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Material and construction solutions of war shelters with the example of Hitler's main headquarters in the Wolf's Lair

Rozwiązania materiałowo-konstrukcyjne schronów wojennych na przykładzie kwatery głównej Hitlera w Wilczym Szańcu

Abstract
The technology of erecting war shelters has been evolving over the centuries alongside the development of technology and building-oriented requirements. Many papers have been published on this subject in recent times. The ruins of the Wolf's Lair war fortress prompted the authors to write this work with a slightly different emphasis than the previous papers. In addition to a brief history of the objects, the work presents the design guidelines used in their construction and describes the construction solutions applied. In addition, where appropriate, the advantages and disadvantages of these construction solutions from an engineering point of view are highlighted.

Keywords: concrete building , war shelter, Wolf's Lair

Streszczenie
Technologia wznoszenia schronów wojennych ewaluowała na przestrzeni wieków wraz z rozwojem techniki i stawianych obiektom wymagań. Pozostałości po twierdzy wojennej Wilczy Szaniec skłoniły autorów do napisania tej pracy – o nieco odmiennym charakterze niż dotychczasowe. Prócz krótkiej historii obiektów w pracy przedstawiono ówczesne wytyczne wykorzystane w konstruowaniu obiektów oraz opisano zastosowane rozwiązania konstrukcyjne. Dodatkowo opatrzono je stosownym komentarzem inżynierskim.

Słowa kluczowe: budownictwo betonowe, schron wojenny, Wilczy Szaniec

1. History, location and military significance of Wolf's Lair

During World War II, a dozen or so fixed headquarters of the occupying forces were established in Europe, serving as command centres for the war front. They were usually found in the mountains and in areas surrounded by lakes and marshes; they were always near the fronts in areas difficult to penetrate. On the whole, they were powerful, massive reinforced-concrete buildings and bunkers. The most famous and most frequently discussed military quarters is Wolf's Lair, located in the Kętrzyn Forest in Masuria (near the former border with the Soviet Union – Fig. 1). The construction of Wolf's Lair was entrusted to the 'Todt' organisation, which under the guise of building the 'Askarnia' chemical plants, began construction work in the autumn of 1940. The construction and extension of the fortress can be divided into three stages: 1940–1941, 1942–1943 and 1944.

Fig. 1. Location of Wolf's Lair [1]

The works started with the modernisation of the railway station in Kętrzyn, the construction of a large platform, railway sidings and utility infrastructure. The forest road to Kwidy (Queden) was paved and the road to Kętrzyn was asphalted. The lifetime of Wolf's Lair was planned for the Blitzkrieg led against the Soviet Union, which was scheduled to start at the beginning of May 1941. At the time of Hitler's arrival at Wolf's Lair (24.06.1941), the quarters consisted of eight single-storey, terrestrial concrete bunkers and several wooden and masonry buildings. Some of these were equipped with metal doors and shutters (in case of an air attack) and rubber seals (in case of a gas alarm).

In the summer of 1942, as a consequence of the prolonged war with the Soviet Union, the 2nd stage of construction commenced. Due to the growing number of persons occupying the quarters, wooden barracks were mostly built – these housed office and residential areas. Due to the risk of air raids, some of these were strengthened with reinforced concrete.

In April 1944, due to the approaching eastern front, the third phase of the extension commenced in Wolf's Lair. Some of the existing concrete buildings were strengthened at that time: Hitler's shelter, the guesthouse (No. 6), two teleprinter terminals. Other shelters were constructed from scratch: for Goring (No. 16), for Martin Bormann (No. 11) and for public use (No. 26). The above-mentioned objects were created on the principle of double walls and ceilings, between which, there was 700 mm of space filled with basalt grit or gravel. In the event of bombing, these would absorb the shock. The complex of facilities built in the years 1940-44 occupied an area of 250 hectares. In total, there were about 200 objects of different sizes and uses, including 7 heavy anti- aircraft shelters, dozens of masonry and concrete buildings and dozens of wooden buildings.

