EXTERNAL STRENGTHENING OF AN 8000-TON GRAIN SILO IN TÖRÖKSZENTMIKLÓS, HUNGARY, WITH POLYPROPYLENE FIBRE REINFORCED SHOTCRETE





Dr. József Almási György Erdei Imre Édes Lóránt Koncz Prof. Árpád Orosz

In the external walls of a reinforced concrete grain silo originally completed in 1967, cracks formed and filtering rainwater impeded its operation. The load-bearing capacity of the silo proved insufficient, its steel reinforcement needed corrosion protection and the restoration of its protective cover was deemed necessary. These conditions necessitated thorough repair. After considering various strengthening techniques, an external shell of wire mesh reinforcement and fibre reinforced shotcrete was selected. In order to control crack formation the silo bins were filled with grain during the aplication of the shotcrete, thus tensile stress in the external shell was basically eliminated. Finally, a protective layer able to bridge surface cracks was applied, which also provided the silo with an aesthetic appearance.

Keywords: reinforced concrete silo, strengthening, restoration, shotcrete, fibre reinforcement, corrosion.

1. INTRODUCTION

The 800-wagon capacity reinforced concrete grain silo in Törökszentmiklós, Hungary, was designed by IPARTERV, and it was put into operation in 1967. See *Figure 1* for the ground plan of the silo block which contains 18 circular bins of 5 m diameter and an adjoining machine room. The thickness of the reinforced concrete walls of the bins and the machine tower is 14 cm and 16 cm, respectively.

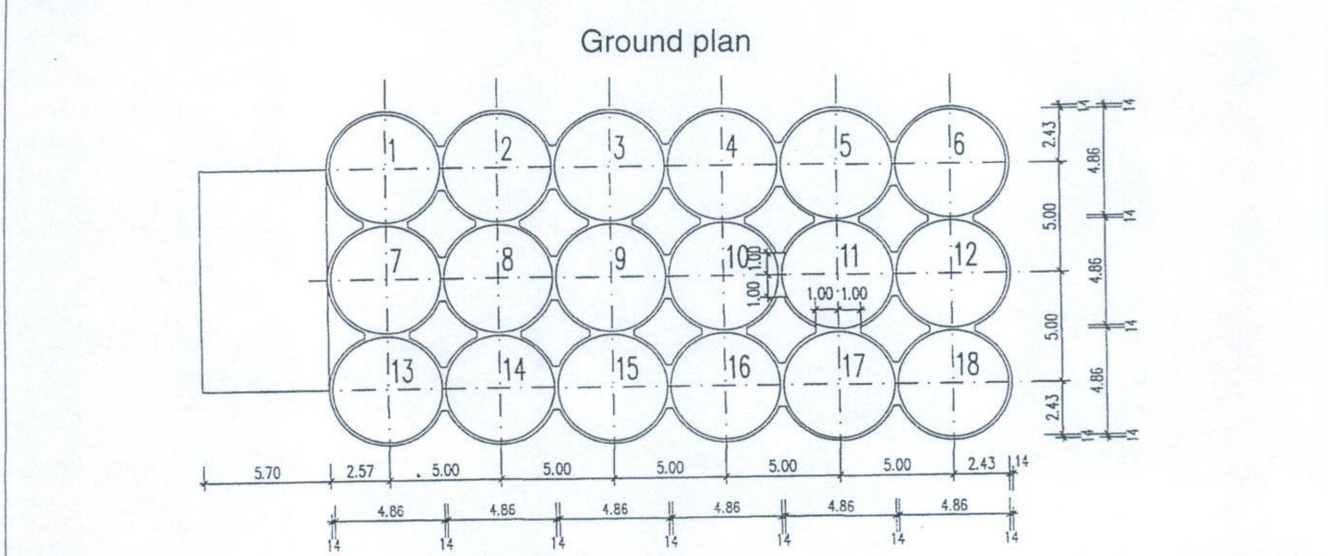
The function of the intermediate bins is grain storage. These consist of conical reinforced concrete funnels with centric discharge orifices at the bottom of circular bins. The funnels are supported by a reinforced concrete circular ring beam supported by columns. At the time of construction of the silo block, sliding formwork was applied and there are construction joints between bins 3 and 4 and bins 15 and 16 corresponding to the two stages of construction. Since it was presumed at the design stage that hairline cracks would appear in the bin walls a *protective layer* was applied on the external surface. During the lifting process of the sliding formwork local rupture and compaction imperfections were observed at the construction joint, which were mended during construction.

After some years of operation, *vertical cracks formed in the bin walls of the silo*. Cracks of growing intensity in the lower third of the bin walls allowed pelting rain to pass through the wall into the bins.

During the nearly 30 years of service of the silo further defects, *horizontal cracks* and corrosion of the steel reinforcement were observed. This necessitated a thorough examination.

The main findings of the diagnostic examination (Herkó, 1999) of the reinforced concrete bin walls are as follows:

Fig. 1 Ground plan of the silo block (Machine room)



- *The steel reinforcement* was 2x∅8/25 cm *according to the plan*, which was applied *at most locations* (but not everywhere) in the construction.
- The concrete cover on reinforcing bars is insufficient (15 mm on the average), which lead to scaling and alligatoring due to corrosion.
- The protective layer has aged and became brittle, and is thus in need of reconstruction.
- There are great variances in the condition of the different bin walls: some bins are in satisfactory condition while others are rather defective and need urgent repair.
- Concrete strength is generally insufficient (C12 on the average), concrete quality and density is uneven, and there are cavities in the concrete.

2. SELECTING A STRENGTHENING TECHNIQUE

The management of the Alföldi Gabonaipari Rt. (Alföldi Grain Industry Corp.) decided to conduct a competition to find the best method of restoration and strengthening. Competitors proposed the following strengthening techniques:

a) Attachment of external and internal *steel bands* on the bins, anchored in the interlocking section of bins.
b) Construction of a new, *internal reinforced concrete shell.*
c) Construction of an *external shell* of shotcrete.
d) Mounting *carbon fibre sheets* on the bin walls.

