obtained from the arctic ground. However, the manufacture of building products and components usually takes place in industrial plants outside the arctic region.

3.2 Materials of load-bearing constructions

Basic materials in arctic construction are the usual steel and concrete. Advantages of steel are good availability, adequate range of special steel qualities, possibilities of using both welded and bolted connections, and finally low price. The main problem in steel construction arises from the brittle fracture behaviour of steel at low temperatures. Another serious problem is the corrosion which takes place, especially in the aggressive sea climate.

The toughness of steel is generally measured by the well-known Charpy V-test. By means of measured energy absorption values, a fracture toughness curve is drawn and the so-called transition temperature between brittle and plastic fracture behaviours is determined. For structures in an arctic environment subjected to dynamic loading (e.g. bridges, vessels, platforms), the steel material must satisfy the fracture toughness requirements at temperatures between -40^{o}C and -60^{o}C.

The toughness of a steel material can be increased

- by decreasing the strength and the grain size of the steel and

- by using magnesium, nickel, copper, chrome and possibly some other ingredients in the steel.

The best structural steel in welded constructions for an arctic environment is often fine-grained medium-tensile steel with high fracture toughness values (Fig. 2).

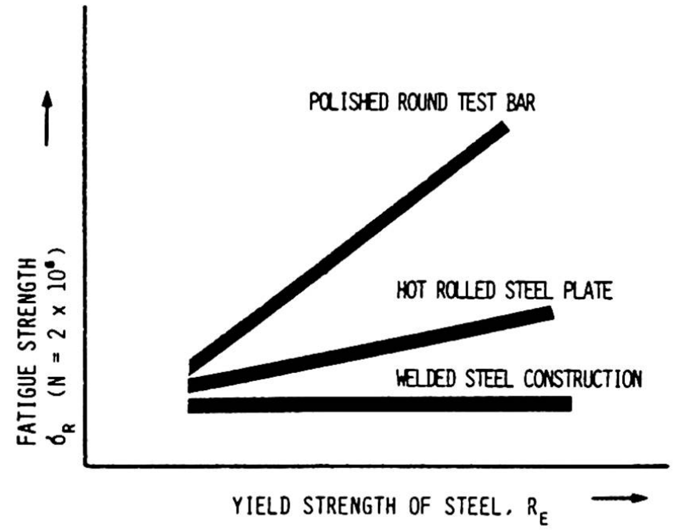

Fig. 2. Interaction between fatigue strength and yield strength of steel. The picture shows that high yield strength values cannot be utilized in welded constructions.

The advantages of concrete in arctic construction include the possibility of using local raw materials, sturdiness and suitability for gravity structures especially in the case of ice loads, good protection against wearing and corrosion, and high fire resistance qualities. In construction projects, the use of either prefabricated structural members or in situ concrete is possible.

The strength of concrete generally increases with decreasing temperature (Fig. 3). The basic problems with concrete construction are concreting works in the cold climate and the durability of concrete in the arctic environment. Special methods for making concrete at low temperatures are often based on heating and protection and on the use of some admixtures. The aggregate and the water can be preheated up to +70^{o}C before the concreting. The temperature of fresh concrete during casting must be between +5 and +40^{o}C. The cast concrete members must be heated and protected until a required strength against the freezing is reached. The admixtures most used for better handling of fresh concrete are freezing point reducing agents and plasticizers. Accelerators can be used for reducing the need for protection.

The main reasons for durability problems with concrete are the freezing of fresh concrete before hardening, the effects of the freezing-melting process in the long term, and the corrosion of concrete especially in a sea environment.

The freezing of fresh concrete causes some expansion of 2 %. The accumulation of ice inside the structure and a considerable loss of strength are possible. Large variations in temperature and the humidity cause a repeated freezing and melting process in concrete. Several freeze-thaw cycles can easily damage the surface parts of a concrete structure. Resistance to freeze-thaw behaviour is based on the optimal porosity of concrete which allows the movement of moisture and the expansion of freezing water in pores. The porosity can be increased to a required level by using air-entraining agents in the manufacture.

Corrosion risks of concrete appear mostly in the sea environment and are caused by clorides, sulphides and carbon dioxide in sea water. Also bridges and other structures in rivers are subjected to corrosion to some extent. The corrosion usually starts from small cracks and leads in the first stage to some deterioration of the concrete surfaces. The corrosion of reinforcing steel takes place in the second stage and results in some loss of safety in the long term.