In October 1944, the Red Army troops reached the eastern borders of East Prussia. It could be assumed that its next target would be, above all, Wolf's Lair. For this reason, on 20 November 1944, the headquarters were transferred to Zossen, near Berlin. Two days later, on 22 November 1944, Field Marshal W. Keitel issued an order to blow up Wolf's Lair. The bombing of the shelters and barracks under the code name 'Inslsprung' was performed on the night of January 24th, 1945. These were the strongest explosions that shook the immediate surroundings. The large concrete blocks flew 20–30 meters. According to witnesses, shocks caused ice to crack in the nearby lakes. Polish sappers calculated that about eight tons of tritium had to be used to blow up one heavy shelter. The ruins of the blown-up bunkers, as well as many undamaged, lighter buildings, can now be seen in the state they were left in that January night in 1945. They only carry traces of time, and they perfectly present the construction solutions used.

2. Contemporary guidelines and regulations for the construction of bunkers

The technology of building shelters has evolved over the years. Further technological developments have been patented and systematised over time. The formation of the fortification zone, the placement of individual objects and their method of elevation have been the subject of scientific papers, textbooks and finally, standards.

The elaboration of detailed guidelines and norms for the construction of fortification objects was preceded by a number of trials and error attempts using different materials, technologies and construction systems.

The development of artillery, and in particular the use of threaded barrels, increased the range of guns, and new explosives increased artillery fire power. Forts have been erected using materials known for centuries – brick structures were surrounded by earthen ramparts and brick embankments. At the end of the nineteenth century, a few gun-resistant domes appeared on shelter ceilings these were cast from steel. However, steel is an expensive material, and although the casting technique of large cast iron and steel castings was developed a long time ago, the transportation and assembly of multi-ton domes has given rise to many problems, especially since the forts were often erected in terrains that were difficult to access.

A major milestone in the development of fortification was the development of Portland cement production technology in 1880. As a result of this, concrete allowed the mould to get any shape and significantly increased the resistance of objects to artillery fire in relation to brick and earth buildings. For comparison, the resistance to an explosion provided by a 300 mm concrete layer on the ceiling of a shelter corresponded to the resistance offered by a 2 m thick earth embankment. As a result of the explosion of a 155 mm demolition grenade, a concrete funnel with a depth of 0.6 m and a diameter of 2 m is formed.

France led the way in the field of the theory of fortification. Here, field tests of the construction and firing tests (Fig. 2) were carried out. The first norms shaping the formula of the concrete mixture were created here.

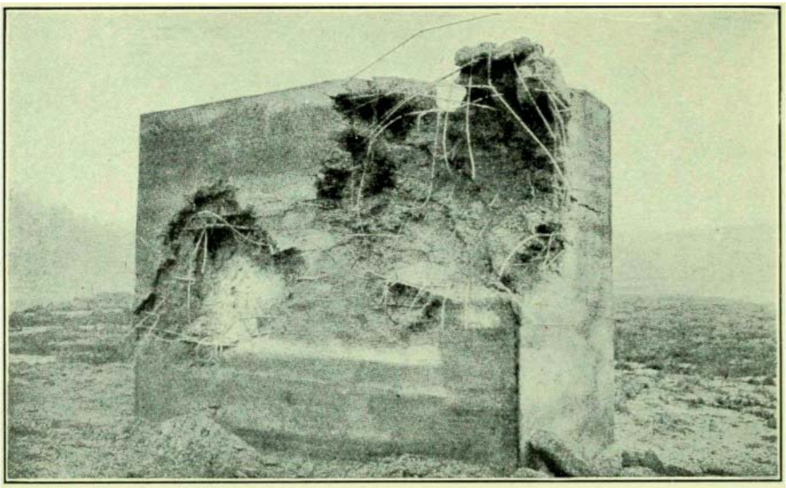

Effect of Two Shells on a Six-Foot Reinforced Concrete Wall

Fig. 2. Polygon test on a 1830 mm (6 ft) thick reinforced-concrete wall [2]