Techniques a) and b) can be applied to partially strengthen the silo, i.e. after repairing the bins in the worst condition *restoration can be scheduled* according to financial means.

In the case of an *external reinforced concrete shell*, it is difficult to carry out partial strengthening and divide the restoration process into stages. This technique features technological advantages and economic efficiency only if *the whole silo block is restored* at the same time.

Having considered all factors, the operator of the silo selected the strengthening technique that applies an external reinforced concrete shell, and the EKS-Service Ltd. was commissioned to execute the plan (Erdei, 2001). The detailed plan of execution was prepared by CAEC Ltd.

3. THE STRUCTURAL ANALYSIS

3.1 Loads

There are several methods for the calculation of the so-called silo pressure produced by the material stored in grain silos. However, the authors do not wish to introduce them in this paper. In the given case, the procedure proposed by Orosz (1998) was chosen for the following reasons:

- It is based on Janssen's theory, which is most commonly applied.
- It provides pressure values both for the storage and discharge states.
- It provides sets of corresponding values, thus it can be applied not only for vertical but also for skew walls.
- It is easily applicable and conservative, i.e. safe.
- It applies such ideal properties of material, which can be applied in the structural analysis *regardless of the type of corn*. Thus the serviceability of the silo does not depend on the type of corn to be stored in it throughout its life span.

z [m]	z/z_0	$1 - e^{z/zo}$	Silo pressure at an arbitrary depth			
			at storage [kN/m²]			at discharge [kN/m²]
			p_v	p_h	p_f	p_h
5	0.99	0.628	28.6	17.2	6.8	28.6
10	1.97	0.861	39.2	23.5	9.4	39.2
15	2.96	0.948	43.2	25.9	10.3	43.2
20	3.95	0.981	44.6	26.8	10.7	44.6
25	4.95	0.992	45.1	27.0	10.8	45.1
27	5.34	0.994	45.2	27.1	10.8	45.2

Table 1 Silo pressures

Physical properties of ideal grain

- Unit weight: $\gamma = 9$ kN/m³
- Coefficient of lateral pressure:

at storage: $k^s = 0.6$
at discharge: $k^d = 1.0$

- Coefficient of wall friction:

at storage: $m^s = 0.4$
at discharge: $m^d = 0.24$

Geometrical data of reinforced concrete bins:
Diameter of the centric surface of the bin wall: $D = 5.00$ m
Internal diameter: $D_i = 4.86$ m
Wall thickness: $t = 0.14$ m
Height of stored grains above the funnel: $H = 27.0$ m

The critical depth is the same at storage and at discharge, since,

$$k^s m^s = k^d m^d$$

$$z_0 = D_i / 4km - 4.86 / (4 \times 1 \times 0.24) = 5.6 \text{ m}$$

The *maximum values of silo pressure* produced by the grain stored in a bin of infinite height are as follows:

- **At storage**

Vertical pressure:

$$p^s_{v,max} = \gamma \; z_0 \quad = 45.5 \text{ kN/m}^2.$$

Horizontal pressure:

$$p^s_{h,max} = \gamma \; z_0 \, k^s = 27.3 \text{ kN/m}^2.$$

Friction pressure:

$$p^s_{f,max} = \gamma \; z_0 \, k^s \, m^s = 10.9 \text{ kN/m}^2.$$

- **At discharge**

$$p^d_{v,max} = \gamma \; z_0 \quad = 45.5 \text{ kN/m}^2,$$
$$p^d_{h,max} = \gamma \; z_0 \, k^d \quad = 45.5 \text{ kN/m}^2,$$

$$p^d_{f,max} = \gamma \; z_0 \, k^d \, m^d = 10.9 \text{ kN/m}^2.$$

At an arbitrary depth, the silo pressure can be calculated using the Janssen formula:

$$p(z) = p_{max} \, (1 - e^{z/zo}) \quad \text{(See Table 1.)}$$

Note that it is assumed in this calculation method that,

$$p^s_v = p^d_v = p^d_h \text{ and } \quad p^s_f = p^d_f.$$

In our case it is sufficient to consider only horizontal pressure. See *Fig. 2* for its distribution along the height.

Instead of an exponential pressure distribution, the distribution of the maximum horizontal pressure is given by straight lines drawn from the origin to the critical depth, z_0, passing through the intersection of a vertical line at $p_{h,max}$ and the tangent of the theoretical curve, according to Orosz's proposal (1998). The theoretical pressure values are lower than these limit lines in all cases so this approximate method proves to be conservative and dependable.

3.2 The state before strengthening

3.2.1 Design forces and ultimate forces

The tensile force in the bin walls, applying the "boiler" formula, is,

$$F_h = n \times R_i \times p_{h,max} = 1.3 \times 2.43 \times 45.5 = 144.0 \text{ kN/m},$$

where, $n = 1.3$ safety factor,
$R_i = 2.43$ m internal radius of the bin.

The daily and seasonal temperature effect is approximately 10% of the discharge pressure, thus the design ring force is,

$$F_{h,d} = 144.0 + 14.4 = 158.4 \text{ kN/m}.$$

The steel reinforcement according to the original plans:

2x∅8/25; $A_s = 402$ mm²/m .
Steel grade: B 60.40, $R_{u,s} = 350$ N/mm²

The ultimate force is,

$$F_{h,b} = 402 \times 350 = 140.5 \text{ kN/m} < 158.4 \text{ kN/m},$$

the deficiency is app. 11%.

In the executed bin walls, the arrangement of reinforcing bars (as found in the explorations) roughly corresponds to the plans. However, due to corrosion, the cross-section of steel bars must be reduced by approximately 10% in the calculation, so the actual ultimate force, assuming steel reinforcement of $A_s \cong 360$ mm²/m, is,

$$F_{h,ex}^{k} = 360 \times 350 = 126 \text{ kN/m} < 158.4 \text{ kN/m},$$

and the deficiency is approximately 20%. Such a deficiency of load-bearing capacity necessitates strengthening based on structural analysis.

