Experimental verification of the load-bearing capacity of a multilevel car park in Bremerhaven

by Klaus Steffens and Peter Wolters

An increasing proportion of construction work involves the maintenance and refurbishment of existing buildings whose load-bearing capacity cannot be established by analytical methods. In some cases, load-bearing capacity can be determined experimentally without damaging the structure of the building. Suitable procedures and equipment are available for this purpose. The following account describes the procedure and equipment used to verify the load-bearing capacity of a five-storey car park with an overall surface area of 100,000m^2 (1,076,000 ft^2). In contrast to the computational method, experimental results reveal substantial surplus load-bearing capacity in the existing structure.

Building and construction work has clearly changed in recent years. Major projects to create living accomodation, production plants and infrastructure are largely complete. There will be few developments requiring land on the scale seen in recent decades. Future work will be increasingly concerned with maintaining and refurbishing existing buildings. New production processes will call for buildings to be put to new uses, so changing the loading. Such cases regularly raise the question of their mechanical implications. This requires an analytical determination of stability following established rules and norms with consideration of defined material and structural characteristics.

This sort of analytical proof is entirely suitable both for planning new work and for checking existing buildings, because generally the savings resulting from surplus load-bearing capacity outweigh the capital investment required to verify it. This is not the case with existing building sections or structures where the type of use has changed or where damage has occurred. If a computational analysis gives insufficient results, this means demolition or rebuilding of these buildings or at least making expensive alterations to them, even though the structure of the building might have sufficient hidden reserves of strength.

Load-bearing capacity is mainly determined by

- reserves of strength in the actual material,
- necessary simplifications in the establishment of the load-bearing system boundary conditions in the analysis,
- necessary simplifications in the theory of static calculation.

In general, surplus load-bearing capacity cannot be estimated by analytical methods. But there are particular cases where it is possible to use experimental methods as a complement or as an alternative in largescale commercial applications to determine and exploit the surplus load-bearing capacity, so reducing or completely eliminating building and related costs.

There are suitable devices available for this type of onsite measurement, which should be non-destructive if at all possible. These devices give reliable measurements even in extreme site conditions.

Formulation of the task

The Bremen Warehouse Company (BLG - Bremer Lagerhaus-Gesellschaft) loads cars onto ships near the container terminal in Bremerhaven. Some 6,000 vehicles must be loaded in a docking period of about 16 hours. To operate within this deadline, covered storage areas must be provided near the quay. A five-level car park 200 x 100 m (656 x 328 ft) and a total floor area of 100,000 m^2 (1,076,000 ft^2) have been built for this purpose as shown in **Fig. 1**.

The floors must be unobstructed if vehicles are to be maneuvered quickly and parked in the shortest possible time. To protect against fire there are no partition walls, but rows of grating strong enough to carry a vehicle have been set into the surface slabs at regular

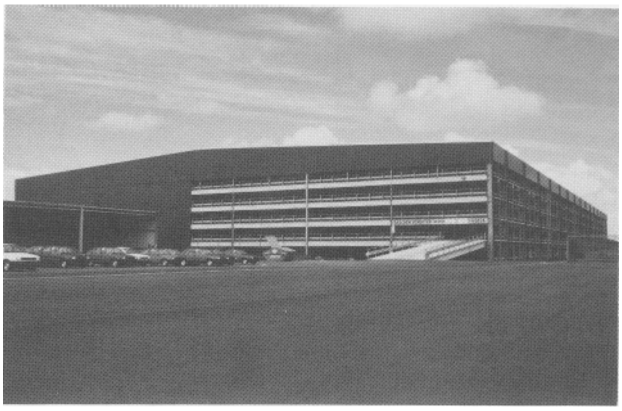

Fig. 1: Five-storey car park in Bremerhaven for stacking cars for sea transport

intervals to localize the damage from fire by providing a vertical outlet for smoke and flames. The ground plan in **Fig. 2** shows the layout of the 1.5 m (5 ft) wide rows of grating. All surface slabs including the gratings and their supporting flanges are designed to be loaded with empty vehicles.

