Assessment and repair of the bearing structure of a multi-storey parking garage

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Abstract
The construction of a multi-storey parking garage in Kikinda, Serbia started 20 years ago. The bearing structure was made of precast concrete columns, beams and ribbed floor slabs. After building of the bearing precast structure, the works were stopped and the unprotected structure was exposed to atmospheric influences (snow, rain, low temperatures). Many of the structure's elements were subsequently damaged due to insufficient concrete cover, badly performed reinforcement and incorrect manipulation of elements during erection. The initial defects and damage worsened to the extent that they not only severely affected the durability of the structure, but also jeopardised the stability and bearing capacity of some structural elements. Fissures and cracks, concrete spalling and reinforcement corrosion were registered on most of the structural elements. This paper presents the damage recorded, and the characteristic instances are illustrated by photographs. The results of subsequent testing of quality of built-in materials (concrete and reinforcement) are presented separately. To establish the actual condition of the bearing structure of the garage, an examination was

done under load testing. The analysis of the results of *in-situ* and laboratory testing and the data gathered through detailed visual examination provided the basis for real assessment of the structure. Some specific repair solutions for durability improvement and insuring of load bearing capacity and stability of the existing structure are also presented.
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garage, precast concrete structure, damage, assessment, corrosion, columns, corbels, durability, repair

INTRODUCTION

The structure of a multi-storey parking garage in Kikinda, Serbia was constructed during 1986–1987. After finishing the bearing structure, the construction works were stopped and the structure was left in an incomplete and unprotected condition (Figure 1).

Since the cessation of works on the structure, until recently, the bearing structure was exposed to atmospheric influences that caused various amounts of damage to different elements (fissures, cracks, concrete spalling and reinforcement corrosion, etc).

With the goal of finishing the structure and providing the designed bearing capacity, officials at the City of Kikinda requested the Institute for Civil Engineering to determine the condition of the structure and to propose appropriate measures of repair. During 2003, a detailed examination of the elements of the bearing structure was completed as well as destructive and non-destructive testing, including load testing of the structure (Folić *et al*., 2006).

Figure 1: Appearance of the garage

THE BEARING STRUCTURE

The structure consists of a ground floor, four upper floors and a loft. Dimensions of the structure in its plan are 41.2×41.2 m with net floor heights of (from the floor to the ceiling): ground floor 3.50 m, floors I–IV 2.40 m, loft 2.20 m. In Figure 2 the arrangement of the vertical bearing elements in plane are shown. The bearing structure of the building is skeletal, with a column grid of 5, 5.6, 10 and 10.6 m.

Basic elements of the bearing structure are:

- *Reinforced concrete columns* of X cross-section and external dimensions of 47×47 cm (Figure 3). The columns are precast of concrete class (CC) 50, designed in one piece and of different heights (3, 4 or 6 stories). The columns are reinforced with ribbed bars of RA 400/500. On all the reinforced concrete columns on which the beams rest, *short cantilever elements* (corbels) were implemented;
- *The longitudinal beams* are prestressed reinforced concrete beams, with a span of 4.5 m or 5.1 m and of 'L' or '⊥' cross-section (Figure 4). Dimensions of the beams in their cross-section are 35×35 cm. Cables of 7Ø5 mm for the adhesive prestressing, and ribbed reinforcement RA 400/500 were used. With the basic building plan of the structure, an additional protection from the torsion of longitudinal tail beams was provided by their connection to the columns and additional concreting of the joint between the beams and columns.

