- Das angewandte Vorspannsystem hat sich als dauerhaft erwiesen. Mit kleineren Ausnahmen bezüglich Genauigkeit war auch die Applikation gut.
- Durch das Freilegen der Ankerköpfe beim Streifen S2 wurden einerseits, gegenüber dem System S1, andere Einspannverhältnisse der Platte in die Widerlager geschaffen. Anderseits zeigte der Belastungsversuch, dass die Vorspannkraft im Streifen S2 dank sehr gutem Verbund trotzdem vorhanden war und die Tragfähigkeit infolge der freigelegten Ankerköpfe keine merkliche Einbusse erlitt.

Die Zusammenstellung der Versuchsresultate in Tabelle 2 soll einen Überblick über die wichtigsten Kennwerte der Versuche geben.

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Material investigations and failure tests on a 20 years old, prestressed bridge over the Glatt near by Zurich

In 1954 when the *highway A from Zürich to Winterthur* was extended, a new bridge over the Alte Glatt near *Schwamendingen* was erected. The structure was a *prestressed concrete highway bridge.* However with the construction of a new freeway the bridge had to be demolished (fig. 1).

On the initiative of the *chief engineer of canton Zürich* it was decided that the opportunity should be taken to make *some material tests on the concrete and the prestress steel* before the bridge was demolished. The bridge was a comparatively recent prestressed concrete structure and had been exposed to highway traffic and extreme weather conditions for some twenty years. Thus the bridge would be able to give information concerning the durability of the construction materials concrete and prestress steel. In addition it should have been possible to test whether the strength of the bridge had been influenced by the continual fluctuating traffic load, and also if normal methods for the calculation of the structural behavior were still applicable.

Bridge loading tests, as they are usually made, allow the behavior of the structure to be determined only under service-ability conditions. However with the bridge over the Alte Glatt it was attempted to also test the *ultimate load behavior* of the bridge.

These considerations led to the decision that the Federal Material Testing and Research Laboratories (EMPA) in Dübendorf take on the job to develop an appropriate test program [1]. There were *a full two months* in which to carry out the tests, but only *a limited budget at disposal.* A complete failure test of the bridge was ruled out. The *test program* evolved consisted substantially of the following tests:

1. Survey of the structural condition of the bridge using visual controls.
2. Moving load tests on the bridge with a truck in order to establish the dynamic behavior of the prestressed deck slab.
3. Extensive material property tests and investigations on the concrete, the reinforcement and the prestressed steel.
4. Static failure tests on two strips cut out of the bridge deck.

The two slab strips mentioned in 4. above differed in the different end restraint relationships between the bridge deck and the supporting walls (the various bridge components formed a continuous frame). In the first strip the anchorage heads were exposed; in the second the full restraint remained. With these conditions the failure test should have been able to clarify the question whether, with the exposure of the anchorage heads of a prestress cable, a structure will fail or not.

Construction and structural condition of the bridge

The bridge built in 1954 had a span of 12.5 m and a width of 21.3 m. It was *prestressed in both the longitudinal and transverse directions forming a slab-frame bridge.* The structural system of the bridge consisted of a continuous frame with the vertical members being the walls and the horizontal member being the bridge deck of 0.35 m thickness. A prestressing procedure based on that of Freyssinet was used. In the longitudinal direction there were sixty-two prestress cables each with 500 kN force and twelve wires of 7 mm diameter. In the transverse direction there were fifteen cables of the same kind each with 500 kN force. There was also reinforcement of 10 mm diameter present.

The *structural condition* of the bridge was able to be checked through a *visual control* of the various elements and also *some laboratory tests.* These showed that the concrete construction was of a high quality concrete with only a few small cracks of maximum width 0.2 mm on the bridge deck underside. The two supports also showed no damage and were free of colouring from the precipitation of lime, which often can be observed on older concrete structures.

On the whole, the bridge was *externally in a very good condition.* It would certainly have been able to continue to fulfil its function for many years to come.