Expansion in the usage of the building required that the existing surface slabs be able to support a vacuum sweeper, but the load-bearing capacity of the surface structure limited its axle loading and size and therefore its effectiveness.

By analytical means it was possible to prove that the reinforced concrete, i.e. the surface slabs and the main beams, could bear higher axle loading from the vacuum sweeper. The result of mechanical calculations on the gratings and their supports showed, however, that their load-bearing capacity was inadequate for a large vacuum sweeper. The grating support flange can be seen in **Fig**. **3**.

When refurbishment models derived from analytical methods were found to be far too expensive and time-consuming (replacement or reinforcement of 4176 m^2 (44,934 ft^2) of grating and 6240 m (20,473 ft) of supporting flanges), it was thought possible to use experimental means to determine the surplus load-bearing capacity of the relevant parts of the building that could not be assessed computationally and that could be used to bear the weight of a bigger vacuum sweeper. The parts of the building taken into consideration were the grating, the supporting flanges and the free edge of the flat concrete surf ace. The following is a description of the short-term, non-destructive test loadings which simulate the loading characteristics of the vacuum sweeper.

Test set- up

A total of 224 identical prefabricated concrete slabs with gaps to take steel grating are built into the four upper levels of the car park. Since the slabs, the gratings and supporting flanges were mass-produced, it was assumed that there was little variation in their load-bearing characteristics. To minimize the expense of the test, and after consulting the client and the test engineer, two representative test areas were selected on the floor of the first upper level for tests to be carried out on the grating, the supporting flanges and the free edges of the concrete slab. These two test areas are indicated in **Fig. 2** as loading points *A* and *B*.

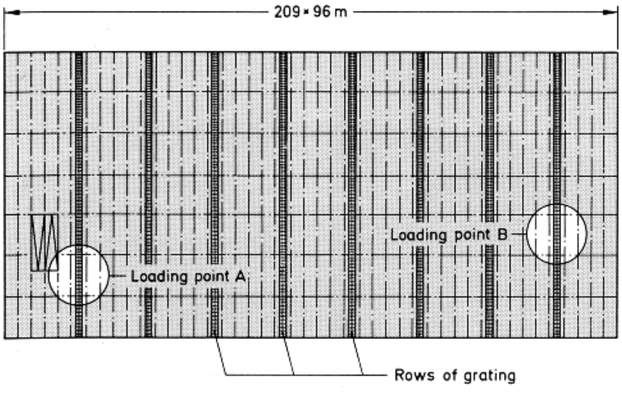

Fig. 2: Ground plan of a car park storage area with gratings in Bremerhaven

The vacuum sweeper has a three-wheeled chassis with a minimum wheelbase of at least 1.20 m (4 ft). The existing construction of the grating excluded the possibility of double loading, so it was sufficient to simulate the loading due to only one wheel in the test. A wooden block measuring 140 mm x 140 mm (5.5 x 5.5 in) was selected as an unfavorable case for the applied loading surf ace. The test load was set at $F \approx 20$ kN (4496 lbf).

Fig. 4 shows the part of the test rig located under the floor being tested. A crane test weight of two tonnes was set up on the ground floor of the car park; a tension bar transferred the weight through a grating hole to a loading plate on the surface of the floor that pressed down onto the grating area through a softwood block and simulated the load presented by the wheel of the vacuum sweeper. In the tensile system between the load and the loading plate there is a hydraulic piston and a type U1/100 kN Force Transducer. The pressure in the hydraulic piston could be fine-tuned with a hand pump. This construction would be easily modified and was inherently safe as the load was permanently standing on the floor. Unintentional overloading would have relieved the ceiling of the load as a result of the greater deformation.