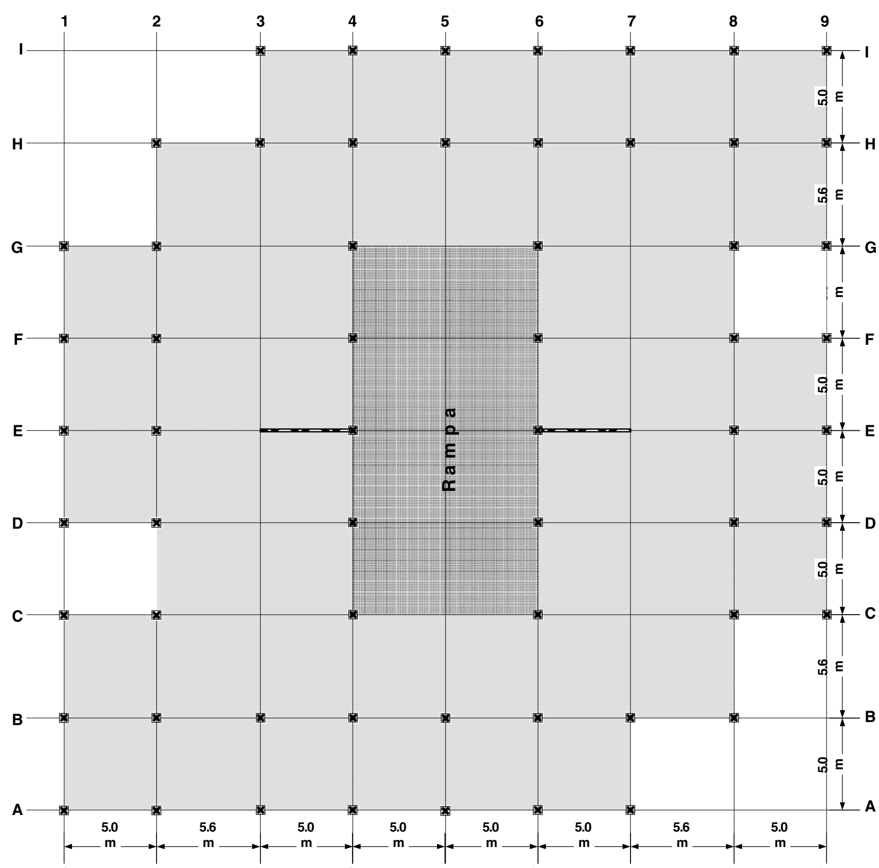

Figure 2: A characteristic plane (first floor)

Figure 3: Reinforced concrete columns and corbels

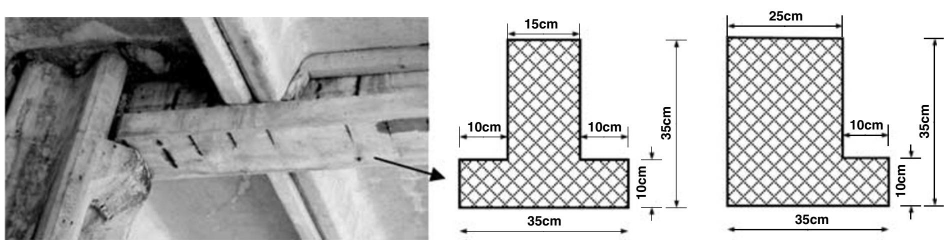

Figure 4: Prestressed reinforced concrete beams with '⊥' or 'L' cross-section

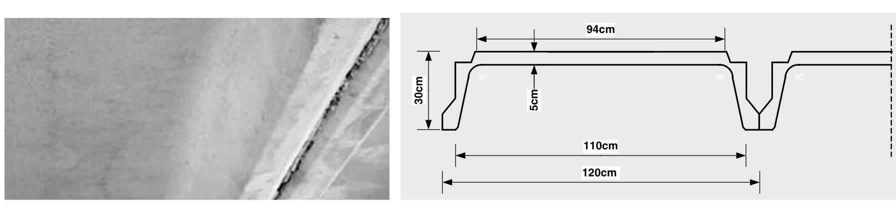

Figure 5: Prestressed ribbed floor slabs

- *The Π floor slabs (ribbed floor slabs)* have a width of 120 cm, a height of 30 cm, a slab thickness of 5 cm and are of different lengths of 4.8, 5.4, 10.4 and 9.8 m (ramp). The Π slabs were adhesively prestressed (cables of 7Ø5 and 3Ø3 mm were used). The joint between the adjacent Π slabs was monolithed on location with concrete (Figure 5).
- *The Π roof slabs (ribbed floor slabs)* have a width of 100 cm, a height of 24 cm, a slab thickness of 5 cm and a span of 9.8 m. The Π roof plates were adhesively prestressed (cables of 7Ø5 mm were used). The ribbed floor slabs were made of MB 40 concrete.
- *The reinforced concrete walls* were executed by concreting *in situ*. The wall thickness is $d = 20$ cm. MB30 concrete and ribbed reinforcement RA 400/500 were used.
- *The foundation engineering* was done in two ways: under the external columns, shallow footings were constructed and interconnected with stiffing beams, while the internal columns were founded on foundation continuous footing (strip) and widened on the column locations. The foundation structure was made of CC 30 and reinforced with ribbed reinforcement RA 400/500.

Figure 6: Uncompleted section of approach ramp

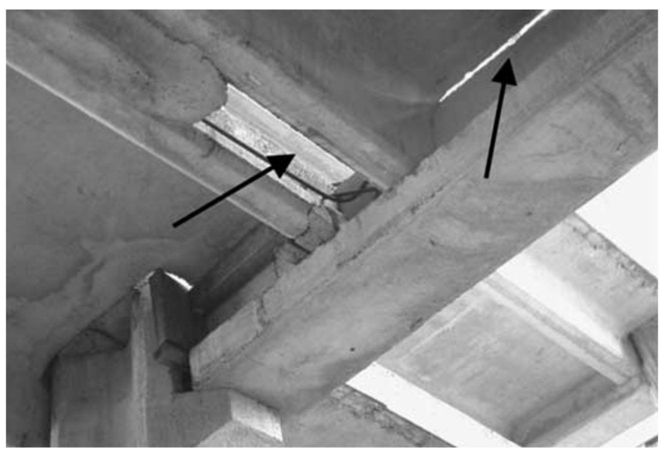

Figure 7: Uncompleted monolithisation of floor structure

EXAMINATION OF THE BEARING STRUCTURE

Several features on the structure were not completed, including the façade and the roof, the lower part of the approach ramp (Figure 6), the staircase and the entire finishing works (floors, fences, installations, etc). The monolithisation of floor structures was not entirely completed as well (concreting of ribbed parts between the Π-slabs, as well as the interconnection of Π-slabs and beams by *in situ* concreting layer over the beams) (Figure 7).