The French General Staff claimed that the construction of the mighty and extensive fortifications of the Maginot Line would protect their country from the greatest threat – the German army. This was the reason why the French focused on improving the building technology. Other European countries followed them, including Germany and Belgium. Table 1 shows the composition of the concrete mix used in the aforementioned countries for the construction of war buildings published in the paper [3]. In later years, the composition of concrete mixtures underwent changes due to technical progress and the development of construction techniques. Changes resulting from the geological structure of aggregates obtained locally from sources near to the construction were also introduced.

In the early nineteen-twenties and early nineteen-thirties of the twentieth century, strength and resistance standards of field fortification facilities were established. These classifications were mainly based on the determination of the resistance of walls and ceilings to the firing of demolition ammunition of a given calibre. Important data derived from the French guidelines for the classification of combat shelters is given in Table 2; this data was used by many countries at that time. The measure necessary for the classification of fortification objects was the reinforced-concrete penetration parameter. The relationship between the necessary thickness of the wall or the reinforced-concrete ceiling and the resistance to artillery fire is described by the following formula [4]:

$$S = \frac{10 \times \text{shell caliber}}{2} \; [\text{mm}]$$

This should be interpreted as follows: a 200 mm diameter pierced a 1 m reinforced-concrete wall or ceiling. Standards and classifications relating to resistance to fire provided the required construction parameters according to the object element.

The classification of the resistance of fortification objects was developed in nineteen-thirties Germany. This classification had four levels: A – resistance to direct artillery fire of a 520 mm calibre shell and the strike of an aerial bomb of up to 1000 kg; B – fire with a shell of 220 mm calibre and a single hit with a 500 kg bomb or 300 mm calibre shell; C – fire with shells of up to 105 mm; D – protection against shattering and fire from light artillery guns. The original classification was extended in 1938 (Table 3).

It should also be emphasised that it is essential to estimate the necessary expenditure for the construction of the fortification facilities. In the German literature of World War II, there was a list of the necessary quantities of materials and labour for the construction of

Table 1. Composition of the concrete mixture and the amount of steel used to construct fortifications in European countries in the early nineteen-twenties and early nineteen-thirties [3]

Material	Germany	Belgium	France
cement [kg/ m^3]	275	400	400
sand [m^3/ m^3]	0.40	0.40	0.30
aggregate (broken stone) [m^3/ m^3]	0.90	0.90	0.90
reinforcement [kg/m^3]	80-120	70	80

commonly erected, 5×5 m reinforced-concrete passive bunkers for one or two infantry units. The requirements and quantity of materials for such a shelter are given in Table 4, and requirements relating to the necessary construction personnel are provided in Table 5.

Although the layouts shown in the tables are relatively large, the construction of such shelters or whole lines of defence was several times cheaper than the development of weapons needed to break them. It was calculated that the construction of such a bunker was 2-5 times cheaper than the cost of the ammunition needed to destroy it. The durability and indestructibility of the shelters were of paramount importance from the perspective of military strategy – neither financial nor human resources were spared on their construction.

Table 2. French classification of combat shelters [4]

Shell diameter	380—420 mm		305—380 mm		210—305 mm		150 mm	
	plain concrete	reinforced concrete	plain concrete	reinforced concrete	plain concrete	reinforced concrete	plain concrete	reinforced concrete
front walls [m]	3.0–3.5	2.5–3.0	2.5–3.0	1.75–2.5	2.0	1.5	1.5	1.2
ceiling slab (with span of 3–4 m) [m]	2.5	2.5–3.0	1.75	2.1–2.5	1.3	1.5	1.0	1.1

3. Main construction principles

In the early nineteen-twenties and early nineteen-thirties engineers have set some rules regarding the erection and maintenance of fortification objects. Technological advances, World War I experiments and field laboratories, and numerous field trials have contributed to the formulation of several important (obvious in today's construction) conclusions. It was noted that:

