THE PRESERVATION OF A GOTHIC CHURCH IN CZECHOSLOVAKIA

Czechoslovakia is not rich in sources of energy. It has no oilfields or sources of natural gas, and water power covers only a fraction of its power requirements. Despite large imports of refined fuels, the major source of its electricity must be coal, particularly brown coal extracted by open-cast mining. This method of extraction, which is very economical when compared with deep mining, involves, however, a number of specific problems. It destroys very large stretches of landscape, the subsequent reclamation and renewed cultivation of which are lengthy and exacting tasks, and frequently means diverting roads and water-courses and even moving whole settlements.

Hence both the Czechoslovak coal-mining industry and the national authorities themselves were confronted with a tremendous problem when a geological survey revealed a coal seam of outstanding capacity only a little way below ground level within the boundaries of the mining town of Most. It was not difficult to calculate that, with an average depth of the seam below ground-level of about 23 m. and an average seam thickness of some 25 m., the benefits of open-cast mining in the area would be considerably higher than the cost of building a new modern town to re-house the local population of 25,000.

But economic calculations cannot be the only criterion for a decision of such vast import as the liquidation of a town several centuries old. The art historians and the architects in charge of the preservation of historical monuments likewise had their say in the final assessment of the whole problem, as did a number of other experts from a very wide range of disciplines. A painstaking inventory of buildings, public utilities and transport networks showed that the standard of such assets in the town of Most was far below the average for the country. This unsatisfactory situation was due primarily to the fact that the rush development of industry, which took place mainly at the end of the 19th century, had its negative side in the unrestricted building of substandard housing and in the creation of urban amenities of very low standard. It was ascertained that the town possessed practically no buildings from earlier periods retaining their original form.

There were exceptions to this general rule, however, namely, valuable sculptures located in various parts of the old town, fragments of Gothic vaults in some of the burghers' houses, and, last but not least, the Late Gothic decanal church of the Virgin Mary, considered by art historians to be the most important building of the Late Gothic period in northern Bohemia.

The building had replaced the Early Gothic basilica dating from the last quarter of the 13th century which archaeological research brought to light in 1971 and of which only an octagonal crypt, with a ceiling vault dating from the first quarter of the 14th century, and the tower, added at the end of that century, were then preserved. This, the parish church, was destroyed by fire in 1515, and the burghers of Most built a new one, the foundation stone for which was laid on August 20th, 1517. The new church was designed by the Saxon builder Jakob Heilmann of Schweinfurt and consisted of three aisles of uniform height with patterned rib-vaults. After his death building continued under Georg of Maulbron, " Master Peter " (probably to be identified with Peter Heilmann), and " Master Jorke ". The building was completed in 1549, as is shown by the date on the Late Gothic boss; further work, completed in the second half of the 16th century, was in the style of the Saxon Renaissance. This latter phase includes several doorways, the roof of the tower, and the elaborate decorative sculpture inside the church, of which only the reliefs on the tribune, the monumental epitaph of the Weitmühle family, two portrait busts, the stone pulpit, the larger font, and the sanctuary have been preserved.

Subsequent alterations to the interior in the age of baroque gave the church its altar, now the dominant feature, the sculptures on the piers by J.A. Dietz, the organ which closes up the rear of the building, and new benches. The Gothic Revival, which came in 1880-1883, brought new furniture and new painted decoration, and the church has since retained the same appearance right down to the present day, when it is held to be one of the most important architectural works of the final stage in the development of Czech Gothic. With its expanded size it represents the three-aisled church at the height of its development, and the system of patterned rib-vaults linked up with the Bohemian Late Gothic tradition, while in form the architectural and sculptural details were reminiscent of the art of Saxony.

The preservation of a number of historical monuments of cultural value and their inclusion in the new town of Most did not involve any particular technical difficulties. But the requirements of the art historians led to far greater problems when it came to preserving this Late Gothic church, which measured 60 × 30 metres and weighed some 15,000 tons.

Studies of the problem by the personnel of the Academy of Sciences and the technological universities, as well as by engi-

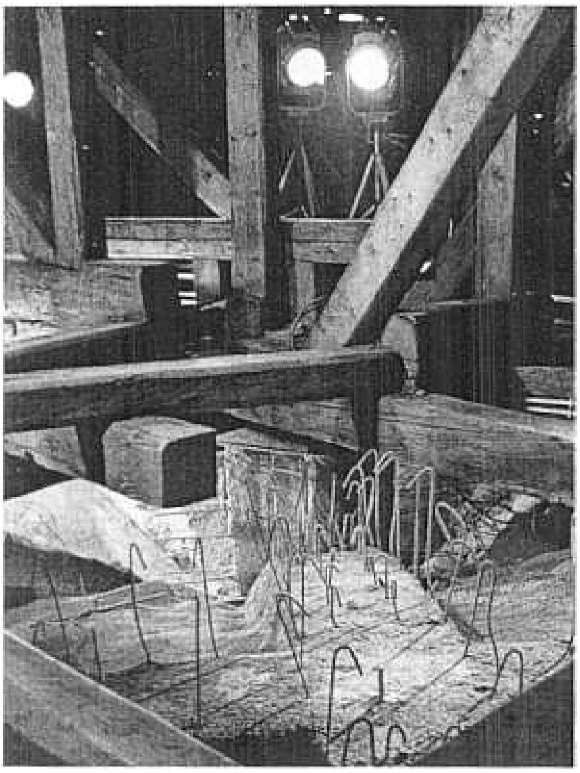


Fig Reinforcement of the vaults

neers, led to the proposing of three alternative ways of preserving the church. i.e.

a) Leaving it on its site in the middle of the future open-cast coal mine.

b) Dismantling the whole building and re-erecting it on a new site.

c) Moving it bodily.

The principal drawback to the first alternative was the fact that the church would remain standing on a solitary pillar of coal in the middle of a coal-field for at least fifteen to twenty years with no possibility of access and no surrounding buildings. Meanwhile its dismantling and re-erection would very much reduce the historical value of the building, apart from the fact that this alternative would require an enormous amount of highly-skilled and expensive labour. In view of all these disadvantages the decision to preserve the church by transferring it to a new site was unanimous.

To begin with, a study was made of the possible sites for the building in the new town. The Chief Architect of Most decided on a site in the immediate vicinity of the medieval hospital and Church of the Holy Spirit, on the outskirts of the town. The prospects are that new housing will expand in this area beyond these historic buildings, so that the three will form the core of the cultural and social centre of this district.

A detailed analysis of the problem revealed the existence of five initial difficulties, i.e.:

1. The new site selected was over 700 metres from the existent one and the difference in level was about 10 metres.
2. The travel was liable to be rendered difficult by the presence of underground voids caused by previous mining activities and not shown on the mining maps; 200 metres of the transfer route passed over the former quarry some 40 metres deep, which had been filled up with refuse.
3. The geological conditions on the new site were rather unusual: the foundation soil consisted in the remains of a coal seam exploited by deep-level mining and there was a possibility of spontaneous ignition and of subsidence.
4. The church building was very large, while also being slender and fragile in design and containing a great many flaws (particularly in the vaults); the individual load-bearing structures (piers and buttresses) were connected only by the masonry of the outside walls and, 18 metres above ground-level, by a brick vault only 15 cms. thick.
5. The church tower was massive, heavy and of very considerable height; because of its faulty foundations it was completely separate from the actual church structure.

Such difficult conditions had never been encountered simultaneously in any other building it had been proposed to move. It was therefore necessary to find a new solution and, in the light of the experience gained in similar operations in all parts of the world, to design new technological equipment to satisfy the special requirements of the case.