All the precast elements of the structure were carried out according to the project documentation. The concrete in the precast elements was built in and compacted according to the prescriptions, that is, a satisfactory homogeneity of the concrete and the flat and smooth surfaces of elements were achieved.

Columns

On reinforced concrete columns, the following defects and damage were registered:

– *Insufficient width of the protective concrete cover* (Figure 8): This defect was registered on approximately 70 per cent of all columns.

Figure 8: Insufficient concrete cover and stirrups corrosion

Figure 9: Corrosion of main reinforcement and longitudinal crack in column

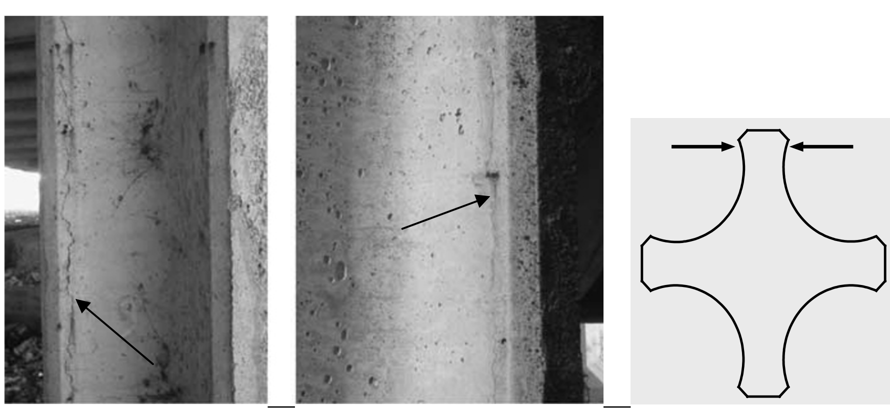

Figure 10: Longitudinal cracks due to corrosion of main reinforcement (registered always on the same corner of the columns due to the position of columns during concreting)

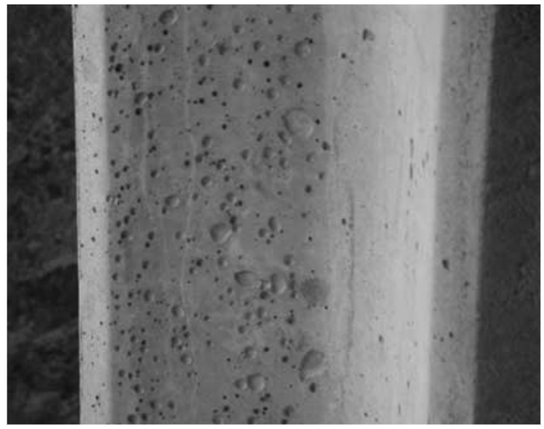

Figure 11: Porous (full of holes) concrete surface

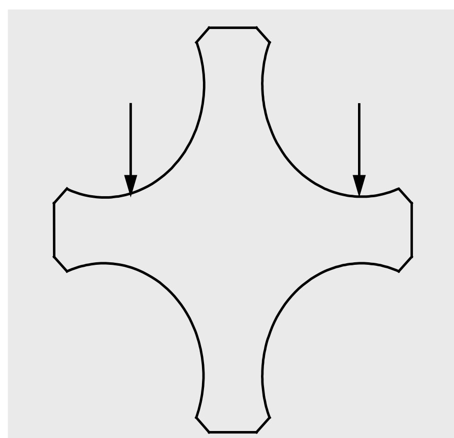

Figure 12: Side of the columns where the air was captured during concreting

- *Stirrup corrosion* (Figure 8): This damage is a local one, that is, there are 'point' traces of corrosion or 'line' traces of length up to 10 cm. The corrosion affected the stirrups on approximately 50 per cent of columns.
- *Longitudinal (vertical) cracks* induced by *corrosion of the main reinforcement* (Figures 9 and 10): These cracks are of width $\geqslant 0.3$ mm and their length is generally larger than 1 m, and they were seen on approximately 50 per cent of the columns.
- *Porous (full of holes) concrete surface* (Figures 11 and 12): This was always registered on the same side of the columns due to the captured air during concreting.

Column corbels

On column corbels, the following defects were registered:

- *Insufficient thickness of the concrete cover* on the oblique front part of corbels (Figures 13 and 14) and

Figures 13: Insufficient concrete cover on column corbels

Figures 14: Insufficient concrete cover on column corbels

– *The protective concrete cover is far too thick* on the vertical front part of column corbels due to the 'incorrect' reinforcement of column corbel (Figures 15 and 16).

Besides the above-mentioned defects, the following damage is registered on column corbels:

– *Separation and breaking-off of concrete pieces* (Figure 15);
– *Crushing of concrete;*
– Corrosion of horizontal reinforcement — stirrups (Figures 13 and 14);
– *Vertical and oblique cracks and fissures* (Figure 17) where the width of cracks exceeds 2 mm.