Table 3. German classification of the resistance of fortification objects to artillery fire from 1938 [4]

Resistance class	Thickness of external walls [m]	Ceiling slab thickness [m]	Thickness of internal walls [m]
A	3.5	3.5≤	1
A1	2.5	2.2	1
B-neu	2	2	0.8
B	1.5	1.5	0.8
B1	1	0.8–1	0.8
C	0.5–0.6	0.5	0.5
D	0.3	0.3	0.3

Table 4. Quantity of materials needed to construct German 5×5 m concrete passive bunkers, [4]

Material	Unit	Quantity
gravel	m^3	38
sand	m^3	38
cement	t	26.5

Table 4. continuation

Material	Unit	Quantity
reinforcing bars of 8-10 mm diameter	m	825
	t	0.51
reinforcing bars of 15-20 mm diameter	m	1600
	t	3.95
connecting wire of 1 mm diameter	kg	70
200 mm 'I' beam (length of 4.2 m)	piece	16
lintel of 200 mm 'I' beam (length of 1.2 m)	piece	4
f25 mm threaded rod (length of 1.2 m)	piece	12
f25 mm threaded rod (length of 0.5 m)	piece	4
shuttering boards	m^2	120
squared and round timber	m	305
steel smooth nails	kg	25

Table 5. Building personnel needed to construct German 5×5 m concrete passive bunkers [4]

Task	Occupation	Number of workers
timbering	carpenters	12 + foreman
reinforcing	steel fitters	8 + foreman
ground works and casting	other workers	24-40 + foreman

- As a material, plain concrete probably protects against the explosion of an artillery shell but, due to its low deformability and elasticity, it splits and cracks not only as a result of fire but also as a result of thermal stress, especially during frost.
- There is a necessity to perform dilatation when erecting retaining walls, earthworks and other long-length structures.
- Plain concrete during explosion poses an enormous threat to people inside the shelter, where heavy debris from walls and ceilings is torn off from the inner surface and wounds and buries people. Initially, this was attempted to be resolved by strengthening the vaults from the bottom with corrugated steel sheeting; however, it was more effective to pour the ceilings on a composite structure of steel T-beams arranged at short distances with separators between them in the form of a filler steel plate.
- A better solution for the construction of bunkers is the construction of a monolithic block rather than a construction made from prefabricated elements which, as a result of shock and vibration, are subject to delamination and faster destruction.
- The foundation slab is necessary in construction because the people who are in the shelter are most threatened by missiles which are coming up from ground (i.e. those

that hit the ground near the object). Because of their explosive force, they penetrate the ground deeply and reach below the walls and into the inside of the shelter.

- The cubature of the object plays a big role. Bunkers of too small dimensions turn over due to the force of the explosion, or are pressed into the ground.
- The use of reinforced concrete proved to be a breakthrough in the construction of fortification objects exposed to artillery fire or aerial bombardment. Smooth rods with a diameter of 10–20 mm were used for reinforcement. Reinforced concrete had greater strength than non-reinforced concrete, and at the same time, it had a high degree of deformability and made it difficult for fragments of concrete to peel off and for the construction to disintegrate. Thus, before the First World War, it became the basic material for the construction of fortification buildings.

4. Functional layout and bunker design

The bunkers that were created at the turn of 1940–1941 were quite inconspicuous. The structural assumptions of these objects were based on the pre-war defence standards of fortification construction, quickly verified by the development of aviation. Their 1.0–1.5 m thick walls and two-meter ceilings were supposed to protect against the explosion of 500 kilogram bombs. Several small rooms in their interior provide the minimum of space for work and sleep. The bunkers were equipped with sanitary installations and electricity. In 1943, the effectiveness of bombing by the British and American aviation considerably increased. Their reach grew so much that they began to attack targets in places which had so far been deemed safe, including East Prussia. The threat of an air attack on Hitler's main headquarter – Wolfschanze, began to be possible. In mid-1943, Hitler decided to expand the facilities of the headquarters. It was decided to reinforce the existing shelters by enclosing them with reinforced-concrete armour resistant to direct impacts of even the largest 10-ton bombs which the Allies were in possession of.