A comparison of the various projects submitted resulted in the final selection of the one presented by Transfera, Prague, which was based on the following principles:

i. The transfer track would be flexible, i.e. would bear deformation during the passage of the building.

ii. Since it would be necessary to compensate, continuously and with a high degree of precision, for track deformations, the number of transfer units would be as low as possible.

iii. The church building would be reinforced with a steel structure which would also serve to enable the transfer units to be located outside the area of the piers, buttresses and outside walls; this would facilitate the construction of the track as well as the assembly and dismantling of the technological equipment.

iv. The transfer would be effected along a track forming an arc with a radius of 548.5 m, at a pitch of 12.3 ‰ in the direction of the longitudinal axis of the church.

v. The deformations would be compensated for by hydraulic cylinders with automatic control.

vi. The horizontal motion would be produced by hydraulic cylinders with a long stroke, capable of alternate working, which would enable the movement of the building to be continuous.

Once these main principles of the project had been established, it was time to speed up the preparations for the transfer.

To begin with the whole building and all its architectural and historically valuable features were subjected to detailed surveying. Simultaneously the interior of the church and all its furniture were surveyed by art historians and all items were

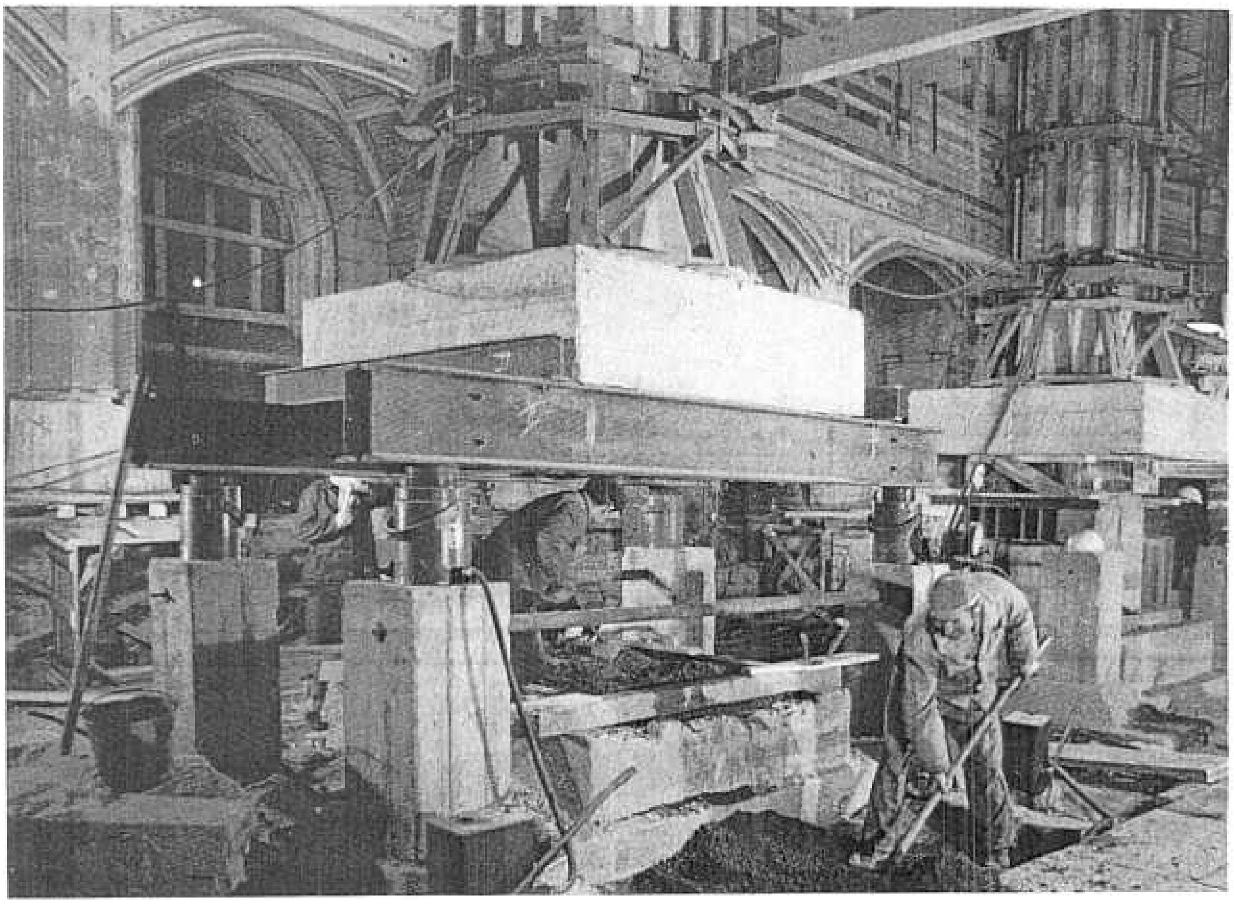


Fig. 2. - Column underpinning.

listed and photographically recorded. The plans for their future reinstatement were prepared at the same time; objects of inferior artistic value were eliminated, and methods were determined for restoring those items which were to be retained.

On the basis of this inventory and classification methods were established for their dismantling and subsequent storage in the nearby depository, and the dismantling began straight away. The individual items were dismantled by specialists and taken to the depository for storage, and from here they were progressively removed for restoration so as to be ready to return to their places in the church when it had reached its new site. The items belonging to the church interior which could not be dismantled were secured and shuttered and the patterned ribs were then fastened to the reinforcing structure.

Once the interior had been cleared it was possible to carry out further surveys, particularly of a historical and archaeological nature.

The historical survey, accompanied by simultaneous assessment of the value of the architectural features preserved, concentrated on two principal problems. The most serious one was that of the preservation of the tower, which, in view of its very considerable weight, concentrated over a very small area, and of the poor state of its masonry, was technically extremely difficult and also excessively costly. A portion of the tower masonry, some 9-10 metres high, from the original basilica destroyed by fire in 1515, had been incorporated into the new tower and surrounded with new masonry which, however, had no bond with it. The lower part of the tower structure consequently consisted in three independent, relatively weak, and badly damaged walls, with voids in between filled with rubble or poor quality lime mortar. Most of the defects in these vertical members were due to the fact that the tower, which was almost 70 metres high, had its foundations only about 60 to 70 cms. below ground level (i.e. still in the frost zone of the foundation soil) in its south-westerly portion, while those of its north-westerly portion, inside the church, reached to a depth of 240 cms.; the result had been very uneven settlement and failure of the masonry. The art historians' survey showed the body of the tower to be very simple in design, without any characteristic architectural features, only two stone doorways and the surrounds of three small windows in the higher storeys being of any historical value. In view of all these circumstances it was decided to pull down the tower before the church was moved and to build a new tower of identical outward appearance on the new site after the church had been shifted.

Another important circumstance which influenced the design of the transfer equipment was the decision to preserve the octagonal crypt in the east end of the original Early Gothic basilica. After investigation of the masonry inside this area it was decided to preserve the crypt vault, including its spandrels and lunettes, by transferring it to the new site, and to dismantle the outside wall masonry and a part of the central column below the vault for subsequent re-assembly.

Another major feature of the art historians' study of the church was their investigation of the plaster, in the light of the assumption, based on the ancient records concerning the construction of the church, that it did not originally have a polychrome interior and that the plastered parts had been merely whitewashed.

The archaeological research, which covered practically the whole of the church interior, revealed the layout of the original church, the dimensions of which — if we except its east end — were identical with those of its successor. The presence of secondary stone elements in the foundations of this earlier building provide grounds for assuming that there was a yet earlier building, dating probably from the first half of the 13th century.