The above-mentioned damage was formed during assembly of the elements of the structure due to incorrect manipulation of these elements during placement into their projected position. The scale of this damage was increased due to the environmental effects of moisture and low temperature. This damage was registered in approximately 45 per cent of all column corbels.

Precast beams

On precast beams, the following defects and damage were registered:

– *Insufficient thickness of the protective concrete covers* (Figure 18) was registered on 65 per cent of the beams.

Figures 15: Separation of cover from column corbels (thick cover and poor reinforcement arrangement)

Figures 16: Separation of cover from column corbels (thick cover and poor reinforcement arrangement)

Figure 17: Oblique and vertical cracks

- *Corrosion of stirrups* (Figure 12) was registered on approximately 60 per cent of beams.
- Corrosion of the main longitudinal reinforcement was registered on 15 per cent of beams.

Figure 18: Insufficient concrete cover and stirrups corrosion in the beam

Figure 19: Local concrete crushing

– *Spalling of concrete* on spots was registered where the reinforcement corrosion is more stressed.
– *Vertical and oblique cracks and crushing of concrete* in the supporting zone of beams (Figure 15) was registered on 20 per cent of supports.
– *Local concrete crushing on the resting place of Π slabs* (Figure 19) was registered on approximately 10 per cent of resting places.

The Π floor slabs

By visual examination it was registered that the insufficient thickness of concrete cover was the only defect of Π slabs and, subsequently, the transverse reinforcement on the lower side of some slabs was visible (Figure 20). Besides the mentioned defect, the following damage was registered on the precast Π slabs:

– *transverse fissures*, width ≤ 0.3 mm, mostly on the bottom side in the middle of the slab;
– *longitudinal fissures*, width ≤ 0.3 mm, mostly on the transition of the slab into the rib of the slab;
– *oblique cracks and fissures*, width up to 0.5 mm, in a supporting zone of the Π slabs;
– corrosion of the transverse reinforcement;

– *spalling of concrete* on the spots where the reinforcement corrosion is more stressed;
– *vertical and oblique cracks and local concrete crushing* on the resting places of ribs of the Π slab (Figures 21 and 22).

Figure 20: Defects and damage of Π slabs

Figures 21: Vertical cracks in the resting places of ribs of the Π slab

Figures 22: Oblique cracks in the resting places of ribs of the Π slab

Figure 23: Defects in RC wall

The specified damage is of local character, and was registered in all the areas of floor structures.

Reinforced concrete walls

By visual examination of reinforced concrete walls, the following defects were registered (Figure 23):

- uneven concrete surfaces;
- insufficient thickness of the protective concrete cover with visible reinforcement;
- concrete honeycombing and segregation zones.

Besides the specified defects, the following damage is registered on the reinforced carcasses:

- *vertical and oblique cracks and fissures* that mostly enclose the entire cross-section of the wall;
- corrosion of the reinforcement.

QUALITY OF THE BUILDING MATERIAL

Concrete

Subsequent determination of compressive strength of the concrete was performed with a combined method by extraction of concrete cylinders from the elements of the structure (21 cylinders) and by determination of the surface hardness of concrete with a Schmidt hummer (Figure 24) (Folić and Radonjanin, 1993). This combined approach was applied as extracting cores of required dimensions from the columns and the Π slabs was not possible. Compressive strength of concrete calculated at age of 28 days, obtained by cores, is shown in Table 1, which identified that in all the examined elements the projected CC was achieved.

On the basis of the analysis of the calculated values of the concrete compressive strength of precast columns and Π slabs, obtained by non-destructive testing of concrete,

Figure 24: Testing of concrete quality

Table 1: Concrete compressive strength (age — 28 day)

	RC walls	Beams	Foundation strip	Ribs
Ground floor	40.3	—	47.2	—
	37.1	—	—	—
I floor	46.8	70.9	—	46.4
	28.9	59.0	—	47.7
II floor	36.0	66.0	—	41.1
III floor	45.0	63.6	—	55.1
IV floor	34.4	63.3	—	59.6
V floor	—	59.1	—	47.4
$f_{k,28,sr}$ (MPa)	38.4	63.7	47.2	49.6

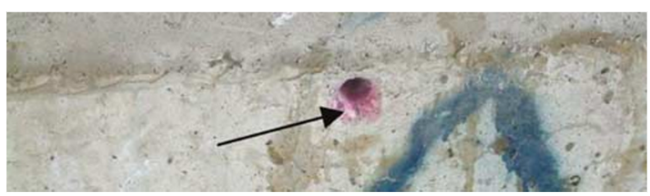

Figure 25: Measurement of carbonisation depth

it is concluded that in all examined elements of the structure, the projected CC is achieved and the concrete is of exceptionally uniform quality.

To check the condition of protective concrete cover in respect of corrosive passivity of the reinforcement, the depth of carbonisation was examined using a colorimetric method using phenolphthalein (Figure 25). The tests were performed on 20 measuring spots, and it is concluded that the carbonisation process is not extended over the protective concrete cover.