The final construction was different from the shelters which had been built prior to the expansion of 1943. They had much larger dimensions, the height exceeded 10 m (Fig. 3), and the thickness of their ceilings reached 8 m. The work connected with the reinforcement of the existing bunkers mainly constituted their enclosure with reinforced-concrete coats which increased their resistance to bombardment. Between the reinforced-concrete armour coats, a layer of grit with a thickness of 0.7 m was used. Fat concrete (at least 600 kg of cement in a cubic meter) and a significant amount of reinforcing steel were used for the construction of the coat. The shelter layout on the example of the Special Communications Bunker is shown in Figure 4 and its vertical cross-section, in Figure 5. The entrances were at the ends of arterial corridors running through the entire width of the shelter. From there, there were corridors leading to small, internal spaces deprived of windows and with a height of 2.0–2.1 m. Entrances to the internal corridor were equipped with gas-tight armoured doors. At the top of some of the bunkers, anti-aircraft defence posts were placed. Much attention was paid to camouflaging objects. The outer walls were covered by a camouflage mix of sea grass, chips and cement. On the roofs, basins were filled with earth were formed and cultivated.

Fig. 3. View of the heavy bunker of Martin Bormann's Shelters in Wolf's Lair (own photo)

5. Construction of ceilings in bunkers

The construction of the ceilings in the fortification buildings evolved along with the resistance needs resulting from the development of artillery or warfare techniques. Initially, these were costly steel domes which were not very resistant to bomb attacks and were buried in earth, brick or concrete vaults, and later secured with corrugated steel

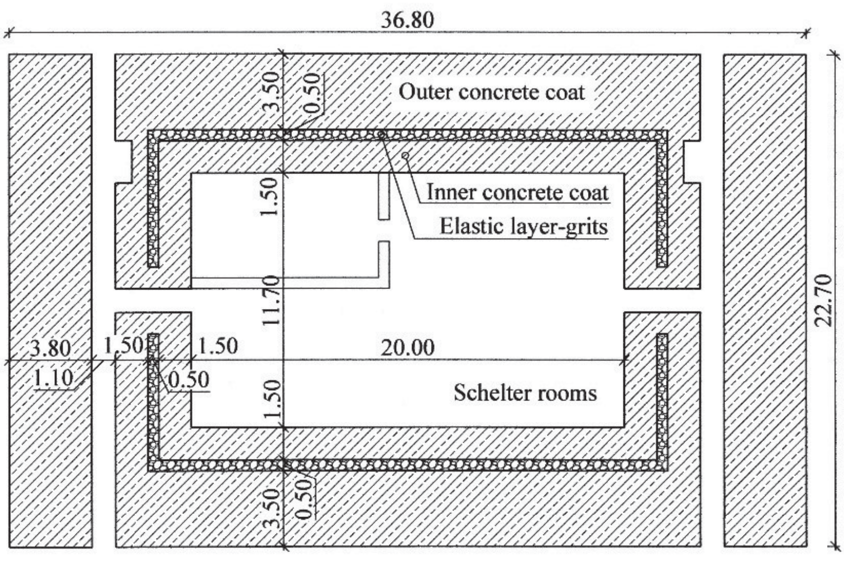


Fig. 4. Plan of the Special Communications Bunker with outer concrete coat [4]