Apart from these architectural vestiges, a number of graves were discovered on the levels of both the older and newer church, together with a number of minor finds, notably a bell-founder's hearth with some scraps of bronze alloy below the floor level of the older church.

Apart from the surveys and investigations for the purpose of assessing the value of the artistic and historical features of the building, numerous technical investigations were also carried out. The most extensive and most important of these was the geological survey, supplemented — in view of the nature of the case — by hydrogeological, geophysical and mining surveys.

These surveys concentrated on three principal areas, i.e.:

a) The immediate neighbourhood of the church, for the purpose of clarifying the state of the foundations of the building, so as to be able to make optimum provision for securing them during the construction of the transfer tracks.

b) The site of the transfer track, particularly the portion located over the quarry area. For a period of one-and-a-half years, the quarry fill, which was of a very poor load-bearing quality, was loaded with a consolidation embankment 200 m. × 45 m. in area, producing a load exceeding by some 15 % that which was to be exerted by the passage of the church. The settlement of the subbase was observed over this period: on the subbase level itself it amounted to as much as 98 cms. About six months after the consolidation of the subbase the loading embankment was removed from it and its elastic deformations were observed again; they now averaged 9 cms. On the basis of this mammoth loading experiment it was possible to assume that the deformations in the fill during the transfer would be about 10 cms. and would not exceed 15 cms.

c) The new church site, where the principal purpose of the geological survey was to determine with maximum accuracy the limit of the open-cast mine and the extent of the disturbance of the coal seam which would result from the mining activities; the location of the outer edge of the quarry was determined with sufficient accuracy by a system of boreholes and trial pits, supplemented by a geophysical survey. However, the physical features of the ground were so complex that some vestiges of mining works were not located until the foundation pits were excavated.

Considerably smaller in extent, but of no smaller importance, were the investigations made on the masonry and mortar used in the church building, the studies for determination of the bulk density of the masonry with a view to calculation of the overall weight of the building, and the research on the future behaviour of the masonry, plaster and ribs of the crypt vault in the different atmospheric conditions on the new site. The study of the condition of the vaults and of the history of the individual phases in their erection and repair was an entirely unique operation.

An assessment of the results of these investigations and surveys provided the basis for the fundamental programme for the preparation of the building for transfer. The main individual problems and their solutions are briefly described in the following breakdown of the project into its various sectors.

Dismantling of the stone elements: doorways, window surrounds, steps, etc.

Those stone parts of the building which were intended for reinstatement and might be damaged in the course of the work were dismantled in advance, before the actual construction operations had begun. The main features concerned were the north and south doorways, the surrounds of the eastern entrance and the door to the tower. The central mullions of the windows and other minor elements in the tower and sacristy were also dismantled.

Dismantling of the tower and other structures

The roof of the tower was first dismantled by a gang of skilled mountaineers who were able to do without the heavy scaffolding originally allowed for, and then the tower masonry was removed by hand. The stone members were loosened without any trouble and were stored in the depository. The tower was first dismantled to the level of the main vaults, further removal of masonry continuing only after these had been reinforced and underpinned by two steel columns. At the same time the sides of the exposed outside wall masonry were secured with a reinforced concrete ring beam.

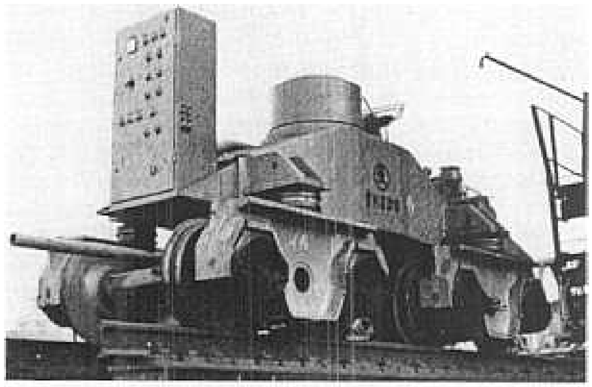
The crypt

The crypt vault was provided on its rear side with a concrete shell, and the whole vault was then propped up from inside by a steel structure. During the erection of the main reinforcing steel structure the crypt vault was suspended from it; it was transported together with the whole church building to the new site, where it was to be supported by the same wall masonry as in its original position.

Principal vaults

One of the most serious problems in the whole of the preparations for the transfer was the securing of the vaults against possible damage, either during the preliminary work or, possi-

Fig. 3. The reinforcing ring beam



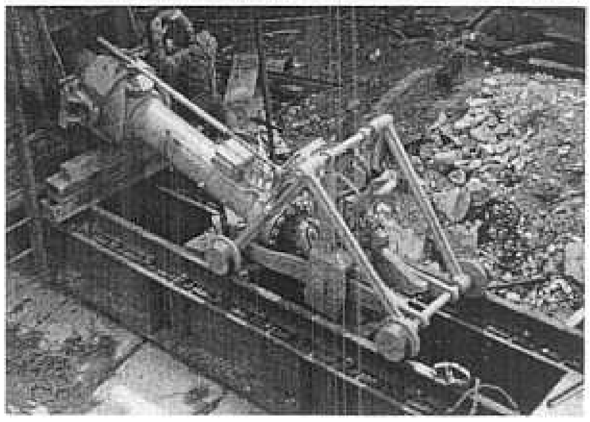


Fig. 4. - Transfer buggy.
Fig. 5. - Pressure cylinder

bly, during the actual transfer. Two opposite alternatives were considered, i.e. either the erection of a rigid grillage structure guaranteeing the stability of form of the whole series of principal vaults, with, however, increased danger of overloading on the individual load-bearing members, or else flexible reinforcement of the vaults by means of a concrete shell on their rear face, while the position of their abutments was secured by an independent horizontal structure. Finally a compromise solution was adopted which combined the advantages of both alternatives, i.e. a flexible extrados shell reinforced with relatively rigid concrete ribs formed by placing concrete along the original masonry ribs. This structure was so designed as to be suitable for conversion, if necessary, into a rigid framework by the addition of concrete walls. In the transverse direction the outside wall masonry of both aisles on the vault abutment level was secured by prestressed ties whose prestressing force corresponded to the horizontal components of the vault reactions.

Underpinning of the masonry

Another interesting building operation was the construction of a ring beam of reinforced concrete and the underpinning of the piers and buttresses. The ring beam was progressively concreted, the replacement of the masonry with concrete beginning at the points where the buttresses linked up with the outside walls. The core of the future ring beam thus formed was provided with all the necessary tensile and compressive reinforcement, corresponding to a load-bearing capacity designed for a maximum deformation of 10 mm. at midspan on a girder loaded by masonry over a span of some 10 m., as well as shear stress reinforcement capable of transmitting a reaction of 500 tons.

After these blocks had been concreted in all appropriate places the masonry in between them was progressively replaced by a concrete girder. The reinforcements of these intermediate parts were welded to those of the blocks. At particularly tricky points where the support reactions were at a maximum the contact surfaces between the block and the rest of the ring beam were given special treatment to improve their bonding.

The slender stone piers were reinforced, both for loading and with a view to the transfer, with a prestressed steel structure which also served for underpinning purposes. The sleeve supporting this reinforcement was slowly lifted by four hydraulic presses until the reinforcing structure transferred the whole axial force of the pier by friction on to auxiliary foundations. It was then possible to replace part of the pier foundation with a concrete block with embedded steel beams, below which the main reinforcing structure was subsequently mounted.

The underpinning of the buttresses proceeded similarly, but at certain points only, so that it was not necessary to subject the supports to the action of hydraulic jacks; it sufficed to grout the upper horizontal joint of the concrete block. During these operations all reinforced concrete members were separated from the old foundations by two layers of steel plate. This simple method for providing an anti-adhesion layer proved to be an excellent one: during the loading of the church building on to the transfer mechanism there was no impact caused by sudden severing of the individual courses, and the separation process went on continuously.