Reinforcement

Samples of reinforcement were taken only from the accessible parts of the structure. With laboratory testing it was concluded that the tested samples of smooth reinforcement satisfy the prescribed quality conditions for mild reinforcement GA 240/360, and that the tested samples of ribbed reinforcement satisfy the prescribed quality conditions for reinforcement class RA 400/500.

LOAD TESTING OF THE STRUCTURE

To establish the actual condition of the bearing structure of the garage, an examination was done by load testing (Radonjanin and Malešev, 1997). The testing load that corresponds with the operational conditions was applied in the field between axis G-H and 2-6 (Figure 26).

Loading was performed in two phases. In phase 'A', six cars were used as a test load (Figures 27 and 28), and in phase 'B' 12 cars were used (Figures 29 and 30). For numeric modelling of the structure under test load, a finite element method was applied. Measurement of stresses and deflections was done with strain gauges and mechanical comparators. A deformeter was used as a control device for measurement of stresses. Arrangement of measuring devices is shown in Figures 31 and 32.

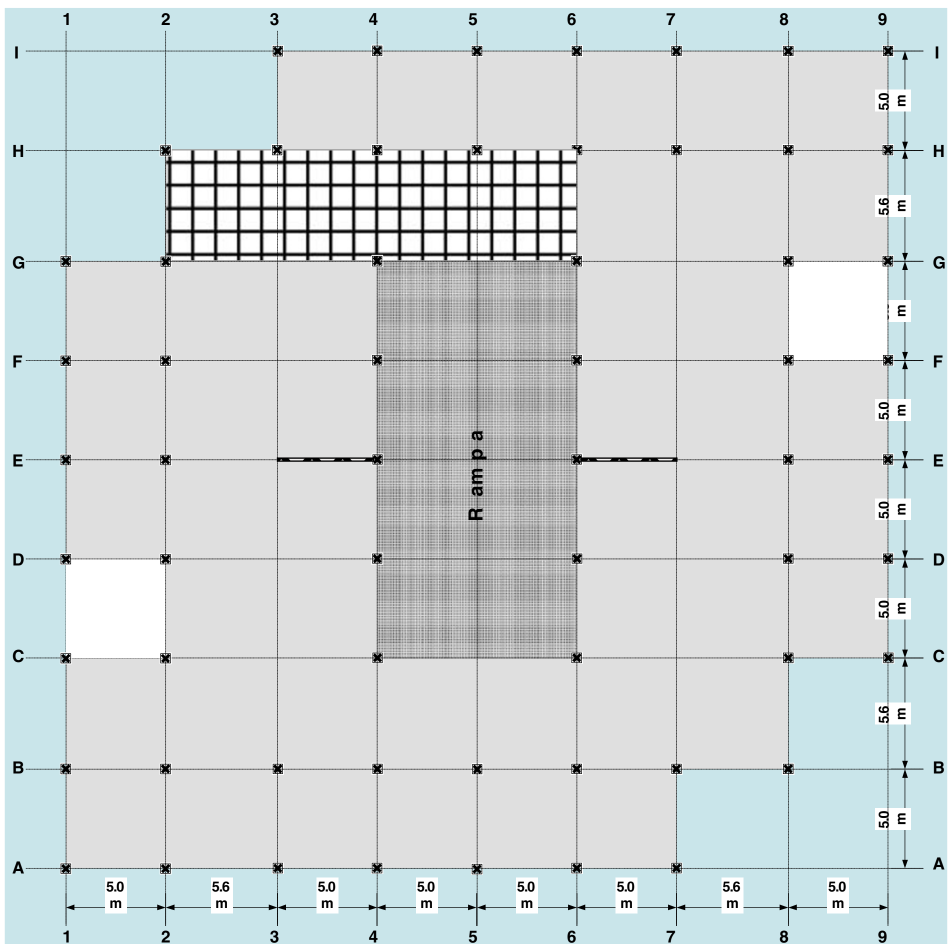

Figure 26: Load testing area

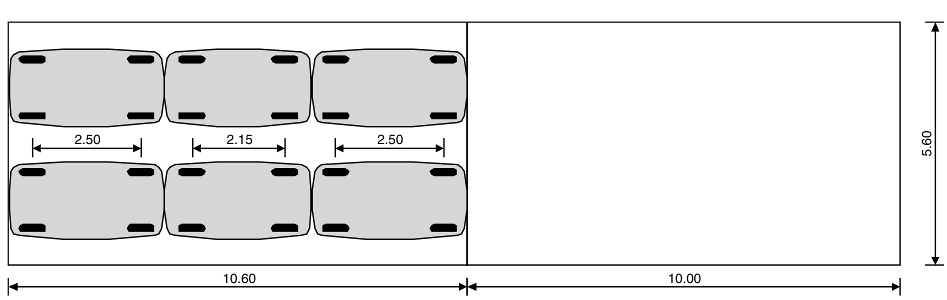

Figure 27: Position of loading phase 'A'

Figure 28: Arrangement of cars in loading phase 'A'