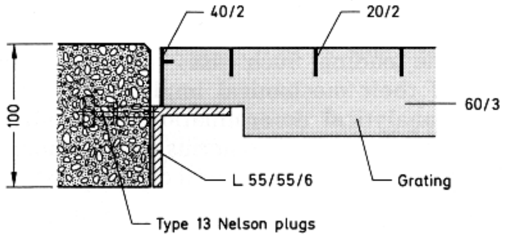

Fig. 3: Grating support in the Bremerhaven multilevel car park

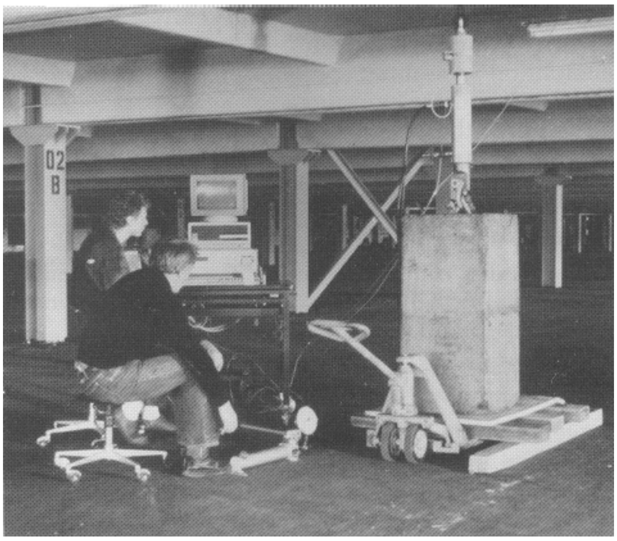

Fig. 4: Test rig consisting of loading equipment and the measuring unit located under the level to be tested

Measuring equipment

Measurements were recorded with a UPM 60 Multipoint Measuring Unit. Signals were continuously recorded and displayed. A U1/100 kN Force Transducer was connected up to measure the force on the grating; several WT10 Inductive Displacement Transducers with ± 10 mm (0.39 in) rated displacement for measuring deformation were installed at various measurement locations in each test at different loading points. The many additional functions available on the UPM 60 ensured that it was well suited to the application. Scale factors made it possible to set the signal to the appropriate units. Automatic zero balancing and interrogation cycle made it easy to use. To keep track of results, they were displayed on the six-digit display and printed out as a listing on the D20 thermal printer.

The values recorded were transferred in on-line mode through the RS 232C interface to an Olivetti PC M24 and displayed as sets of data, force-deformation graphs or block diagrams, depending on requirements. The compact switching unit, a connection panel for the sensor leads and the microcomputer with its monitor and 20 MB of mass storage were easily transported in a car and moved around on a trolley. **Fig. 5** shows the measuring equipment and computer set-up on a mobile bench. The UPM 60 Multipoint Measuring Unit enables measurement via computer or the measuring device itself. The measuring equipment was not affected by the rough weather conditions on the site: low temperatures, drafts and relatively high humidity.

Test procedure

The relative deformation of the structures being tested was recorded and their behavior under changing load was observed as determined by the applied load. Attention had to be given for the appearance of any developing cracks. Deformation was measured on the individual sections of the grating, the supporting flange and the free edge of the concrete while they underwent loading with a program that started at zero and increased in 1 kN (225 lbf) increments. The load was removed before moving on to the next increment.

The removal of the load after each new increment made it possible to approach the upper limit of the elastic characteristics, i.e. the start of plasticization, on the monitor diagram; to be on the safe side, this was defined as the load-bearing capacity. This meant that all the structures were still useable. The transient loading corresponded sufficiently to the actual loading of the vacuum sweeper. Apart from electrically recording the measurements, a measuring lens was used to make a visual measurement of the width of the cracks, ω, in the concrete (display $\Delta\omega$ = 0.1 mm/3.9 mils).

Fig. 6 is a view from above onto the loading plate and the inductive displacement transducers in the test on the grating. The steel gratings are all made the same (1.24 m (4 ft) wide, 1.50 m (5 ft) long) and fitted with an anti-shear pin on their abutting points. Tests were carried out in which a load was applied on the transverse force coupled free edge and in the middle of the grating. The bending of the grating was measured.