The main reinforcing structure

Since the building was a large one and its load-bearing features were mainly vertical members — piers and buttresses with discontinuous external masonry mutually connected by non-rigid vaults — it was necessary to provide an additional three-dimensional structure to afford the whole building sufficient rigidity for the transfer. After an analysis of various alternative systems, a special lattice steel structure was designed, with four longitudinal girders parallel to the outside walls, and a system of fourteen transverse girders so designed that their chords passed in most cases through the windows of the ancient building or below the ring beam. The points of intersection of the longitudinal and transverse girders provided the bearing points below which the transport equipment would be placed.

The transfer tracks inside the church

The work of constructing the transfer tracks inside the original church building was one of the most exacting phases of the preparations. Since in the western part of the building these tracks were situated below the foundation base of the outside wall masonry and piers, it was necessary to secure the clay subbase against buckling, and for this reason pile walls were built along both sides of the track trenches. The individual piles were connected with a capping beam into which the ties connecting the walls on both sides of the foundations were anchored. The prestressing in these ties caused active deflection of the walls, which minimized the subbase deformations.

The transfer track

The construction of the transfer track connecting the old and the new foundations of the church building represented another part of the preparations. The track was built under complex and heterogeneous geological conditions. The principle of its design was determined primarily by two basic requirements, namely:

a) It must be entirely safe, though it could show vertical settlement of up to 10 cms. below the travelling building.

b) It would be used only once.

The track structure was therefore divided into two parts, which were as follows:

i. The substructure, which provided a uniform subbase and replaced the alluvial deposits, which were of poor load-bearing capacity.

ii. The superstructure, consisting of reinforced concrete panels supporting longitudinal steel girders 8 metres long, which carried the rails.

In view of the anticipated speed of transfer it was possible to restrict the length of the superstructure to 160 metres and progressively to dismantle the track behind the church, subsequently reassembling it in front.

The actual deformations occurring in the track were in line with the working assumptions. It was possible to observe the influence of the time history of these deformations, which occurred on a subbase consisting of natural layers of overburden clays; they increased, according to the duration of the loading period, to as much as 4-6 cms., depending on the speed of transfer. During the travel over the former quarry, where the subbase had previously been consolidated, they exceeded 10 cms.; however, they were roughly equal along the whole length of the church, with no large increase due to rate of travel.

The new foundations

The design of the new foundations was the outcome of an evaluation of several alternatives, including wells, diaphragm walls, compacted earth, etc. It was finally decided to adopt a rigid box structure, which presented a number of advantages in comparison with other types of foundation, i.e.:

a) It did not noticeably increase the load applied to the foundation base.

b) It was very rigid, and capable of sustaining local subbase subsidence.

c) It was rigid enough to permit rectification of the building as a whole if necessary, through pressure grouting of the subbase. With this eventuality in view the subbase was divided into individual coffers so that the grouting pressure could be graduated. The base plate of the box structure was provided with grouting tubes.

d) It provided new additional space which could be used for various purposes (storage, archives, etc.).

The whole of this foundation was carefully waterproofed, so that the rooms it contains are perfectly dry and may be properly ventilated. The rigidity of the structure and the solidity of its subbase proved adequate when the transfer of the church took place. The degree of deformation of the new foundations was uniform, reaching an average of less than 5 mm.

In the technological area of the project as in the constructional area the technicians had to cope with the design and development of new mechanisms and plant which in many respects had no analogy anywhere in the world, and to carry out their tests without any possibility of a trial operation.

It was necessary, first of all, to solve several fundamental problems influencing the design of the individual parts of the transfer plant.

The principal problems connected with the selection of the machinery included the choice of a suitable type of transfer vehicle, of traction mechanisms to set the building in motion and of a control system whose purpose would be to maintain the position of the masonry after transfer within previously-stipulated tolerances.

The actual designing of the plant was preceded by a number of

Fig. 6. - Main measuring centre.

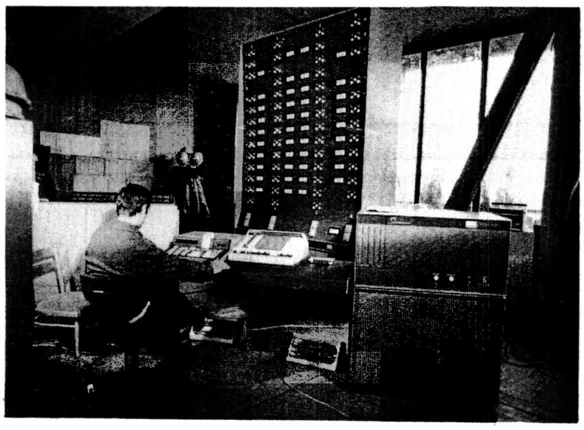


Fig. 7. - The main control room.

Fig. 8. - The main control room.

checks and tests.

Particular attention was devoted to the designing of the cars on which the building was to be transferred from the old site to the new. The result was a four-axle transfer buggy of a load-bearing capacity of 500 tons whose axles were interconnected and so balanced as to guarantee identical wheel pressures. It was designed to suit a track similar to a railway line. The problem of rolling kinematics at extremely low velocities was successfully solved in such a way as to preclude changes in travelling resistance. At the same time the problem of the positions of the 53 buggies in relation to the building was so solved as to ensure the transmission of the lateral forces as each buggy travelled along the track, notwithstanding certain variations in direction.

Each buggy was equipped with a hydraulic cylinder with a 270-mm. stroke, so designed as to compensate, via the control circuit, for any settlement of the subbase as a result of the load exerted by the building, within the agreed tolerance in relation to a reference level. The mechanical device for arresting the piston position with which the cylinder was provided automatically disconnected the hydraulic circuit in case of failure of the control circuit or vibrations in it. The cylinder and this arresting mechanism were driven by an independent hydraulic device, operation of the cylinder being controlled by a control circuit. A given elevation was stipulated for every bearing point, and this was subsequently maintained during the transfer with an accuracy of ± 1 mm. The reference level from which the elevation was measured was obtained by a system of hydrostatic water levels whose pick-ups transferred the position of the measuring point to an analog signal. A programmed calculator was used as a control mechanism capable of very speedily effecting the mathematical operations required for determination of the length of impulse to the hydraulic cylinders. The calculator was provided with input converters for the conversion of the analog data supplied by the pick-ups into digital form, and with an output converter of relay circuits and hydraulic system. The working of the control circuit effecting the actual position rectification may be described as follows:

The input circuits read the data provided by each pick-up three times. From these three readings the calculator determined the amount of deviation from the selected vertical position and the length of impulse required (with the opposite sign) for the elimination of the deviation. The control system could either operate so as to maintain a constant position of all bearing points in relation to the point selected (or preferred), or could determine an arithmetical mean for all deviations which was subsequently considered as the required reference value. This second method could reduce the number of control interventions to a minimum. The whole operating frequency of the control procedure was programmed and repeated in preselected cycles which enabled the number of interventions to be adjusted in the light of the experience acquired in the course of the transfer, the frequency and magnitude of the deviations and the character of the operation.