Resistance to corrosion can be increased in several ways. Some possible methods are increasing the tightness of concrete by prestressing, the use of special materials and ingredients in the concrete mix (e.g. special hydraulic cement) and the use of non-corrosive or specially protected reinforcing steels. The use of copper or zinc has been considered in this connection.

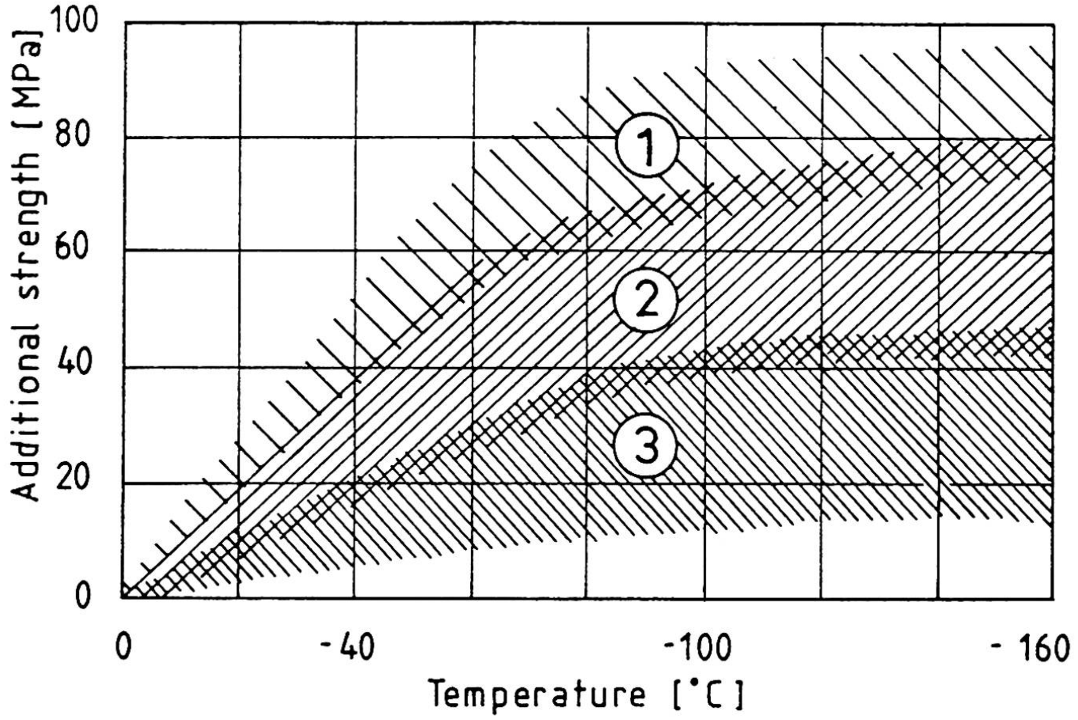

Fig. 3. The effect of temperature decrease on concrete strength in the case of 1) wet concrete 2) moist concrete and 3) dehydrated concrete (+105^{0}C).

3.3 Other building materials

There are several other building materials in addition to steel and concrete which can be successfully used in the arctic climate. These include wood, aluminium, brick and block products and some plastics. Insulation materials for thermal, frost and acoustic insulation as well as coatings and protection materials are also needed on a large scale. These are not considered in this paper.

Wood retains its mechanical properties very well in the frozen condition. Also glued wood products, such as plywood and glued beams and arches, can be used if the glues used in their manufacture are suitable for the required temperature and moisture states. Timber constructions are mostly used for housing. Application in small bridge construction could also be possible.

Aluminium would be an ideal material because of its good processability, high strength values, and high corrosion resistance. The large-scale use of aluminium is prohibited by its high price. Possible objects of use are light gauge plates and profiles for buildings, light offshore modules, mast structures, storage tanks etc.

The applicability of bricks, blocks and other light-weight material products is quite limited, there being problems connected with possible moisture and frost damage. Therefore the strength values as well as porosity and moisture properties should be checked before use. On the other hand, the use of light-weight concrete has aroused quite a lot of interest because of the advantages in transportation both on land and sea.

4. DESIGN OF STRUCTURES

4.1 Loads and actions on structures

The load-bearing structures are normally dimensioned for their own weight, service loads, and wind and snow loads. In the case of harbour and marine structures, also the effects of waves and currents are to be considered. In arctic regions several other loads and effects must be taken into account. The following list contains the most important factors for the design of structures in the Arctic.