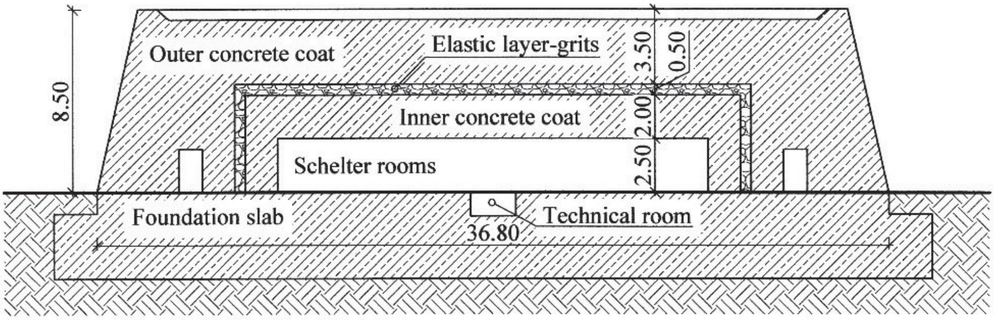


Fig. 5. Vertical section of the Special Communications Bunker with outer concrete coat [4]

sheeting. If necessary, the roofs evolved to concrete and later, reinforced concrete cast on steel beams or whole reinforced concrete cast in a traditional wooden formwork. Below are some ceiling solutions used in Wolf's Lair.

5.1. Concrete and reinforced-concrete ceilings on steel beams

After many less successful attempts, the concrete ceiling on the steel beams became such an effective solution that it became an important element of fortification architecture for many years. Steel 'I' beams were laid parallel at intervals of 0.4–0.7 m and the filling between them was several-millimetre-thick steel sheets based on lower footers (Fig. 6). Steel beams constituted both a self-supporting formwork required for the concreting stage as well as reinforcement of the lower zone of the slab ensuring its bending resistance. Such a solution allowed the pouring of a slab with a thickness of up to 2 m without additional support (Fig. 7a). A tight steel coating protected against breakage of concrete elements from the bottom during fire or explosions. The maximum span of the ceiling was 7.20 m. Initially, a concrete slab was cast on a steel structure. With the development of reinforced concrete, a spatial net was used to provide horizontal reinforcement in both directions and in the vertical direction (Fig. 7b) thus giving the composite slab.

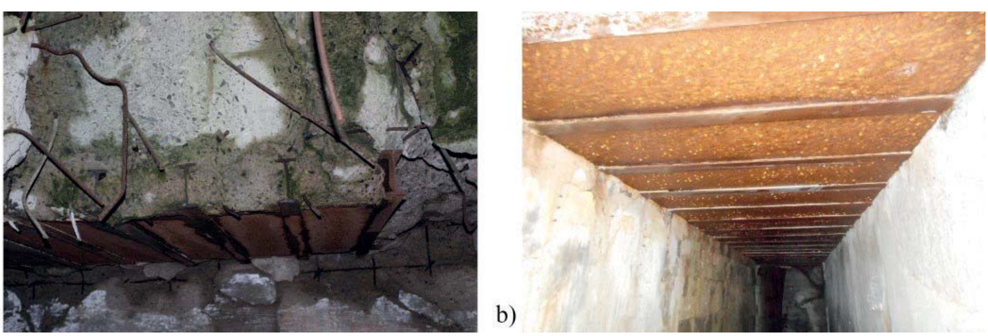
a)  b)

Fig. 6. a)Composite slab on steel beams cross-section, b) the view of the slab in good condition (own photos)

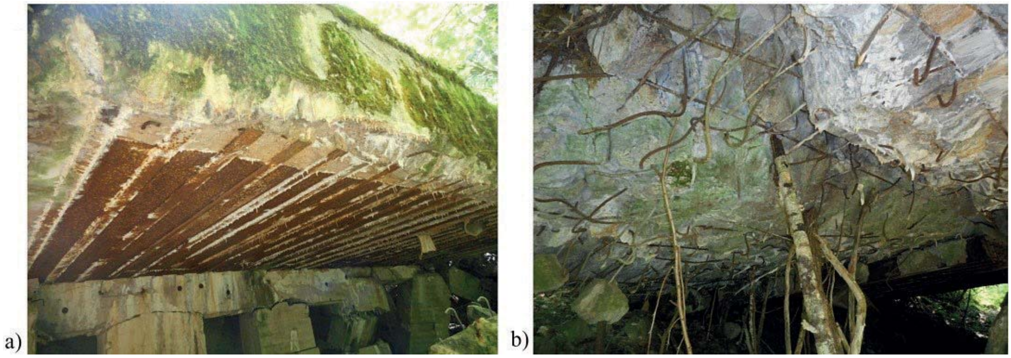


Fig. 7. a) View of a thick slab on steel beams b) and dense steel reinforcement (own photos)