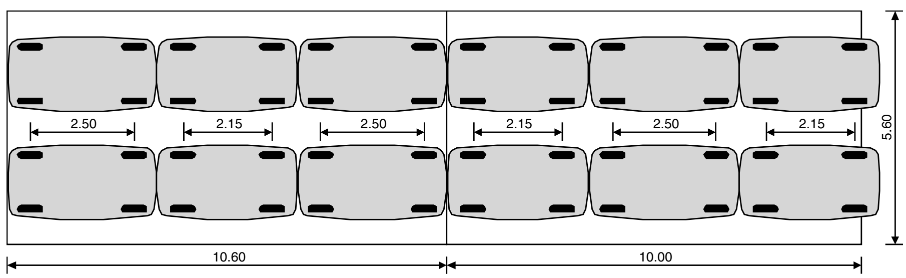

Figure 29: Position of loading in phase 'B'

Figure 30: Arrangement of cars in loading phase 'B'

Calculated values for the deflection of the precast Π slab in loading phase 'A' are shown for longitudinal direction in Figure 33 and in Figure 34 for transversal direction. Deflections of precast Π slabs in loading phase 'B' are shown in Figures 35 and 36.

By comparison of the obtained test results with the designed values, it was concluded that the behaviour of the structure under load testing is normal (measured deflections are smaller than calculated ones, and residual deflections are in allowed limits).

The obtained value of dynamic coefficient of 1.50 is larger than the calculated value (1.33). Slenderness of the floor structures is confirmed by vibrating of Π slabs owing to

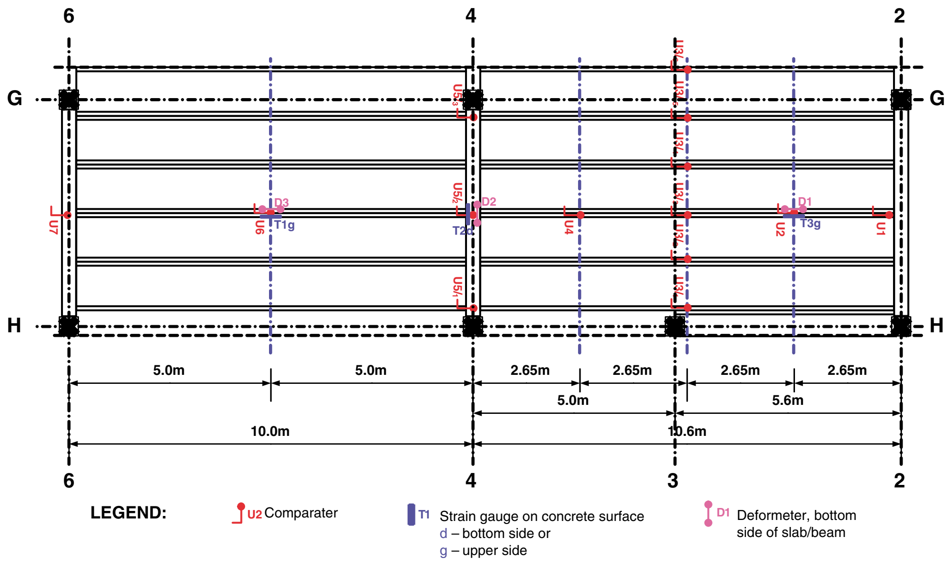

Figure 31: Arrangement of measuring devices

Figure 32: A view of the comparators in testing area

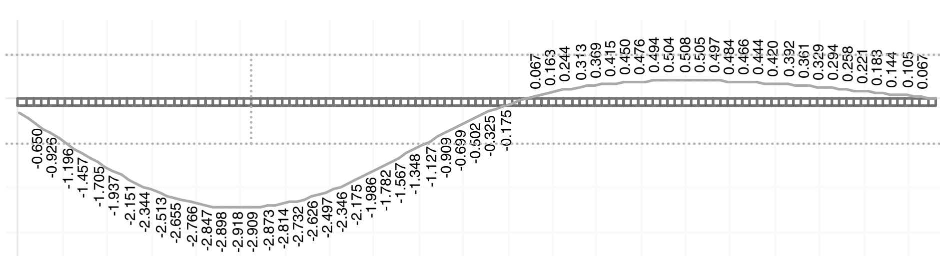

Figure 33: Deflections in longitudinal direction in loading phase 'A'

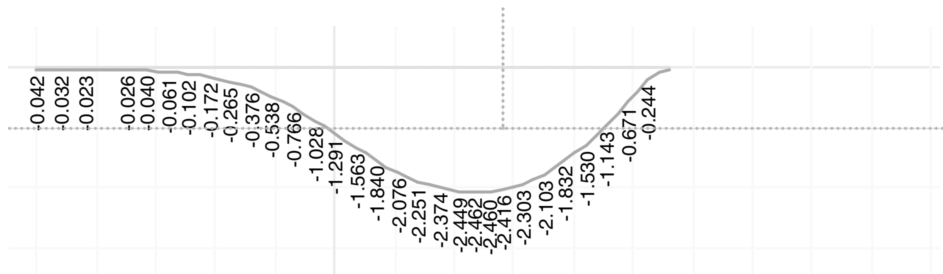

Figure 34: Deflections in transversal direction in loading phase 'A'