The operation of the position-control system was checked experimentally before a final try-out on a control loop, using a prototype of the transfer car, and at the same time the constants for the computer programme were established. After

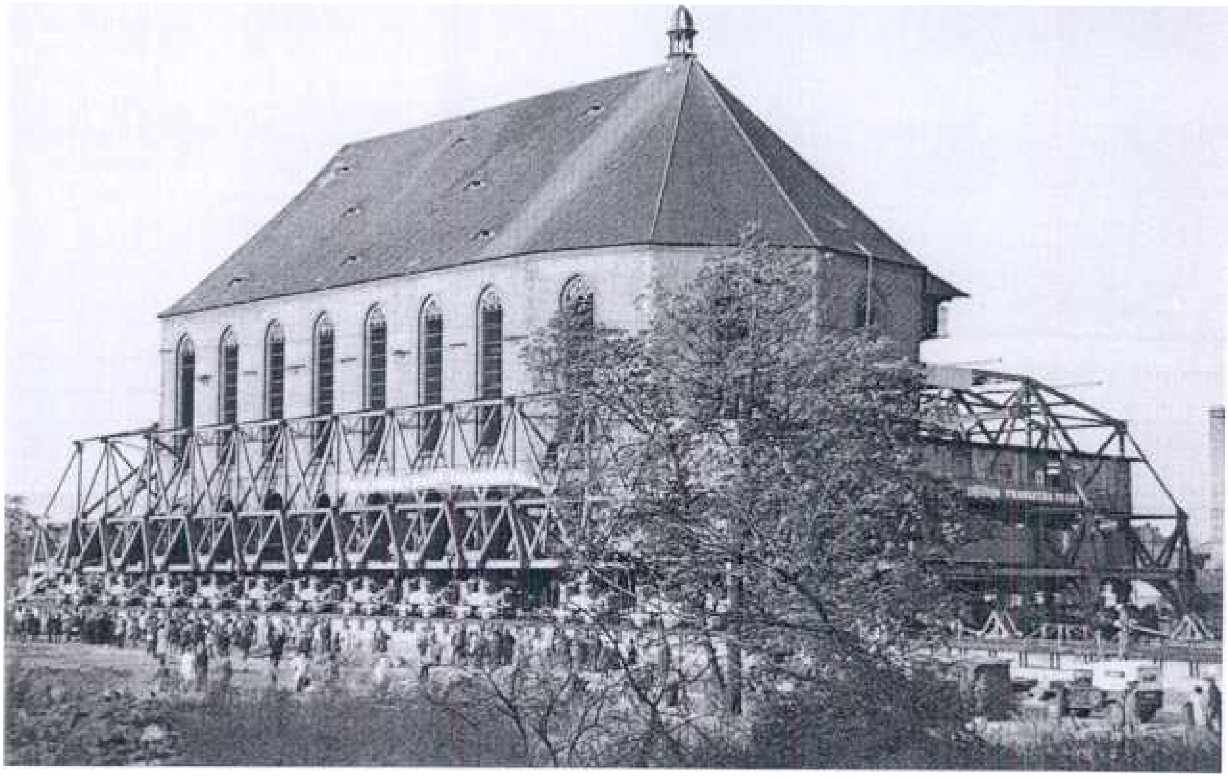


Fig. 9. The church half-way along its journey.

the assembly of the actual plant the numerical values of these constants were measured individually for each pick-up. Apart from such practical testing of the control system the prototype of the transfer car was also used for a try-out of the latter's kinematic properties, determination of the magnitude of the tractive resistance, and strain gauge measurements of the stresses in its principal parts, the data thus obtained being subsequently used as criteria for the manufacture of the series of 52 transfer buggies. For the purpose of these experiments a testing plant was produced on which it was possible to obtain various régimes and investigate the reliability of the individual structural details.

Parallel with the progress on the transfer buggies work proceeded on the design of the traction mechanisms. In an endeavour to reduce the possibility of generating dynamic forces to a minimum while simultaneously exerting very powerful tractive forces for the shifting of the building, it was decided to use hydraulic cylinders arranged for regular alternate working without any interruption in their motion. Four cylinders were placed behind the building to produce the forces exerted in the direction in which it was to move, while another four were placed in front of it to act in the opposite direction, thus braking the movement of the building by a constant adjustable force. This arrangement enabled the building to be accurately positioned by the forces applied and to be set in motion by differentiating the forces exerted by the two sets of cylinders. Since each set comprised two pairs of cylinders with alternating strokes the motion of the building was never interrupted. All the cylinders were of identical design, i.e. a capacity of 175 tons and a 3,500-mm. stroke. Each group had its own hydraulic drive unit suitably connected for the purpose served. The anchorage of the tractive force was provided for by means of an anchorage mechanism built into the transfer track structure, so that it was not necessary to build separate anchorage structures. The cylinders were fastened to this structure by means of a cross-pin cardan joint. The alternating movement of the cylinders could be controlled both automatically and manually, the former system being used to alternate pairs of cylinders while the latter could also be used to alternate two individual units.

Before being placed in position under the building each buggy was tested once again in the plant which had been used for the testing of the prototype; however the scope of this final test was limited to its actual functioning and to the settings of the control circuits. The traction cylinders were similarly tested for the anchorage of their maximum force.

To ensure continuous control and monitoring of the stresses in the steel reinforcing structure and in the original masonry, as well as to supply supplementary data on speed of motion and acceleration and similar data required for control of the transfer operation, an extensive measuring system was installed. 525 pick-ups in all were installed in the building, 81 of which were induction sensors which would indicate any reciprocal displacement of important parts of the original masonry and the behaviour of previously-existent cracks; 45 resistance strain-gauges embedded in reinforced concrete structures measured the effects in members subjected to severe stresses, and 313 strain gauges served for measurement of the stresses in the steel structure, particularly during the loading. Another 106 strain gauge dynamometers followed the reactions transmitted to the buggies, so that even where a buggy was arrested or there was failure of the hydraulic system it would be possible to read the magnitude of the reactions of the individual buggies. A similar system of measurement was also used for indicating and recording the time history of the tractive forces. To check the magnitude of the horizontal transverse forces produced by the building and applied to the control row of transfer cars, 14 strain gauges were provided.

For recording the motion of the building a pick-up of special design was used, capable of differentiation with an accuracy of 0.1 mm. The dynamic stresses in the building were checked by a system of 11 induction sensors for measuring acceleration, installed in the direction of the motion, in the direction perpendicular to it and in a vertical direction.

The strain gauge pick-ups and the displacement pick-ups were connected to an automatic measuring plant permitting individual reading or control printing of all data within five minutes, or the printing of a part of the data in a continuous cycle. The motion of the building, its acceleration, and the time history of the tractive forces were continuously monitored visually on the screen of an oscilloscope and recorded by a measuring tape recorder whose record was converted into a graphic record.

The results of the measurements were examined at regular intervals and the findings were used as a basis for readjusting the transport parameters or the transfer régime.

The requirements of continuous operation could not be met without a constant supply of electric power for the drives, controls and other devices. For this reason a cable was installed along the transfer track with outlets to which mobile supply lines were connected. The supply system was duplicated, the change-over from one system to another being effected without any disconnecting.

Liaison between the individual working points was ensured by a system of telecommunication with 20 stations.

The control points were concentrated in control centres from which the individual technological groups were operated by a remote control system. The main control centre was the nodal point on which all control activities, control systems and measuring systems depended.

The actual transfer, planned to take 60 days, necessitated painstaking preparation covering organization, coordination of the activities of the various disciplines involved, and, last but not least, measures to deal with unforeseen circumstances and remedies for any trouble or failure. Several alternative programmes for the control and operation of technological equipment with continuous three-shift working were prepared, to suit a variety of situations. The control and operating teams were trained and were acquainted in detail with the scope of their activities. Since the character of the project did not permit any genuine trial operation, it was necessary to train the operators on mock-ups, and on the actual plant in idle operation. The valuable experience derived from such try-outs within the framework of the preparations was made use of in the preliminary work on the actual transfer.