5.2. Reinforced concrete ceiling in wooden formwork or on corrugated steel sheeting

After the dissemination of reinforced concrete and appreciating its advantages, today's reinforced concrete slabs are commonly used in wooden formwork. Such ceilings were constructed in small defensive structures. Their spans did not exceed 5 m. Wooden formworks – often in fragments – have been left visible in the interiors of buildings until today (Fig. 8). A better type of formwork was corrugated steel sheeting used as permanent formwork. The use of plates from the underside provided additional air tightness and limited the fall of concrete fragments.

Fig. 8. View of left fragment of wooden formwork (own photo)

5.3. Ceiling constructed on pre-tensioned concrete beams – the first application of prestressed concrete on Polish land

Another solution in the construction of ceilings was casting the slab on pre-tensioned concrete beams. The modern form of reinforced concrete was actively used in the construction industry in the 1930s. This was the so-called technology of active reinforcement where preliminary compressive stresses were applied to the concrete, acting against tensile stresses extending from external loads. The initial stress system is introduced by tensioning wires of low-relaxation steel, which are able to maintain tensions for a long time. Throughout the lifetime of the structure, through the adherence of the wires to the concrete (pre-tensioned concrete), or through additional anchorage at the heads of the element (post-tensioned concrete), the tensioned tendons act on the concrete element with the force with which they have been tensed. The force from the tendon, through its eccentric application in relation to the centre of gravity of the element, causes an inverse state of bending stresses generated by the external loads.

T-section pre-tensioned prestressed beams were already used in the thirties to make ceilings with a span of several dozen metres – this was necessary for the protection of high volume armour (e.g. U-Boats). Due to the considerable advantage of prestressed concrete structures in terms of bearing capacity relative to other solutions, they have also begun to be used in smaller but strategically significant command centres. This is undoubtedly the first application of prestressed concrete on Polish land in the Wolf's Lair complex.

During the second stage of the modernisation of the fortress, pre-tensioned concrete beams were delivered from Cologne and used to reinforce lightweight brick buildings (Fig. 9). Beams with an inverted T-shape had a maximum span of 12 m and a height of 0.45 m. Available for research study by the authors, the sections of the beams were prestressed with 82 wires with a diameter of 2.5 mm, placed in the lower footer with a width of 0.25 m and 8 wires in the upper section of the web. Figure 10a shows the cross section of the beam inverted by 180 degrees relative to the position of mounting into the ceiling, and Figure 10b is the cross section of the ceiling. The composite slab had different thicknesses depending on the span and the required load capacity for a given building. Height of the beams was in the range from 450 mm to the total height of about 1.2 m. Depending on the expected load on the slab and its span, different spacings of beams were used. With more prestressing required, the beams were laid for contact (Fig. 11a), one next to the other. With smaller spans and slab thicknesses, the beams were parted and the space between them was supplemented with shuttering boards placed on the lower footers (Fig. 11b and c).