Moving load tests

The moving load tests were aimed at determining the *dynamic characteristics* of the bridge. These characteristics were the *natural frequency* f_0, the *damping coefficient* δ (logarithmic increment) and the *impact load factor* φ, caused by a single vehicle. So that these dynamic measurements could be carried out, a truck with a total weight of 150 kN travelled at speeds between 5 km/h and 40 km/h along the longitudinal axis of the bridge deck ($\simeq$ bridge centre line, fig. 4). The *vertical oscillations* of the bridge were measured and recorded by various devices at different positions. A so called *«bump test»* was made to test the influence of possible unevenness in the bridge deck on the shock sensitivity of the bridge. Here the truck drove over a 50 mm thick and 280 mm wide board placed in the middle of the bridge.

From the measured and recorded oscillation amplitudes (fig. 5) an *impact load factor along the longitudinal axis of symmetry* could be calculated. This was according to the formula

$$\varphi = \frac{A_{\max,\,\mathrm{dyn}} - A_{\max,\,\mathrm{stat}}}{A_{\max,\,\mathrm{stat}}} \cdot 100\ (\%)$$

$\varphi_{\max} = 17\%$ (without board)
$\varphi_{\max} = 170\%$ (with board)

The natural frequency of the bridge calculated from the recorded measurements came to 8.59 Hz. The calculated frequency of the first oscillation based upon certain assumptions for the moving load tests came to 8.66 Hz. The logarithmic increment δ (the damping constant) came to an average value of 0.204

$$\left(\delta = \frac{1}{n} \cdot ln \frac{A_0}{A_n}\right)$$

It is possible today to determine the expected dynamic characteristics (δ, f_0) of a simple bridge with a program using available computer facilities. Tests carried out precisely, which necessitate a certain minimum input, are able to verify the theoretical characteristic values. This is demonstrated by the above example.

Material investigations on the concrete, reinforcement and prestress cables

Concrete Quality

Drilled concrete samples of 50 mm diameter were taken from various structural elements of the bridge. Information concerning the state of preservation of the concrete after over twenty years exposure to the continuous action of weather and loading was sought. A number of the samples were used for *compression tests* from which the modulus of elasticity was also obtained. The *average value of the cube compressive strength* obtained from these tests was 87.5 N/mm^2. A standard deviation of 12.1 N/mm^2 led to a variation coefficient of 14%. For comparison the values from the strength tests made in 1954 still existed. These had produced an average cube compressive strength of 55–60 N/mm^2.

Various *chemical analyses* were made in addition to the strength tests. These were to determine the *density*, *water absorption*, *cement content* and *carbonisation*. The results could be verified by earlier results. These results showed the same connections as the tests. Thus it could be concluded that the methods of analysis were also valid for the old concrete.

The cement content of the concrete was of the same order as that used for current construction concrete. The degree of carbonisation for several concrete samples was very small. The carbonised depth came to a maximum of 1.2 mm. The deeper concrete reacted as strongly alkaline which indicated a dense high quality concrete.

Reinforcement

The reinforcement the various structural elements consisted of *cold worked steel 40* (Torstahl 40) *for the longitudinal reinforcement* and *Caron reinforcement* (Caronstahl) for the *secondary transverse reinforcement*. Some samples of the reinforcement were taken from the bridge *after* the failure tests. A static tensile strength test was made on these examples. The yield stress σ_s and the ultimate tensile strength β_z found are shown in Table 1.

The concrete cover measured on the bridge and also on some drilled samples came in all cases to at least 25 to 30 mm, thus fulfilling the current SIA Code requirements (Code SIA 162, Sect. 3.28[1]), which require a minimum 25 mm cover. No trace of corrosion was found on the reinforcement samples taken, no doubt because of this good concrete cover present.

Prestress cable

Material examinations carried out on several 1 m long sections of prestress cable were made in order to examine *the state of preservation* of the cable (fig. 6 and 7).

The cable showed *externally* to be *in good condition* with respect to corrosion and anchorage. Also, a strong bond between the construction concrete and the cable sheath was found to be present. Once the sheath was opened the inner of the cable could be examined. To a large extent (95%) there appeared small voids in the otherwise dense and compact grout filling. These voids originated from air bubbles entering during the injection of the grout into the sheath. Only a leak at the ends would allow this as there was no air outlet tube at the cable middle. The upper surfaces of the voids were often coated with a whitish layer from the lime precipitating out of the water.