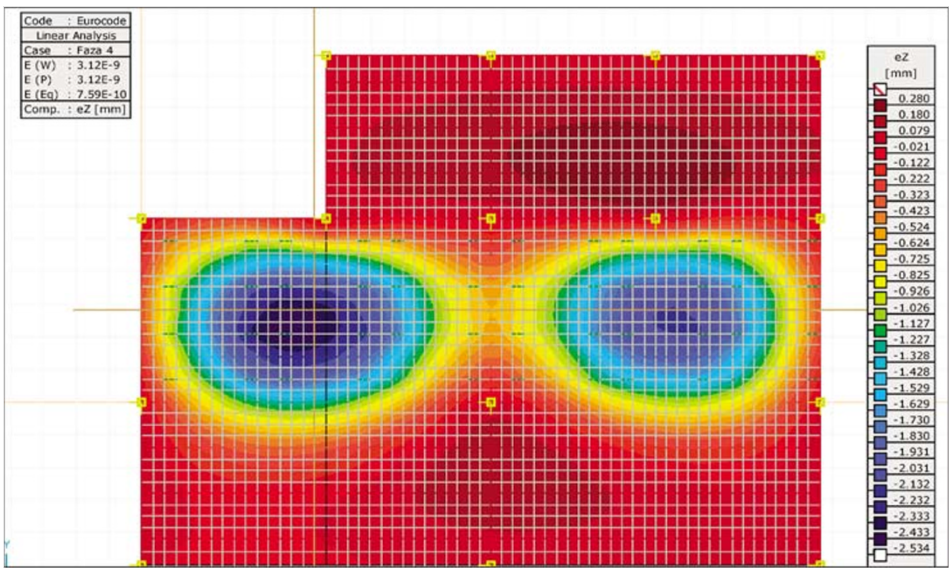

Figure 35: Calculated deflections in loading phase 'B'

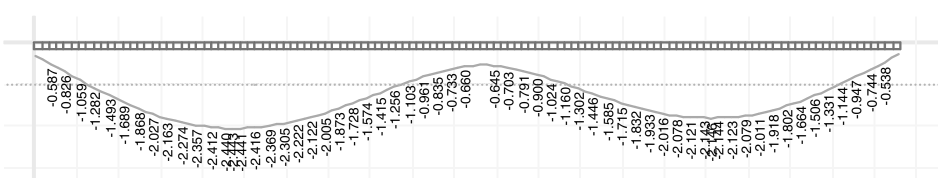

Figure 36: Deflections in longitudinal direction in loading phase 'B'

the dynamical load (the moving vehicles and people). Since the structure was not finished (the monolithisation was not finished and the top coating was not executed) after completion of the structure, the suppression of vibration, that is the reduction of dynamic coefficient, is to be expected.

ASSESSMENT OF THE STRUCTURE CONDITION

The main problem with all the bearing elements of the structure was the thin protective concrete cover that induced further damage on elements of the structure (reinforcement corrosion, cracks and fissures, spalling of concrete).

All the registered damage on bearing elements of the structure, except the damage on column corbels and supporting zones of precast beams, were of such intensity that they did not jeopardise the bearing capacity or the stability of the structure. The existing damage, however, represents a specific danger for durability of the structure, particularly since during use it will be exposed to further various aggressive influences (carbon dioxide, de-icing salts, low temperatures, water, etc). Damage on column corbels and supporting parts of the beams (cracks, fissures, concrete crushing and separation of concrete parts) threatens the bearing capacity and the stability of the structure as their extent significantly reduces the effective supporting area.

The concrete that is built into the precast elements is correctly inserted and compacted, and its compressive strength satisfies the projected CC. Both the smooth (mild) and the ribbed reinforcement built into some elements of the structure satisfy the prescribed quality conditions.

REPAIR OF THE STRUCTURE

On the basis of analyses of the condition of the bearing structure elements and with a goal to ensure the serviceability, bearing capacity, stability and durability of the structure, it was concluded that it was necessary to undertake the following measures:

– To ensure the durability of bearing elements of the structure, it is necessary to undertake appropriate repair measures to protect the built-in reinforcement and concrete (by placing an additional protective concrete cover of required thickness and/or covering with appropriate protective coating). With these works, it is necessary to comprehend all the examined elements of the structure (columns, precast beams, reinforced concrete walls, Π slabs).
– In order to ensure the bearing capacity and stability of the construction, it is necessary to undertake some constructional repair measures in supporting zones of particular elements of the bearing structure (column corbels, supporting parts of beams and the supporting parts of ribs of Π slabs).
– In the repair project, several solutions for repair and strengthening of supporting parts of the structure elements (column corbels, supporting zone of beams, resting places of ribs of the Π slab) were considered (additional reinforcement and concrete, FRP strengthening, additional steel elements, etc) (Folić and Malešev, 2005). The variant with new supporting elements, which provide extra supporting zones for precast beams and slabs, was adopted for execution. Figures 37 and 38 show the arrangements of semi-prefabricated steel elements and their fixing to existing structure elements.