Fig. 7 depicts how the test on the supporting flange was set up. The supporting flanges (L 55/55/6) of the grating are fixed to the reinforced concrete surface of the prefabricated slabs with concreted-in Nelson plugs (type 13, α = 400 mm/15.8 in). The worst wheel loading

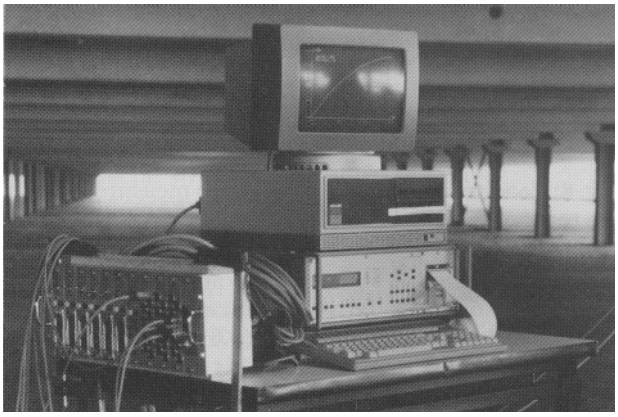

Fig. 5: Trolley carrying UPM 60 Multipoint Measuring Unit with Olivetti M24 PC and connection panel for sensor leads to the measuring point

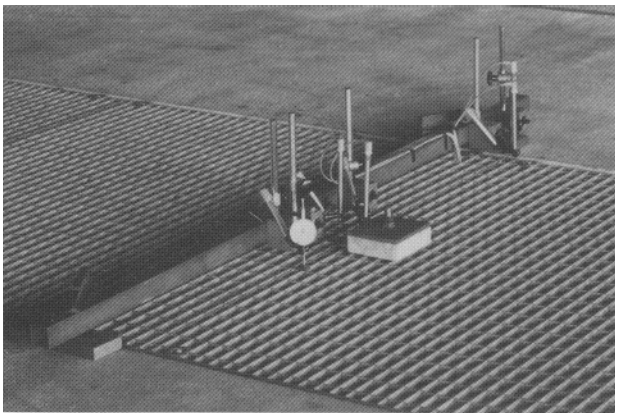

Fig. 6: Load transfer and inductive displacement transducer in the test on the grating

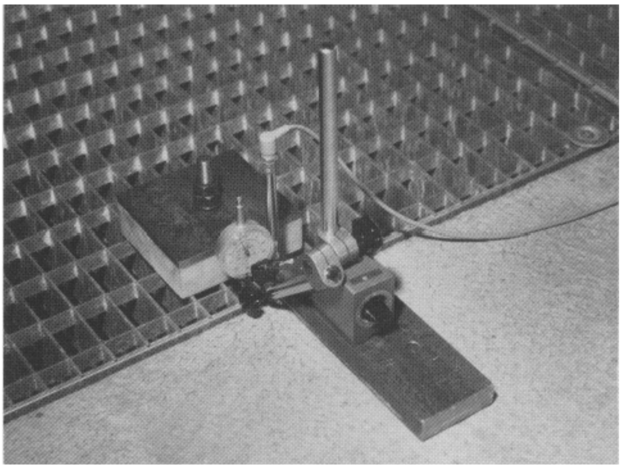

Fig. 7: Load transfer and deformation measurement in the test on the supporting flange

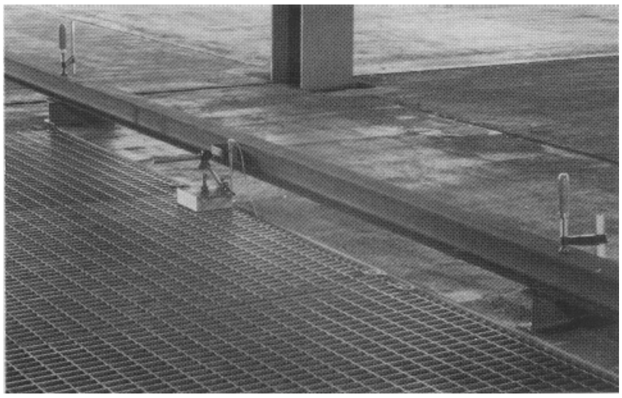

Fig. 8: Load transfer and deformation measurement in the test on the free edge of the concrete surface

position was chosen above a plug and measurements were made of the relative displacement of the supporting flange at around 15 mm (0.6 in) distance from the edge of the concrete slab; this is essentially the result of elastic angular deformation.