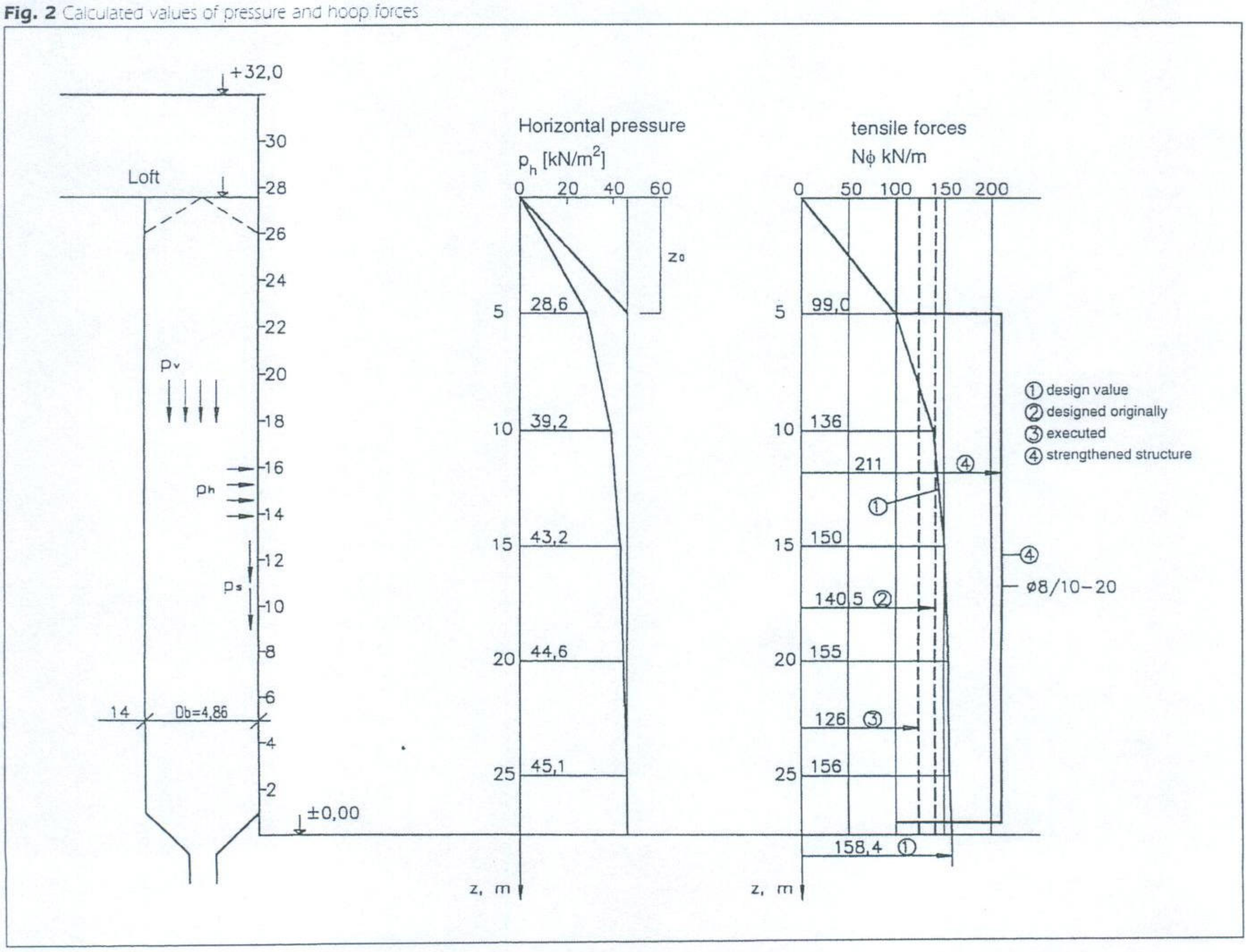
3.2.2 Cracking sensitivity

When carrying out the check of cracking sensitivity a method proposed by Scandinavian researchers was applied, according to which the silo wall is safe if the cracking sensitivity coefficient,

$$k = A_{sh} / D_i \geq 0.24 ,$$

where A_{sh} is the applied horizontal reinforcement [cm²/m],
D_i is the internal diameter of the bin wall [m].

Fig. 2 Calculated values of pressure and hoop forces



In our case, substituting the reinforcement ***according to plan*** gives:

$$k_t = 4.02 / 4.86^2 = 0.17 < 0.24 .$$

substituting the ***existing*** reinforcement

$$k_t = 3.60 / 4.86^2 = 0.15 < 0.24 .$$

Thus, neither case is safe for cracking sensitivity according to the proposed limit.

The required area of reinforcement based on cracking sensitivity is,

$$A_{s,r} = k \times D_i^2 = 0.24 \times 4.86^2 = 5.66 \text{ cm}^2/\text{m} > 3.60 \text{ cm}^2/\text{m}.$$

Thus, an increase of approx. 60% is necessary.

3.3 THE STATE AFTER STRENGTHENING

Quantity of steel reinforcement

According the structural analysis, when calculating the steel reinforcement needed for strengthening, there are two options:

- taking the existing reinforcement into account and designing supplementary reinforcement, or
- applying the quantity of reinforcement that can take the total tensile force.