Fig. 9. View of the slab with pre-tensioned beams and concrete topping

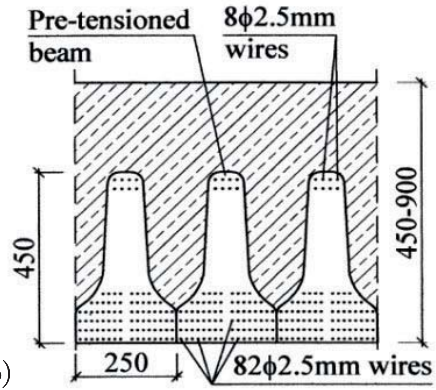
a)  b) 

Fig. 10. a) View of pre-tensioned beam cross section (own photo), b) slab cross-section

a)  b) 

c) 

Fig. 11. a) Different spacing of pre-tensioned beams depending on slab load and span: for contact, b, c) spaced with shuttering boards (own photos)

6. The current conservation status of objects

Most of the heavy concrete shelters in the Wolf's Lair fortress were either completely or partially blown up. At a distance of about 25 km northeast, there is the Mamerki fortress with many similar shelters, but these are intact. The condition of the concrete objects in Mamerki is almost perfect (Fig. 12a). The steel elements of the ceilings actually show signs of corrosion, but the condition of the concrete is satisfactory. The technology used in the construction of the facilities was adequate and thus, the objects have survived intact for almost 80 years.

The nature of the ruins of the blown-up shelters shows the strength of the structure and also the difficulty and huge investment cost of their destruction mentioned in Section 2.

a)  b) 

Fig. 12. a) Building of electric transformers in Mamerki, b) view of separated but entirely preserved wall of heavy bunkers (own photos)

Fig. 13. Concrete wall blocks of heavy bunkers (own photos)

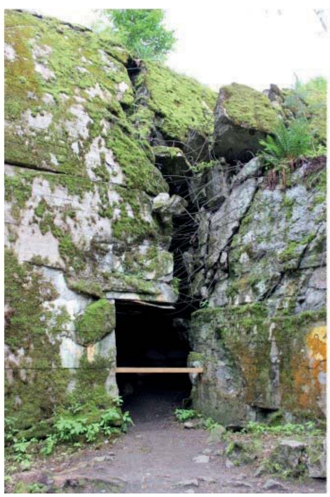
a)  b) 

Fig. 14. View of the importance of reinforcement in ensuring ductility and compactness of concrete structures (own photos)

Many of the walls of the bunkers have survived almost completely or with few cracks (Fig. 12b), despite being subjected to strong explosions. Solid concrete walls often rest on great concrete blocks (Fig. 13). The number of explosives needed to separate them and shift them to great distances was impressive. Figure 14 shows the role of reinforcement in structural resistance to explosions. Fragments of walls were actually moved several dozen centimetres but were not separated. In Figure 14b, this is particularly noticeable, the surface of the fraction on the left fragment corresponds exactly to the surface on the right-hand fragment. This demonstrates the fragmentation and elongation of the concrete reinforcing bars. Such ductility of reinforced concrete structures is certainly achieved by the use of smooth rods that lose more adhesion over longer distances than ribbed rods and thus offer greater elongation. This example shows the advantage of smooth reinforcement over ribbed in explosion-prone objects and the need for reinforcement of high ductility.

It is also worth to note the durability and resistance of composite ceilings to explosions, which in many cases have been preserved as a homogenous form or large sections of composite slab. The strength of the bond (especially for reinforced concrete slabs) was achieved by using steel beams and spatial internal reinforcement.

7. Conclusions

Undoubtedly, many of the technologies we use today, such as mobile telephony, internet, GPS etc. were created for the needs of the army and later popularised for civilian purposes. Also, the first computer was invented and built to speed up the calculation of ballistic missile routes (ballistic curves). Although it is hard to say that concrete construction has been invented for military purposes, it is safe to say that the two world wars have significantly contributed to its development and improvement. Today's reinforced concrete and its existing construction products are not much older than 100 years. However, many buildings have not survived from the early years of use of reinforced concrete, and those that have been preserved are often in poor condition. The condition of the objects not damaged by explosions in Mamerki and fragments of constructions in Wolf's Lair show, however, the advancement of concrete technology and appropriate construction solutions as long as 80 years ago. The materials and solutions used in the construction of military fortifications were certainly helpful, and should continue to be so, in understanding and properly forming concrete structures – especially massive structures.

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