Besides structural repair of bearing elements, some appropriate repair measures for protection of the built-in reinforcement and repair of concrete defects were proposed (Radonjanin and Malešev, 2006).

The repair measures for cracked edges, corroded main reinforcement and stirrups in columns and beams consisted of:

– The removal of concrete up to the sound concrete, so as to free the main reinforcement and stirrups (Figure 39).
– Cleaning of visible parts of reinforcement from rust.
– Preparing of concrete surface (cleaning of dust and dilapidated concrete parts).
– Coating of the bared reinforcing rods with corrosion-inhibiting cementitious mortar.
– Applying of thixotropic fibre-reinforced mortar as a new concrete cover.

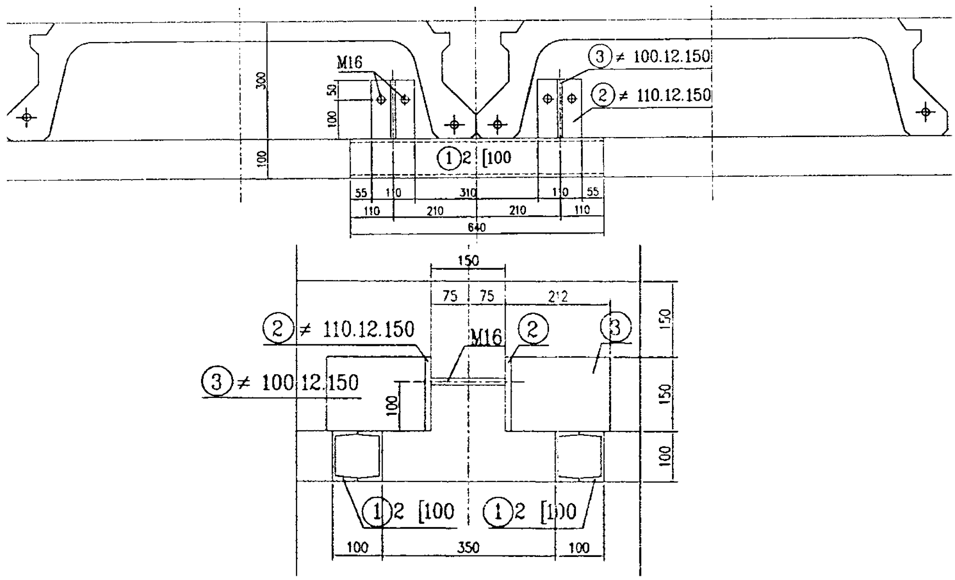

Figure 37: Strengthening of supporting parts of slabs (additional supporting area for resting of slab ribs)

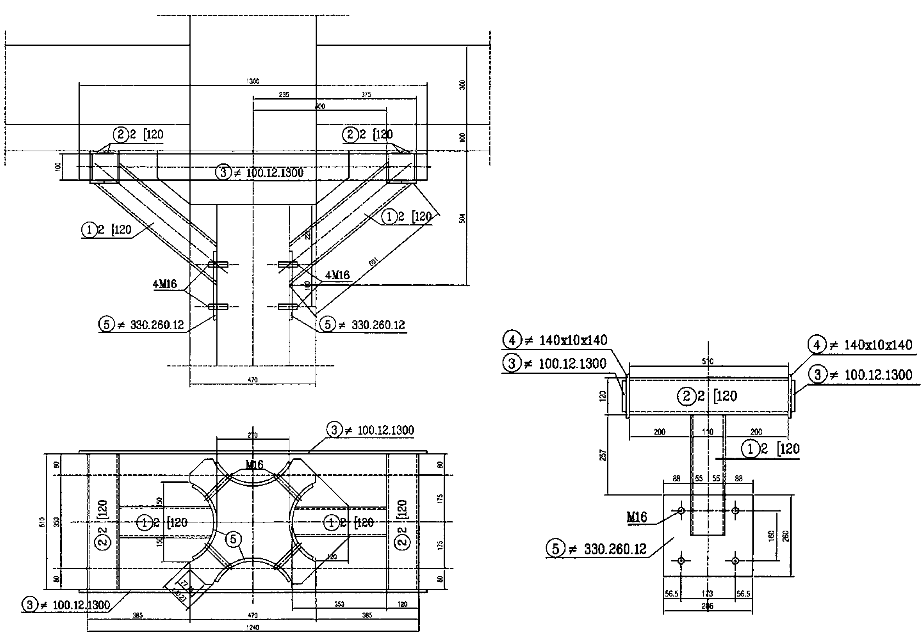

Figure 38: Strengthening of column corbels and supporting parts of beams

Repair of insufficient concrete cover and micro cracks was executed by applying elastic polymer modified cementitious mortar on the concrete surface (Radonjanin *et al*., 2003). This kind of protective cover provides corrosion protection of reinforcement and bridges existing micro cracks. It also protects concrete from chemical attack (de-icing salts, sulphates, and carbon dioxide).

Cracks in reinforced concrete walls were repaired by classic injection method (epoxy resin with low pressure injecting pump).

Figure 39: Forming of opening in concrete at the place of corroded rods

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