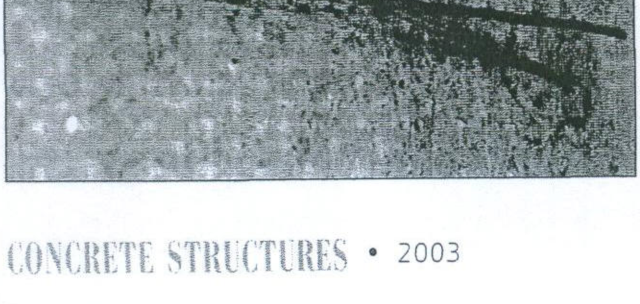
In the preliminary examinations it was observed that concrete strength was relatively low and uneven, there were cavities in the concrete at construction joints, the concrete cover was insufficient and there were severe cracks in the bin walls. These facts made it questionable whether overlap splices of the existing steel reinforcement would still be effective. The exploratory examination raised some doubts about the amount of reinforcement actually applied at construction and also about the spacing between reinforcement bars. *Figures 3 and 4* illustrate that these doubts were well grounded. Following high-pressure washing of the surface it was found that splices of insufficient overlapping opened up and the concrete cover peeled. It was also revealed that, at some locations, the distance between reinforcing bars was more than 40 cm instead of the designed 25 cm.

Due to the above-mentioned facts, it was decided to neglect the existing reinforcement and therefore the *total tensile force would be taken by the new, strengthening reinforcement.*

The new reinforcement, according to the design of strengthening, is Ø8/10–20 welded wire mesh of steel grade B 60.50, which has a cross-sectional area of $A_s = 503$ mm²/m. The ultimate force is,

$$F_{ult} = 503 \times 420 = 211.0 \text{ kN/m} > F_d = 158.4 \text{ kN/m}.$$

Fig. 3 Opened up overlap joints



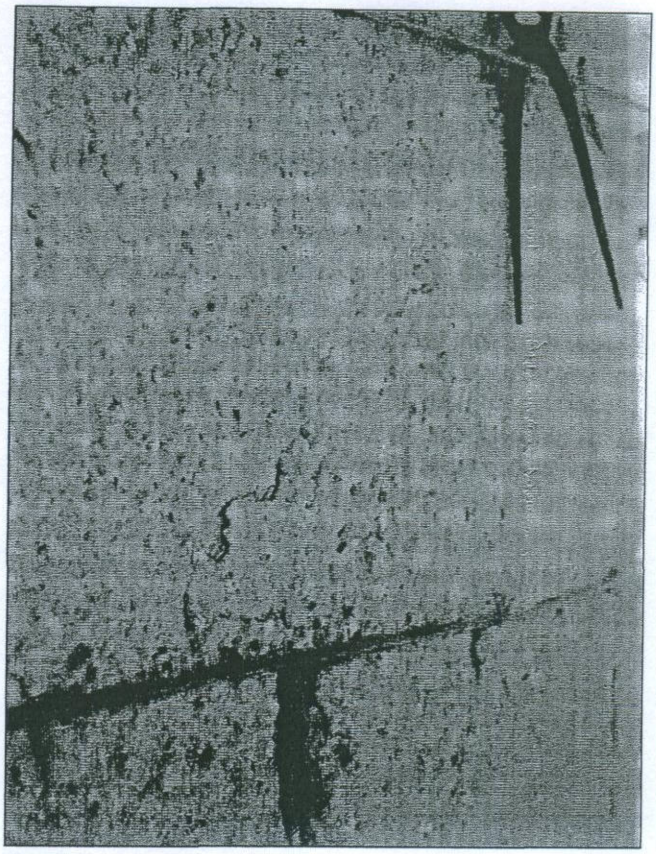


Fig. 4 Spacing of steel reinforcing bars

The cracking sensitivity coefficient is

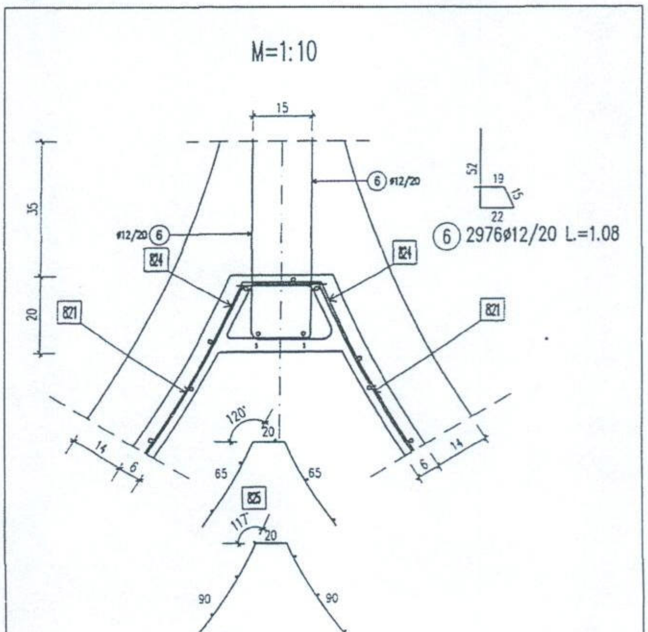
$$k_t = 5.03 / 4.86^2 = 0.213 < 0.24,$$

which is still less than the proposed lower limit, but it is closer to that.

Anchorage of the welded wire mesh

The dimensions of the welded wire mesh to be placed in the shotcrete shell were chosen in such a way that no vertical splice was necessary, except in the corner bins.