No less importance attached to the preparation and coordination of the work of the subcontractors who were responsible for dismantling and reassembling the track, for inspecting its state of repair and for servicing the technological equipment.

Before loading started the whole plant was checked and the control system for the loading programme was set. The haulage equipment was anchored and the building was exposed to the effect of the design forces. The initial lifting was carried out in 1-mm. stages. The transfer of the reactions to new points of application deformed the steel structure: the deformations thus produced were continuously measured and where they affected the planeness of the masonry support their effect was eliminated. To deal with the deformations at the points supporting the buttresses and outside wall masonry the vertical position of the hydraulic cylinders was altered by the feeding of new input data into the calculator; deformations in the steel structure at the points providing support for the piers were eliminated by a change in the thickness of the bearing plates inserted between the underpinning structure and the steel structure. These plates were relieved by means of auxiliary hydraulic presses controlled separately. In this way a satisfactory transport base was continuously provided, with tolerances on the planeness of the masonry support maintained at ± 1 mm.

In the course of the loading the stresses on the steel structure, the displacements of the individual structural members and, in particular, the verticality of all buttresses and piers were continuously checked. The verticality of the various structures was measured by a specially-adapted laser and an auxiliary hydrostatic surveying system. To sever the building from its foundations it was lifted 150 mm.; this made it possible to demolish part of the old foundations, thus preparing the way for it to leave its old site. At this stage the building was also accurately weighed and its bearing plane was levelled. The calculator was fed a new control programme in order to maintain the loading elevation.

After a thorough check on the state of all structures composing the building the actual transfer began. On the side of the pushing cylinders pressure was continuously increased until the motion started. The first movement was recorded by a motion pick-up. After several metres had been travelled traction speed was increased to 2 cm./min. by adjustment of the quantity of oil supplied to the traction cylinders.

The transfer proceeded continuously and entirely according to plan. Three shifts of men alternated regularly in the operation of the whole plant, the dismantling and reassembly of the track

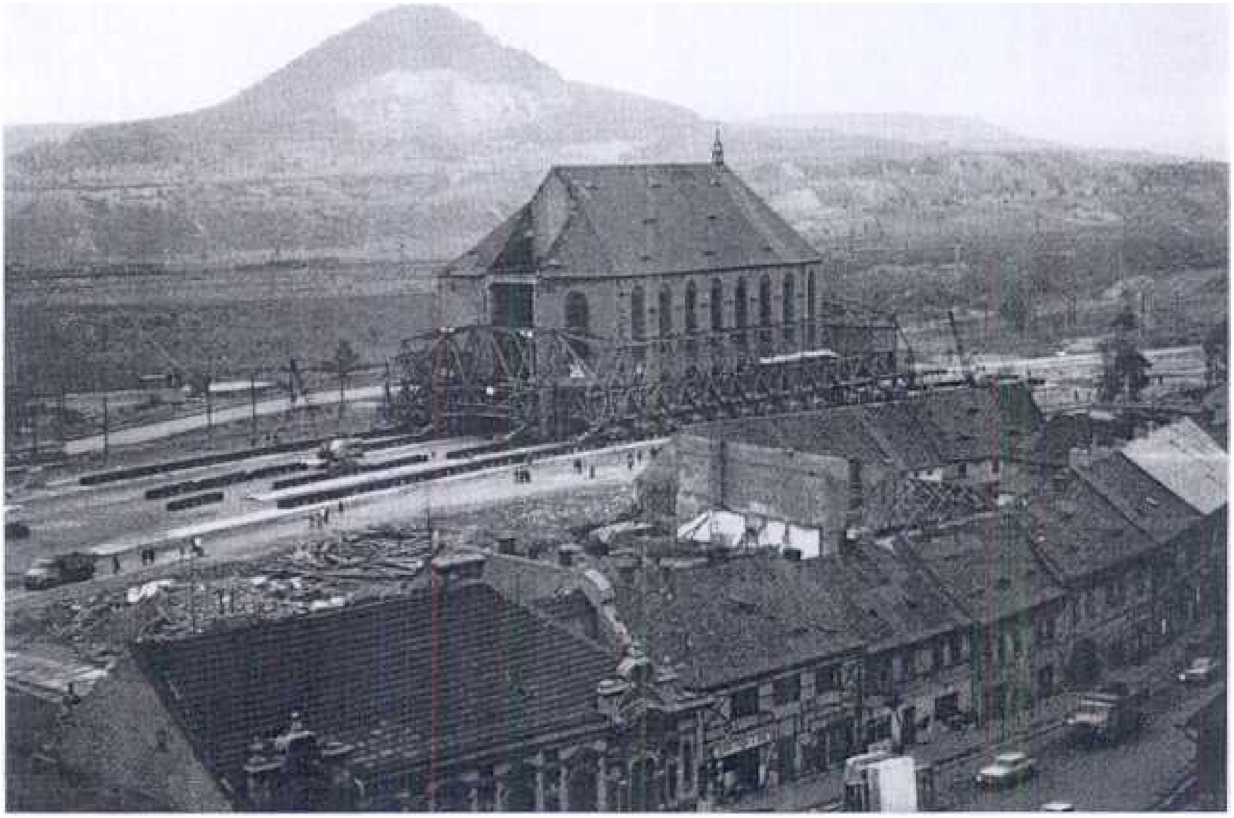


Fig. 10. - General view.

being carried out on day shift. After the first four days, in the course of which the reliability of the whole plant had been demonstrated, together with the satisfactory state of the building and of arrangements for its transfer, the time-schedule and organizational programme could be more accurately determined. The average speed of travel was increased to 2.45 cm./min. With all mechanisms seen to be operating reliably it was possible to reduce the frequency of the checks and of the use of the control system and to simplify the arrangement for alternating the traction cylinders.

During the first few metres of travel attention was focussed mainly on the magnitude of acceleration during the changes in speed, particularly during the starting and stopping of the transfer motion. It was ascertained that it would be possible to stop and re-start the transfer process without allowing the rate of acceleration to exceed 1 cm./sec^2. During repairs on individual transfer cars or during routine checks on them each car examined was disconnected or temporarily stopped, the control programme regulating the position of the building being adjusted accordingly.

The arrival of the building on its new site was complicated by the need to dismantle a part of the braking equipment and one transfer buggy. The plans for the whole operation had initially contained a detailed programme for the completion of the transfer, and it was found to be possible, by adopting the measures originally proposed, to complete the travel over the last ten metres with incomplete control equipment.

After 646 hours of travel, in the course of which it covered 841.1 metres, the building took up its new position. It was stabilized for five days on its new box-type foundations; i.e. it was maintained in a horizontal position which precluded any settlement of the "box". It was then secured in position and parts of the special transfer equipment were dismantled. The building, once secured, was now ready for the last phase in its preservation, namely, the reconstruction work and the reinstatement of its furniture.