In the test on the free edge of the concrete surface, the end area of a slab was loaded on its free edge, as **Fig. 8** shows, and the bending of the slab was measured relative to the adjacent transverse girder, together with any crack that developed. The load-bearing capacity of the supporting flange was also checked without measuring deformation.

Test evaluation

The measurements were logged for each loading point. The monitor was able to give a graphical plot of load against deformation on site. **Fig. 9** illustrates one of these load-deformation graphs. Curve *b* shows the deformation under load. The permanent deformation measured each time the load was removed is shown separately in line e, so that the elastic and the permanent deformation could be evaluated separately.

The results for all structures tested at a maximum test load of F = 19.5 kN (4384 lbf) showed an almost elastic characteristic. No cracks appeared in the concrete. The results from loading point A made it possible to place a limit on the test program for loading point B. Here it was possible to dispense with the need to determine the load-bearing capacity for the grating and the surf ace slab. The results of the measurements for the supporting flanges confirm the previously determined load characteristics, so it was possible to make a reliable statement statistically as well. Overall it was possible to conclude from the results for all the measured points that the test load F = 19.5 kN (4384 lbf) was below the effective breaking load.

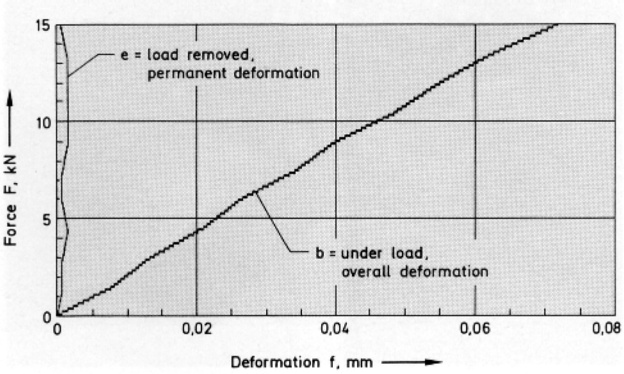

Fig. 9: Load-deformation graphs obtained during onsite testing

It was not possible to make any conclusions about the capacity up to the actual breaking load, since it was decided not to increase the loading to the point of causing structural damage. For the purposes of further assessment the load F = 19.5 kN (4384 lbf) was regarded as being equal to the breaking load. Dividing this established breaking load by the safety factor y gave the maximum permissible wheel loading that determined the type of vacuum sweeper which could be used.

Summary

The results of the experimental investigation into the load-bearing capacity of individual structures in the multilevel car park in Bremerhaven revealed the surplus load-bearing capacity of the existing structure. It was possible to make better use of the facility, contrary to the results of the computational procedure, without time-consuming and extremely expensive structural reinforcements.

As the diagram in **Fig. 10** shows, the use of modern experimental methods, combining electrical measurement and recording on a UPM 60 Multipoint Measuring Unit with a powerful personal computer, can lead to financially impressive results for structures facing change in use or rebuilding. With the standards of measuring equipment, microcomputers and software that have been reached, experimental verification procedures will assume increasing importance as an alternative to analytical calculations, particularly for verifying the strength of existing structures.

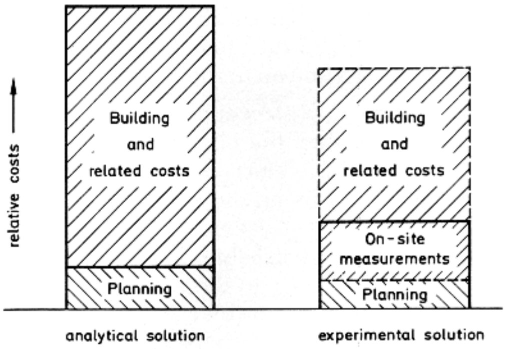

Fig. 10: Cost benefits using modern experimental methods for proving the load-bearing capacity of existing structures

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