Fig. 5 Reinforcement at the anchorage of the welded wire mesh



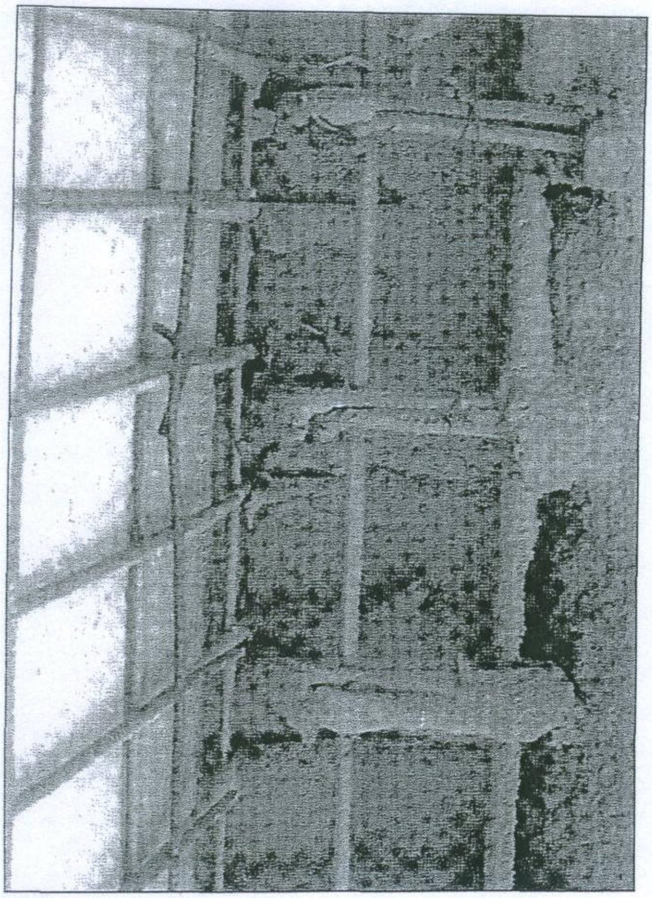


Fig. 6 Anchorage of the welded wire mesh

The anchorage of the welded wire mesh at the junction of the bins is illustrated in *Fig. 5*. A vertical reinforced rib is formed which is anchored to the junction of the bin walls by tie bars bonded in holes bored into the concrete. *In order to check the efficiency of the anchorage of the tie bars, on-site pull-out tests were performed. The required depth of bored holes and the adhesive strength were determined on the basis of the test results.* This is common to the design of such strengthening structures and it is always necessary to perform such a test since this is the only reliable way to find the anchoring force which depends on the actual concrete strength. See *Fig. 6* for structural design details of the anchorage of the welded wire mesh and for the construction joint to be formed.

Filling in the bin during the shotcreting

If the bin is filled in with grain during shotcreting and the discharge pressure and the ring force are produced after hardening of the concrete shell, then no tensile stress will be produced by the silo load in the external shell, and there will be only compressive stress when the silo is empty. This is an effective way of preventing crack formation as well as controlling crack width. However, considering construction safety regulations this procedure can be followed only if there is no danger of splitting and failure of the bin during reconstruction.

Assuming that the actual unit weight of the corn ($g = 8\ kN/m^3$) acts as a short-time load (for approx.. two weeks), the hoop force is,

$$N_g^0 = 0.8 \times p_{h.d} \times R_i / 0.9 = 0.8 \times 45.2 \times 2.43 / 0.9 = 99.5\ kN/m.$$

Considering the ultimate force based on the existing reinforcement, the safety rate is,

$$n = N_{g.ult}^k / N_g^0 = 126 / 99.5 = 1.25 > 1.0.$$

Therefore the silo bin can be filled in at a low risk.

4. PRINCIPLES AND CHARACTERISTICS OF THE STRENGTHENING TECHNIQUE

The ***advantages*** of the application of an external reinforced concrete shell are as follows:

- The strengthening needed for static reasons, the reconstruction of the bin walls, corrosion protection of the steel reinforcement and the provision of a silo block with an aesthetic appearance can be achieved in a single technological procedure.
- During the execution of strengthening, the operation is independent and there are basically no restrictions.
- Strengthening of a silo block can be performed in a few months.

Nevertheless, the following factors are to be taken into consideration at the application of the strengthening technique:

- The execution can be started *only in good weather conditions.*
- It is advisable to add PP plastic fibre reinforcement to the concrete in order to prevent the formation of shrinkage cracks in the relatively thin (6-8-cm-thick) shotcrete shell.
- Special care should be taken to cure the concrete properly.
- Care should be taken to protect neighbouring buildings and completed surfaces from drifting dust produced at surface cleaning and concrete projection, taking the prevailing wind direction into account.

The technological steps of the strengthening technique are as follows:

- High-pressure sandblasting of the surface.
- Removal of loose concrete flakes and the application of a corrosion protective coat.
- Mounting and fixing the steel reinforcement, i.e. the welded wire mesh and the tie bars.
- *Filling in the bin with grain prior to concrete projection.* The grain should remain in the bin until the new concrete shell is 14 days old.
- Concrete projection, evening; construction joints.
- Application of a protective layer.

Note that the properties of the original concrete of the bins should be taken into account when specification of the shotcrete grade is drawn up since the composite action of the existing wall and the new shell can be ensured only if their values of longitudinal rigidity are close. It is well known that structures of higher stiffness "take more load", and those of lower stiffness "evade loads". *Thus, in order to facilitate a composite action between existing and new structures, it is very important to ensure that their deformation and stiffness properties are close enough.* In our case, due to the low strength of the existing concrete, it was presumed that the shotcrete shell of far higher stiffness would provide the major proportion of the total load-bearing capacity. Therefore, it was deemed to be advisable *to make the new external shell capable of supporting the total silo load, which was taken into account during the design of its reinforcement.*

5. EXECUTION, TECHNICAL INSPECTION AND QUALITY CONTROL

5.1 Pre-treatment of the concrete surface

For the restoration of bin walls, a scaffolding was assembled which provided access to three bins at the same time.

The success of the whole process of reconstruction and strengthening depends on the pre-treatment of the concrete surface. In order to facilitate a composite action between the existing concrete and the shotcrete, the silo surface should be carefully cleaned, loose and alligatoring concrete parts should be removed until a concrete layer of sufficient strength (app. C12) is reached.

The existing outer cover, the cement mortar and other materials that impede proper contact (limestone and silicate dust, fine sand, etc.) were removed from the bin walls and the surface of the machine room. For surface cleaning a sandblasting method was applied and mobile sand throwing machines (using sharp silica sand of 0.5-1.25-mm grains) were employed. An environment-friendly electric compressor of 20 m^3/min capacity provided 7 m^3/min/machine air volume and 7-8-bar pressure required for dry sandblasting.