The *covering* of the single prestress wires with grout was mostly very good. However often a section of the wires lay against the sheath. There was no surrounding grout at this contact line and some corrosion showed, but the majority of the prestress wires were free from all corrosion.

Static and *dynamic strength tests* on fifty prestress steel samples produced results which were within the current strength requirements. The average yielding stress came to 1477 N/mm^2, and the ultimate tensile strength to 1622 N/mm^2. The actual condition of the bridge prestress was able to be tested on five transverse cables. The forces in these cables were able to be found by measurement of the shortening of single wires after they had been cut through. An average elastic modulus of $E = 202$ kN/mm^2 was obtained leading to an effective prestress force of 427 kN per cable. This was 84.6% of the original value. The prestress losses of around 15% after 20 years of service are of the expected order. They correspond quite well with the estimated value of 12% calculated in 1954.

Static failure tests

General

The structural analysis of the bridge predicted a collapse load of 20 MN for the total bridge. This meant that a failure test on the whole bridge with relatively moderate expenditure was not possible. The tests were thus *limited to two immediately adjacent slab strips each of 0.90 m width*, which was limited by the arrangement of the longitudinal cables in the bridge deck. Both strips were cut out of the bridge deck with diamond saw plates. The width of the cuts was 3 mm and the cuts from were made as vee-cuts. This was to prevent a possible tilting of the section and thus jamming in the main structure during loading.

The separated strips differed in their end restraints. The end restraint for the strip (S1) was as for the bridge deck in the supporting walls, providing a frame action. In the second strip the three anchorage heads of the longitudinal cables were exposed, thus eliminating the fixed end restraint. The effect of exposing the anchorage heads could also be tested. *The two strips formed well defined structural systems* for which firstly, *exact computations could be made*, and secondly, *a static failure test of normal work input could be made.* The system with the strip S1 formed a frame. The strip S2 formed a simply supported beam. These simply calculated structural systems should have been able to show whether the behavior established theoretically and through countless laboratory tests actually coincided with reality.

Loading arrangements

The loading arrangement for the failure tests on the two strips consisted basically of the following (fig. 9):

- 4 steel cross beams arranged at right angles to the strip, their ends supported on concrete cubes and fastened to the still intact bridge sections with tensioned rods.
- 8 hydraulic controlled 250 kN tension/compression loading press cylinders with a raising height of 0.30 m. 2 cylinders were fastened to each cross beam.

In order to achieve a desired distribution of the load over the whole of the strip, the loading points of the four load groups were placed at approximately the quarter points of the span. The bridge deck still in tact hat to be loaded with additional weight so that it did not lift as the strips were loaded. This *additional loading* consisted of lead bars and concrete cubes of a total weight of 2×676 kN (fig. 9).

The aim in these failure tests was to observe and examine *the carrying behavior of the two different structural systems* and also to compare the ultimate load and moment with the theoretical values. The tests brought out several points worth mentioning [2]:

- In strip S1 there was to one side an inconsistency in the path shape of the prestress cable. This led to a somewhat unexpected failure. Nevertheless the calculated safety factor did not exceed the code value. So with small errors a large factor of safety could still be obtained.
- The deflections of both systems were extremely large before the limit of the carrying capacity was reached. This favourable deformation capacity could be traced back to the additional steel cross-sectional area of the prestress cable in the slab strip.
- The calculations based upon the recorded concrete strains demonstrated that the prestress was still very effective within the elastic range, even after taking into account the prestress losses.
- The theoretical values for the ultimate load and ultimate strength were verified by the test results. Thus the plasticity theory was shown to be a reliable model for the calculation of the structural strength. The mechanisms generated during the tests also corresponded very well to the expected.
- On both strips the start and development of the plastic hinges at places of large steel strains could be very easily observed. Although the prestress wires were yielding at these points nowhere did they actually fail. The eventual failure of both strips came about through a compression failure of the concrete at centre span.

- The prestress system used proved itself to be durable. With some small exceptions with respect to geometric inaccuracy the application also proved to be good.
- Exposing the anchorage heads in strip S2 created another end restraint system as regards to strip S1. However the load test showed that due to very good bond the prestress force was still present. Also the carrying capacity was not noticeably diminished by this exposure of the anchorage heads.

The summary of the test results in table 2 gives a general view of the most important characteristic values obtained.

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