Ice loads are of primary importance in the design and dimensioning of harbour and off-shore structures as well as of bridges. The basic load types are:

- static loads from the pressure of ice cover and ridges

- dynamic loads caused by moving ice and the combined effects of ice and waves

- impact loads from floating ice and icebergs.

Other effects caused by moving ice are wearing and scouring phenomena. Scouring of the sea bottom and marine foundations is often caused by movements of icebergs and large ridges. In the most serious cases the scores can have a depth up to 20 m. Worthy of mention is still flooding of rivers raised by the break-up of ice or ice jams. The combined effects of running water and ice often cause very high loads on bridge structures.

Special influences on arctic design also result from the low temperature values and the large temperature variations as well as large differences in the summer and winter temperatures. Material effects which have to be considered are the brittleness of metals and the freezing as well as the freezing-melting process in porous materials. In strength calculations, large thermal stresses especially in massive structures must be taken into account.

4.2 Foundations

In the building of foundations on land in the Arctic, the main problems arise from the yearly melting of permafrost, risk of additional melting caused by the heating of structures, movements of soils, and extensive floods.

The design of foundations can be based on the following three principles.

- Utilization of zones free of permafrost where the stability and the load-bearing capacity of soils are adequate.

- Maintaining the soils in a frozen condition by the use of special constructions.

- Allowing the melting of frozen soils up to a certain dimensioning depth.

The second alternative is maybe the most common in arctic construction and is generally based on the use of pile foundations. The piles are driven in to the required depth (3...5 m) inside the permafrost and a free air space between 0.5 and 1.5 m is left between the structure and the earth's surface. Special pile types, where the heat flow along the pile is prevented, have also been developed. Another method, specially applied to light-weight structures, uses a sufficient layer of some insulation material under the structure.

The third alternative method mentioned above can be used only in special cases. If a soil has a very good load-bearing capacity and small deformations in the melting and freezing process, or if there are rocks or other stable solid layers close to the earth's surface, the melting up to some calculated depth can be allowed.

4.3 Structural systems

Ice conditions and ice loads play a very dominant role in the planning and design of marine structures. Ice phenomena in rivers, such as effects of ice jams and break-up of ice, also have appreciable influences on bridge design. When building on land, the main problems are not associated with structural design. Basic problems are generally involved with the material selection, the transportation, and the construction methods on the building site. This fact has had a significant influence on structural systems used in the Arctic. Instead of building on site methods more advanced systems consisting of prefabricated elements, space units, small- or large-scale modules have been developed in great numbers.

Steel structures have very good prospects in arctic construction. Typical applications are caisson-type structures for harbours, terminal structures, oil and gas pipelines, factory buildings, warehouses, towers, buoys, masts, bridges etc. Construction units of steel can be manufactured in a factory, transported to the building site, and assembled by welding or bolting. A trend towards using very large modules with a high stage of prefabrication is obvious e.g. in the building production plants, factories and office buildings.

The design of arctic steel structures is quite similar to that in the sub-arctic climate. In the selection of steel material for welded and dynamically loaded constructions, the toughness criteria must be taken into account. Careful dimensioning should also be made for the fatigue of the total construction and for the stresses caused by the combined effects of snow and wind as well as by large temperature variation. High-quality corrosion protection is also required especially in the aggressive sea climate, because the preparing of the protection in an environment like this is sometimes quite impossible.

Concrete structures have certain special advantages in arctic construction as mentioned earlier. Typical objectives of use are caisons and other harbour structures, foundations in general, industrial plants and power plants, storage buildings, bridges etc. Both construction with on site methods and prefabricated construction units can be used in building with concrete. In the former case, the compatibility of water and local aggregates should be tested beforehand.

In the design of concrete structures, special attention should be paid to the corrosion resistance, the fatigue, and the thermal stresses in solid structures. Corrosion protection can be based on the high quality and the successful selection of materials of concrete mix, optimal tightness of protection layers, prestressing, and the protection of reinforcing steels. Although the fatigue properties of concrete structures are in general good, extensive diagonal cracking and low-cycle fatigue failures can sometimes take place especially in the presence of cyclic shear and torsion. Brittleness of reinforcing steel can in such a case cause damage to the total structure.

Thermal stresses in massive structures are usually larger than e.g. in steel structures. In concrete structures, the highest stresses are appreciably reduced by the creep of material. On the other hand, continuously repeated creep effects cause forced stress in the structure. Very careful study of the effects arising from low temperatures and large temperature variations is therefore to be recommended.