Manual and mechanical chisels were used to remove loose and low-strength concrete. Chiselling-off was at some locations as deep as 50-70 mm. Since this process was simultaneous with sandblasting the revealed reinforcing bars were also sandblasted. The reduction in cross-sectional of the revealed reinforcement bars was *more than the presumed rate*.

After surface cleaning and chiselling, it was observed that more material was needed for replacement than it was presumed based on preliminary examinations.

See *Figures 3 and 4* for concrete surface defects revealed on the cleaned surface.

5.2 Checking the existing concrete of the bin wall

Although the preliminary expert examinations had not provided detailed data, it was obvious that the concrete strength was relatively low and uneven. As it was unclear whether a bond-tensile strength of 1 N/mm^2 (which is sufficient for the bond joint of the existing bin wall and the new concrete shell) could be achieved, great care was to be taken to anchor the welded wire mesh in the shell.

A visual inspection of the silo led to the conclusion that the formation of vertical cracks was caused by defective grouting of the supporting bar holes. Due to the severe corrosion of the horizontal reinforcement, which led to peeling concrete cover and alligatoring and bleeding of more than 10mm width, there was a danger of accident, which in turn made a thorough general examination inevitable.

CAEC Ltd. measured the compressive and bond strength of the existing concrete surface and a report on the rupture strength tests of the steel reinforcement was also prepared.

Concrete strength was examined at 5 locations using non-destructive testing, employing Schmidt hammer. The measured mean concrete strength was 16.0 N/mm^2, the characteristic concrete strength was 12.0 N/mm^2.

Bond strength was examined by tearing a 50mm adhesive pad off the surface at 5 locations. The mean bond strength was 1.2 N/mm^2, the measured minimum strength was 0.52 N/mm^2.

Based on these examinations it was observed that the bond strength was sufficient but uneven. It was established that the concrete grade was C12 and that the ultimate strength of reinforcing bars, corresponding to their measured ultimate strength, was 300 N/mm^2.

Following each stage of surface cleaning by sandblasting and mechanical and manual exploration, the resulting surface was thoroughly checked for dust, old cover, impurities and other loose matter.

5.3 Properties of shotcrete

Requirements:

- Concrete grade: C 20 (MSZ 4719 – MSZ 4720)
- Maximum grain size: D_{max} = 8 mm
- Continuous grain-size distribution
- Low initial crack-proneness
- Maximum size of air pockets: 5 mm
- Dosage of polypropylene plastic fibre: 1.0 kg/m^3
- Special care at concrete curing

Accordingly, the deformation capability of the concrete to be applied should be higher than average and PP plastic fibre reinforced concrete satisfies this requirement. A further advantage of plastic fibre reinforcement is that it prevents formation of shrinkage cracks at an early stage, and it reduces the amount of concrete falling off at shotcreting.

Concrete composition

Shotcrete was made of factory-prepared sacked concrete mixture to ensure an even concrete composition.

The total amount of shotcrete was made of factory-made shotcrete mixture for spray application, to which water was added within the ejector (dry process).

The composition of shotcrete is as follows:

	(weight) kg
Water (water-cement ratio = 0.25)	100 l/m^3
Portland cement CEM I 42.5	400 kg/m^3
Mineral sand (0-8 mm)	1689 kg/m^3
Chemical agent	12 kg/m^3
PP plastic fibre	1 kg/m^3

The strength grade of the 25kg sacked concrete, type Keston MM4 and MM8, is C20. Polypropylene fibre was added in the factory.

Strength control of shotcrete

The manufacturer constantly monitored the flexural-tensile strength and the compressive strength of the shotcrete mixture. Monitoring involved the following strength tests:

Laboratory testing of 4 x 4 x 16 cm^3 test specimens (conforming to MSZ EN 196-1: 1996, sections 9.2 and 9.3) resulted in 6.88 N/mm^2 mean flexural-tensile strength and 45.86 N/mm^2 mean compressive strength. Both of them are higher than the relevant values in the technical specification.

The strength and evenness of projected shotcrete was checked by *tear-off tests applying adhesive pads*. The measured mean tearing-off tensile strength was 1.28 N/mm^2, which is sufficient to ensure a *proper composite action* with the protective layer.

CAEC Ltd., which prepared the working design, carried out sampling observations.

Concrete grade

Laboratory tests (conforming to MSZ 4715) of 15 x 15 x 15 cm^3 test specimens cast on site resulted in a concrete grade of

C20 according to MSZ 4719, based on the compressive strength of the concrete. The test specimens reached the characteristic strength value (of 25 N/mm^2 for concrete cubes) corresponding to this concrete grade.

The performed tests proved that;

- the shotcrete is of grade C20,
- its quality is even, and
- concrete surfaces are properly evened.

5.4 Reinforcement fixing

Reinforcing steel

According to the strengthening plan, welded wire mesh was fixed on the surface of the bin walls between levels +2.0 m and +22.8 m, +22.8 m and +27.4 m, +27.4 m and +32.0 m is ∅8/10–20, ∅7/10–20 and ∅4.2/10–20, respectively. The steel grade of the wire mesh is B 60.50, MSZ 339 strength class.

Checking the anchorage of the wire mesh

Fig. 5 illustrates the overlap splices of wire mesh fixed on the external surface of the bins and their anchorage at the interlocking section of bins.

To check the reliability of the anchorage, on-site pull-out tests were performed on tie bars bonded into the bored holes of the wall. The average of measured pull-out forces was 55 kN, which is higher than the 39 kN force specified in the specification. Tie bars of ∅12 mm diameter were bonded using adhesive type AM 1000 quick mix (Techno-Wato) in 350-mm-deep and ∅16 mm diameter holes bored in the bin walls.

Fixing the welded wire meshes

Welded wire mesh fixed with dowels to bin walls are arranged in a 50/50 cm grid. These dowels provide the required stiffness during shotcreting and they also ensure a joint to the relatively weak existing concrete.