If today, when the whole transfer has been successfully completed, we make a re-appraisal of all the measures proposed, both for the preparatory work and for the actual transfer, we can not only say that all parts of the transfer equipment fulfilled

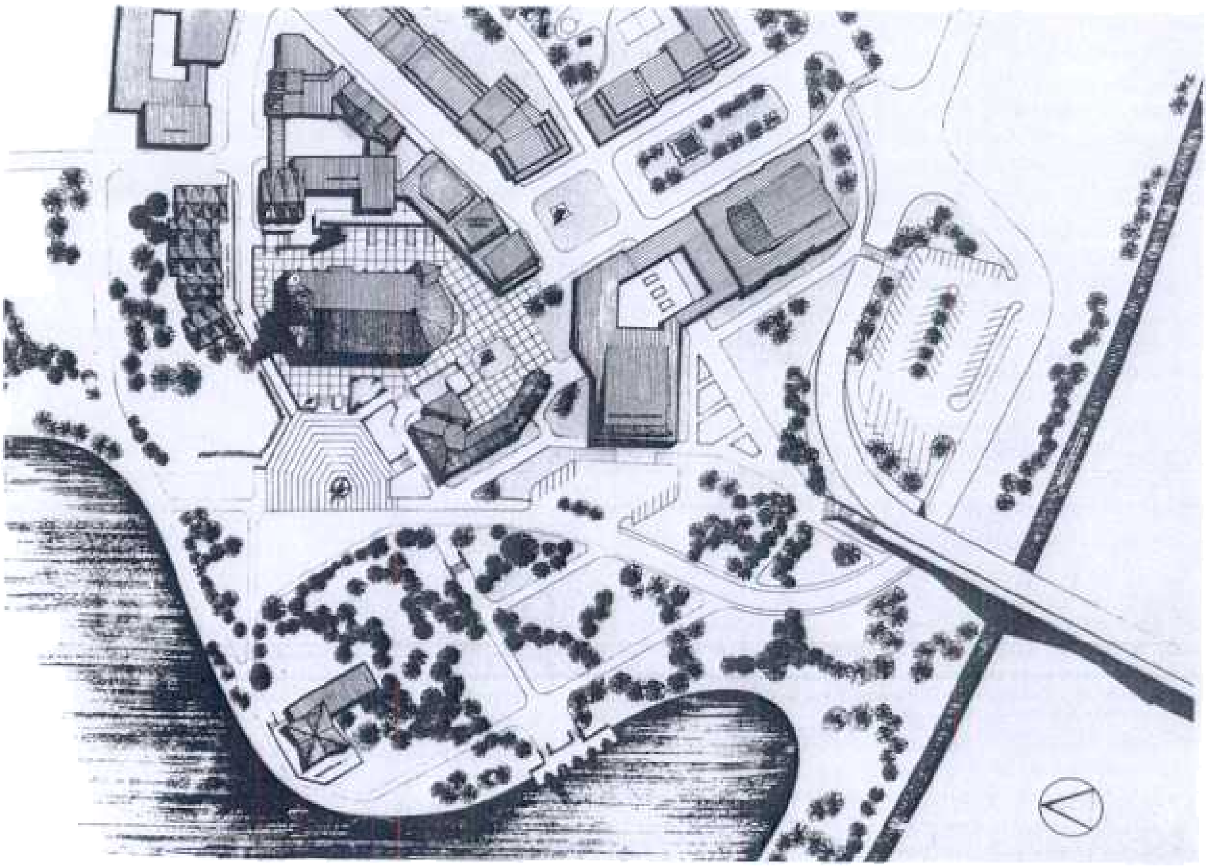


Fig. 11. - The plan established with a view to the re-siting of the church.

their functions; we can stress that all showed themselves to be most satisfactory. When we come to examine the building work involved in the whole project, particular stress must be laid on the faultlessness of the system for reinforcing the piers, which, apart from providing the required rigidity, very greatly facilitated underpinning and loading.

During the loading process, as in the course of the transfer, the reinforcing concrete ring fulfilled only its secondary function, namely, distribution of local loads due to support reactions, since the transfer equipment regularly maintained the transport position of the building within the stipulated tolerance of ± 1 mm. In its principal function, which was to increase the rigidity of the structure, it gave a satisfactory performance during the preparations as such, when it served to preclude any sudden drop in the subbase below the southern part of the west end of the church.

The steel structure guaranteed uniform transmission of forces to the reinforced concrete ring beam, the piers and the buttresses during the loading period. During the transfer its rigidity greatly facilitated the elimination, via the control system, of any irregular settlement of the track, by keeping the deformations in the original masonry within negligible limits. This is best shown by the measurements of the changes in old cracks, which widened by only 0.2 mm.; in a single case a widening of 0.5 mm. was recorded. These figures make allowance for temperature changes as well.

If we re-appraise the technological aspect of the project, we may say that the transfer plant as initially designed likewise proved highly satisfactory. There was no need in the course of the transfer to adopt any major measures or intevene in any vital way to deal with unforeseen situations, failures or cases of unreliable operation.

The principle of duplicating all important elements on which the safety and reliability of the plant depended and making provision for all necessary measures at the design stage proved itself to be entirely justified. In particular, the possibility of transition from automatic control of the traction mechanism to manual control and vice versa, the deliberately wide ranges of values from which settings might be selected and the possibility of putting certain parts of the plant out of operation without stopping the whole transfer process, were very much appreciated during the work.

In practice the adjustability of the plant was exploited after only a few metres of transfer, which was in fact a sign that the tractive resistance of the whole system was far from reaching the degree allowed for. The braking force needed to be increased and the operating zone of the oil pressure shifted towards the maximum, which meant reducing the reserve capacity of the braking force. The problem was solved by a change in the system for alternating the braking cylinders, as a result of which three cylinders were now constantly in operation, the fourth representing a reserve. Another example was the change-over to manual control of the vertical position of the bearing points during failure of the automatic system. In this connection mention should also be made of the practical importance of the correct selection of automatic control, when it was necessary to replace the automatic system by four operators.

The system of transfer cars, the use of flexible elements to connect with the building and the design of the transfer cars themselves did not give rise to any difficulties. It was discovered that during the transfer the travel resistance was constantly on the decrease, obviously as a result of the additional strengthening of the rolling section of the wheels. In this way, not only did the absolute magnitude of the traction resistance drop from 1.5 % of the vertical load to 0.9 %, but the anticipated alternating factor practically disappeared. The positive influence of this was reflected in the maximum magnitudes of the forced accelerations, which were mostly inferior to 2 cm./sec^2 (measured in a longitudinal direction in the vaults). For comparison we may mention that a tram passing in the vicinity of the church produced vibrations with an acceleration of 0.5 to 1.0 cm./sec^2.

The suitability of the use of the automatic control system has already been assessed. As an illustration of the perfect functioning of the control circuits for verticality it should be mentioned that in no case did the deviation from the required figure exceed 0.4 mm. at any point within the controlled zone. In other words, the requirement that the vertical position must be safely maintained within $\pm$ 1 mm. of the optimum value was fully complied with. In the course of the transfer some 50,000 control cycles and nearly 350,000 interventions of the hydraulic cylinders of the buggies were recorded. A further testimony to such remarkable accuracy is the fact that movement in old cracks was truly minimal.

It was only natural that the operation of the plant, which lasted more than a thousand hours, was not totally devoid of failures. But with increasing experience, and particularly after the elimination of some initial faulty elements, the frequency of failures decreased. Functional failures of the mechanisms were primarily due to impurities in hydraulic circuits. This could not have been prevented in practice, since the assembly of the hydraulic elements had proceeded side by side with completion of the building operations. However, these defects, which were remedied when the whole plant was in full operation, were not enough to endanger the continuity and the safety of the transfer.

In conclusion it may be said that all measures envisaged within the framework of the preparation of the building for transfer and all the plant developed for the purpose wholly complied with the requirements and parameters imposed by the project, both functionally and operationally.

The preservation of the Gothic church of Most by its transfer over a distance of 841.1 metres was undoubtedly an exceptional project in many respects. It involved a combination of many extreme and unusual conditions which made the task, exacting enough in itself, even more complicated. Let us summarize these once again:

a) The building's proportions.
b) Its unusually heavy weight.
c) The slenderness and fragility of its structural members.
d) The lack of horizontal reinforcement.
e) The poor state of the vaults and tower.
f) The exceptionally complicated geological conditions along the transfer route and on the new site.