In case of the given bin size, *the welded wire mesh*, consisting of ∅8 mm steel bars, *can be bent over the surface*. A wire mesh of larger bar diameter would need pre-bending before fixing, and would also cause fixing difficulties.

After checking the cleanliness of the surface, 35-cm-deep holes were bored in the interlocking section of bin walls, into which the *anchoring reinforcement (tie bars)* would be placed. Doubled anchoring bars were bonded in the holes at 20 cm spacing, along the length of the interlocking section of approximately 22 cm width. Bond quality was checked by pull-out tests at random locations.

Before bonding the tie bars, on-site bent, canal-shaped wire mesh was fixed at the interlocking vertical segments of the bins and they were joined to the wire mesh fixed on the bin walls with 0.90 m and 0.65 m overlaps, alternately. Two steel dowels per m^2 were applied for mounting and fixing the welded wire mesh, and a minimum distance of 1 cm from the wall surface was kept.

The fixing of the 2.40 x 6.00 m wire mesh needed special care and attention with regard to lifting to the required height along the external side of the scaffolding. Some anchored nodes of the scaffolding had to be released so that the wire mesh could be moved to the bin wall. Moreover, some difficulties occurred fixing the bending hoop ∅8 mesh over the bin surface.

5.5 Shotcreting, construction joints

The surface was pre-moistened before shotcreting to obtain a mat surface ideal for shotcrete.

Concrete projection was done from the top to the bottom of the bins.

Due to the *results of the structural analysis* and cracking sensitivity bin walls were *externally strengthened with a 6 cm-thick reinforced shotcrete shell* between levels +2.00 and +26.70 m. In order to *protect the reinforcement against corrosion* and to prevent the outer concrete layer from peeling off, bin walls between levels +26.70 m and +34.00 m were strengthened with 3 cm-thick shotcrete shells with a wire mesh for crack prevention.

The minimum thickness of the concrete cover in the case of the 6 cm-thick and the 3-cm-thick shells was 20 mm and 15 mm, respectively.

At the horizontal construction joints of the concrete shells, rigid cut-off elements (made of steel profiles, bent over the surface of the bin wall) were applied to reduce the formation of hairline cracks. This ensured that the shotcrete shell and the concrete cover were of sufficient thickness and properly compacted. Vertical construction joints were formed at the vertical anchoring ribs. In the first stage, the strengthening shell was only 6 cm thick at the interlocking section of the bins, after which, at the strengthening of the next silo bin in the second stage, the anchoring rib was completed, which entirely covered the construction joint. The concrete crust was removed from the steel reinforcement before the second stage was started.

After the required thickness was reached, the concrete was levelled, partly to facilitate the application of the protective layer and to ensure a continuous and even layer thickness, and partly to provide the silo with aesthetic appearance.

The shotcreting was arranged in such a way that vertical construction joints were formed only at the interlocking sections of the bins. At horizontal construction joints, bent steel profiles (as mentioned above) fixed to the welded wire mesh, were applied.

The applied construction joints feature the following advantages:

- They ensure that the concrete cover over the wire mesh is 25 mm thick and even.
- The stiffness of the steel profile ensures that concrete projected around will be sufficiently compact.
- After the removal of the steel profile, concrete will be shooting on a compact surface to form a new concrete shell.
- The construction joint is perpendicular to the surface, which prevents such a case that levelling of the new shell results in a thin concrete layer on the existing concrete, which may lead to alligatoring and peeling off.

According to experience, the formation of hairline cracks (which is otherwise unavoidable) is very rare at such construction joints.

By the application of a bent steel profile on a bin wall, an evenly curved surface was formed and earlier rough areas were covered. This provided the silo with an aesthetic appearance.

5.6 Protective layer

The application of a protective layer is indispensable as it covers unavoidable hairline cracks forming in the shotcrete shell (mainly around construction joints, caused by shrinkage, cracks of the existing bin wall and temperature effects). It prevents rainwater from filtering into cracks and having a damaging effect and it provides the silo block with an aesthetic appearance. The application of a protective layer was also advisable because shotcrete often has air pockets, thus the new shotcrete shell needs special protection against weather effects.

Requirements for the protective layer, applied in layers, are as follows:

- elasticity, capability of bridging cracks.
- capability of adhering to an *existing* surface.
- resistance to UV radiation.
- vapour permeability.
- light reflective properties (to reduce the heat effect of solar radiation).
- ability of being mended.

The applied material, type KESTON FLEX II, satisfies all the above requirements. Based on tear-off tests applying adhesive pads, the surface bond strength was nearly 1 N/mm^2, thus almost twice the specified value (0.5 N/mm^2) was obtained.

The life span of the protective layer is approximately 10-15 years, so its condition should be examined once in every 10 years.

Both the shotcrete shell and the protective layer were applied on the existing, cracked structure, which may lead to formation of hairline cracks due to static reasons and temperature effects. Therefore, a protective layer was selected that can bridge a crack width of 0.2 mm.

6. CONCLUSIONS

After more than 30 years of service the reinforced concrete silo required urgent reconstruction as its defects impeded functional operation. Thorough expert examinations were carried out to explore the defects. It was observed that the cracked state of the silo needed improvement and strengthening was also necessary for structural reasons. After a careful analysis of various strengthening techniques, the optimal technique was selected: construction of an external reinforced concrete shell was proposed.

There are some reinforced concrete silos abroad, namely in Canada (Collins, 1997) and the former Yugoslavia, which were strengthened with shotcrete shells. However, in these silos, the reinforced shell reached only two thirds of the total height of the silo wall, and no external protective layer was applied. In the case of the Canadian silo, *crack formation* in the concrete shell was observed a few years after strengthening, which stresses the importance of the application of an external protective layer that can bridge cracks.