All this meant very costly, absolutely reliable and extremely accurate equipment. However, after six years of preparation the transfer of this Gothic monument was carried out without a hitch. The manner in which the transfer was executed was proof of the absolute operational reliability of the original equipment devised for the purpose.

The preservation of a historical monument by transfer to another site is to be classed as a rule as an extreme measure which should if possible be avoided. However, the rapid development throughout the world of a highly industrialized society is going in many instances to conflict with the desire to preserve the cultural heritage of the past.

The complicated and exacting work of moving the Gothic church of the Virgin Mary in Most in Czechoslovakia is proof that there exists a reliable system of preservation even for such exceptional cases.

Otakar NOVÁK CSc
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Engineers

RESUME

Les modalités d'extraction du charbon en Bohême — mines à ciel ouvert — ont rendu nécessaire la destruction d'une partie de la petite ville minière de Most. Son église collégiale, Notre-Dame, reconstruite dans la 1re moitié du XVIe siècle, est un intéressant monument de style gothique tardif, important pour l'histoire de l'architecture de cette région. C'est une église à nef et bas-côtés, couverte de voûtes aux nervures délicates. Il fut donc décidé, pour assurer sa sauvegarde et sa mise en valeur, de la déplacer pour l'implanter à proximité de monuments anciens situés dans un quartier épargné par le développement du bassin houiller. Ces bâtiments anciens constituent aujourd'hui un ensemble au centre de la nouvelle ville de Most.

Plutôt que de démembrer l'église pour la remonter ensuite, on décida de déplacer toute la construction d'un seul bloc, sur une voie ferrée. Six ans furent nécessaires pour mener à bien toutes les études et les préparatifs de cette opération exceptionnelle : il fallait déplacer de 810 m un édifice voûté, long de 60 m, large de 30 m et pesant près de 15.000 tonnes avec sa crypte du XIVe siècle.

Des études exhaustives furent menées, dans différents domaines, pour permettre cette opération et lui donner toutes les chances de succès :

- Etude archéologique de l'église et de son mobilier; ceci a permis de préciser son histoire, de retrouver des tombes et des vestiges des églises antérieures.

- Etude architectonique de l'église : ce fut l'occasion de constater certains désordres dans les voûtes et de décider des renforcements nécessaires pour garantir la stabilité et la rigidité de l'édifice durant le transport. On renonça, alors, à déplacer la tour avec l'ensemble, en raison de son mauvais état de conservation et de ses fondations insuffisantes.

- Etude du sous-sol sur le parcours et sur le nouveau site de l'église : le sous-sol de Most est tout entier bouleversé par d'anciennes carrières et galeries de mine, plus ou moins remblayées. Il a fallu renforcer le terrain sur certains points du parcours pour éviter tout affaissement. Les fondations nouvelles de l'église furent particulièrement soignées.

- Etude et construction du matériel et de la voie pour le transfert : la motrice et les 52 boggies supportant l'église furent conçus pour cette opération. La voie fut terrassée sur tout le parcours, mais les superstructures (plaques de béton armé, supportant les poutrelles qui portaient les rails) ne mesuraient que 160 m de long et étaient démontées et remontées au fur et à mesure du mouvement de l'église sur la voie.

- Renforcement de l'église : la crypte et les voûtes de la nef firent l'objet de soins particuliers. L'église toute entière fut ceinturée par un chaînage de béton armé. Les piliers et les contreforts furent renforcés par des structures d'acier et repris en sous-œuvre, pour les faire reposer sur des blocs de béton. Pour conférer à l'ensemble une rigidité suffisante durant le transport, il fut nécessaire de l'enserrer dans une structure formée de poutrelles d'acier entrecroisées dans les trois dimensions. Les éléments les plus fragiles, décor sculpté des portes, remplage des fenêtres, ont été démontés et transportés à part.

L'église fut soulevée de 15 cm au-dessus de ses fondations anciennes et commença son voyage. Le mécanisme de traction consistait en 4 vérins hydrauliques à l'arrière du bâtiment pour pousser et 4 à l'avant pour le freiner, contrôlés et réglés automatiquement par ordinateur depuis la salle de contrôle. Chacun des 52 boggies placés sous l'église était équipé d'un vérin hydraulique et contrôlé de la même façon. De très nombreux points de contrôle sur la voie, les boggies et le bâtiment étaient reliés aux centres de contrôle automatique pour suivre dans ses moindres détails le déroulement du transfert et pouvoir intervenir dans l'instant.

Grâce à ces remarquables travaux, le transfert se déroula sans aucun incident : l'église parcourut ces 810 m à la vitesse de 2 à 2,45 cm/minute en 646 heures (jour et nuit, des équipes se relayèrent). Le bâtiment n'a subi aucune déformation du fait du transfert. Mais l'ampleur des moyens mis en œuvre montre bien que le transfert en bloc d'un grand monument ne peut être qu'une solution d'exception.

Fig. 1. - Renforcement des voûtes.

Fig. 2. - Reprise en sous-œuvre d'un pilier.

Fig. 3. - Ceinture de renforcement en béton armé.

Fig. 4. - Motrice utilisée pour le transfert.

Fig. 5. - Vérin hydraulique.

Fig. 6. - Centre de mesures principal.

Fig. 7. - Salle de contrôle principale.

Fig. 8. - Salle de contrôle principale.

Fig. 9. - L'édifice en cours de déplacement.

Fig. 10. - Vue générale.

Fig. 11. - Plan pour l'insertion de l'église dans son nouveau site.

ESUMEN

ıra abrir une nueva mina de carbón a cielo abierto — como suele hacer en Bohemia — fue preciso destruir en parte la ›queña población minera de Most. Su iglesia, de estilo gótico rdío, reconstruida en el siglo XVI, presentaba gran interés ıra la historia de la arquitectura en esta región. Esa iglesia ·tá cubierta por elegantes bóvedas nervaduradas. Se deció, para asegurar su salvaguardia y puesta en valor, traslaırla en un barrio donde sería rodeada por otros monumentos ıtiguos. Estas construcciones iban a constituir un conjunto teresante entre los nuevos barrios de Most.

ſás bien que desmembrar la iglesia para reconstruirla desıés, se prefirió trasladar todo el edificio en bloque (sin su ımpanario), sobre une vía férrea. Los estudios y preparatiɔs para esta operación excepcional tomaron seis años: se ·ataba de trasladar de 810 m, con su cripta, un edificio aboedado, largo de 60 m, ancho de 30 m y pesando cerca de 5000 toneladas.

ara preparar esta operación y asegurar su éxito, varios estu'os fueron necesarios:
estudios arqueológicos de la iglesia y de su mobiliario;
estudios arquitectónicos de la iglesia: había ciertos desordenes en las bóvedas, y obras de fortelecimiento fueron necesarias para garantizar la estabilidad y la rigidez del edificio durante el traslado. La iglesia fue ceñida por una armadura de hormigón armado y rodeada por una estructura formada por viguetas de acero entrecruzadas;
- estudios geológicos del subsuelo del nuevo sitio y de la vía: el subsuelo de Most estálleno de galerías y pozos de antiguas minas;
- concepción y construcción del material y de la vía para el traslado: una automotriz y 52 boggies especiales para sostener la iglesia.

La automotriz, los boggies y varios puntos de medida en la vía y en la iglesia eran controlados por computador desde varios centros de control automático, para seguir el traslado y poder intervenir al instante. Gracias a estos señalados trabajos, el traslado se efectuó sin incidentes: la iglesia recorrió esos 810 m con una velocidad de 2 a 4,5 cm/minuto, en 646 horas (cuadrillas se turnaban día y noche). Pero la importancia de los medios empleados demuestra bien que el traslado de un gran monumento no puede ser más que una solución excepcional.