In Hungary, the first silo that was strengthened with an external shotcrete shell was a 20000-ton silo in Marcali (Orosz – Csató – Tamáska, 1999). In this case, a shell was formed along the total height of the silo with reinforcement up to 2/3 of its height, above which reinforcement was applied only at a few locations. However, the total surface of the silo was covered by a protective layer. This was the first silo which employed plastic fibre reinforced shotcrete and the experience gained was promising. Following the strengthening and after three years of operation (with total utilization of capacity) no cracks or defects were observed in the silo. There was only one location (at a horizontal construction joint) where the paint was peeling off.

Compared to these cases, the following improvements were carried out in the strengthening technique applied at the silo in Törökszentmiklós:

- The total height of the new shell is made of shotcrete with reinforcement.
- The reinforcement applied in the strengthening shell is capable of taking the total tensile force produced by silo load.
- The horizontal reinforcement (the welded wire mesh) has no splices, except at the corner bins.
- There were only horizontal construction joints in the shotcrete shell on the bin wall.
- Application of steel profiles at construction joints had a favourable effect: hardly any hairline cracks were formed after concrete shooting.

During the reconstruction process the client regularly checked the materials to be applied and their quality certificates, either directly or indirectly, via the technical inspector. Each significant stage of the reconstruction was carefully checked, and each completed stage gained acceptance individually.

Based on regular technical inspection and quality control during the reconstruction process, the concrete grade of shotcrete is C20.

The technical inspector observed that surface cleaning, reinforcement fixing, shotcreting projection and curing, together with the application of the protective layer were carried out properly.

It was repeatedly proved that plastic fibres reduce the crack-proneness of shotcrete which has lately been a well-known fact in case of large concrete surfaces (e.g. pavements, carriageways).

The primary advantages of the strengthening technique applying an external shotcrete shell are as follows:

- Structural strengthening, reconstruction and corrosion protection can be performed in the same technological stage.
- During reconstruction the silo can remain in operation with basically no restrictions.
- The protective layer provides the wall long-term protection and an aesthetic appearance.

In future cases of silo restoration more care should be taken when examining the structural condition, both with regard to determining the actual concrete strength and the exploration of the reinforcement.

The contractor kept to the specified time schedule of reconstruction at each stage, thus the client did not have to face any unexpected difficulties in the operation.

The conclusion can be drawn that:

- the introduced strengthening technique is of high quality and effectiveness and its application needs a short time period, and
- it ensures undisturbed operation of the silo for a long time.

7. REFERENCES

Collins, M.P., Seabrook, P.T., Kuchma, D., Sacré, P. (1997), "External Repair of Cracked Grain Silos", *Concrete International,* 1997. nov. pp. 22-28.

Erdei, Gy. (2001), "Ajánlatelemző szakvélemény a törökszentmiklósi Alföldi Gabona Rt. 8000 tonnás gabonasilójához" (Expert opinion for deliberation of tenders on the 8000-ton grain silo of the Alföldi Grain Industry Corp. in Törökszentmiklós) in Hungarian, 2001. *Manuscript.*

Folic, R., Ivanov, D., Desovski, Z. (1995), "Results of Testing and Repair of Cells of 8000 Ton Silo". *Proceedings of the Sixth International Conference on Structural Faults and Repair.* London, Volume 3. pp. 67-74.

Herkó, D. (1999), "A törökszentmiklósi 8000 tonnás vasbeton gabonasiló szerkezeti felülvizsgálata" (Structural examination of the 8000-ton reinforced concrete grain silo in Törökszentmiklós), in Hungarian, *Expert opinion,* 1999. *Manuscript.*

Orosz, Á. (1998), "Megjegyzések a silónyomás számításához vasbeton gabonasilók esetében" (Notes on the calculation of silo pressure in case of reinforced concrete grain silos), in Hungarian, *BME Építőmérnöki Kar*

Vasbetonszerkezetek Tanszéke Tudományos Közleményei, 1998, pp. 172-180.

Orosz, Á., Csató, Gy., Tamáska, J. (1999), "A marcali 2000 vagonos gabonasiló megerősítése" (Strengthening of a 20000-ton grain silo in Marcali, Hungary), in Hungarian, *Vasbetonépítés,* volume I., 1999/2, pp. 55-62.

Orosz, Á. (2001), "Vasbeton silók javítási módszerének megválasztása" (Selecting a restoration technique for reinforced concrete silos), in Hungarian, *A BME Építőmérnöki Kar Hidak és Szerkezetek Tanszéke Tudományos Közleményei,* 2001. pp. 145-150.

Dr. ALMÁSI, József (1940) Civil Engineer, MSc. Places of employment: Láng Engine Works (1958), Foundation Engineering Company (1964-66), TUB Department of Reinforced Concrete Structures (1967-95). Managing Director of Cronauer Almási Engineering Consulting (CAEC) Ltd. since 1995. He is a member of the Hungarian Group of *fib* and holder of the László Palotás award (2002).

ERDEI, György (1954) Civil Engineer, MSc, Managing Director. Places of employment: HŐTECHNIKA Construction and Insulation Company (1979-81), SZOLNOKTERV (1981-86), PROFIL Engineering Studio (1987-90), MANOKA (Sevilla EXPO '92) (1991-92), REKONTERV Ltd. (1993-95), Erdei and Co. Ltd. (since 1996).

ÉDES, Imre (1951) Civil Engineer. Places of employment: GELKA (1970-71), Fűtőber (1975-76), Alföldi Grain Industry Corp. (since 1976), Head of the Technical Department.

KONCZ, Lóránt (1967) Civil Engineer, MSc, Technical Manager. Places of employment: Adam Hörning GmbH, Mauer & Söhne GmbH, Germany (1992-95), Technical Manager at the EKS-Service Ltd. (since 1995).

Dr. OROSZ, Árpád (1926) Civil Engineer, MSc, retired University Professor. Places of employment: MÁV Bridge Construction Company (1953), Railway Scientific Research Institute (1954-56). Teacher at the Technical University of Budapest since 1956, Head of the Department of Reinforced Concrete Structures (1977-91). Retired in 1995. Specialist fields: design, restoration and strengthening of reinforced concrete structures, basins, silos, etc.