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OLD BRIDGES IN NEW TIMES. Searching for hidden quality

Abstract

Many bridges in The Netherlands are meanwhile 40-50 years old. Those bridges have been designed according to old design codes, which do not reflect the state of the art of today anymore. Moreover, the traffic loads have been increased substantially. If those bridges are recalculated according to modern design codes they often do not fulfill the safety standards. In spite of that, those bridges mostly do not show significant distress, which denies the results of the analysis. Obviously there are hidden reserves in bearing capacity. To detect and quantify these is an important task.

1. Considerations with regard to service life design

Until quite recently, the design of reinforced concrete structures was only based on structural safety and serviceability. Experience with damage due to corrosion and doubtful concrete quality showed, however, that design for durability should be on the same level as design for safety and serviceability. In future codes design for service life should become a major design task. In this respect the development of a new Model Code for Concrete Structures should be noted. Figure 1 shows schematically the idea behind design for service life. At the vertical axis the capitals R and S represent Resistance (R = Resistance) and Load (S = Sollicitation, Fr.) respectively. The dotted line with upward tendency represents the increase of traffic load in time.

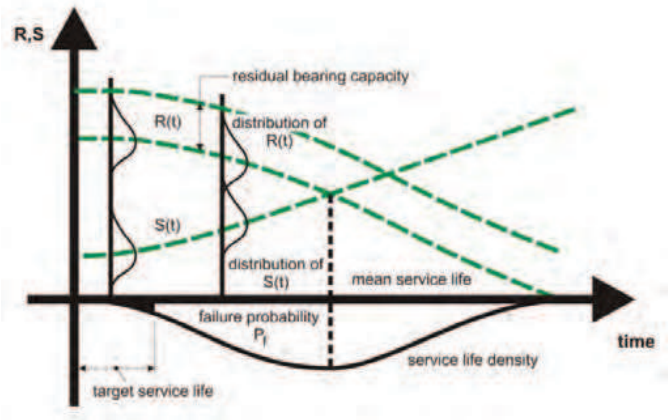


Fig. 1. Representation of the principle of design for service life

The lower of the two declining dotted lines shows the decrease of bearing capacity in time. Both the bearing capacity and the load are subjected to scatter. The condition Z = R(t) – S(t) means that the structure fails, which should be avoided with a defined degree of reliability. If the corresponding reliability index β is exceeded, the decision should be made to upgrade the structure.

2. Results of a "quick scan" assessment of the bearing capacity of Dutch Bridges

In the Netherlands the bearing capacity of many bridges, built in the period 1960-1970, was investigated. The results of "quick scans" carried out by design offices, showed a remarkable result. Table 1 shows a small selection of different bridge types. The assessment of the bearing capacity was carried out under the assumption of modern traffic loads and actual building codes, whereas for concrete and steel the original design strengths were used. The last column in Table 1 shows the so-called UC-values, where UC stands for "Unity Check". In this analysis the safety values for the loads and the materials are removed: the UC-value is the relation between maximum load on the bridge in use to the bearing capacity. If the UC-value is larger than 1, this means theoretically that the bearing capacity is insufficient. The Table shows unexpectedly high values. In all cases the shear capacity is governing.

The highest UC values were found for T-beam decks and solid slab bridge decks (Fig. 2 and 3).

Table 1. Results of quick scans for some bridges

Bridge number	Category	Year	UC-Value
37E-122	Culvert	1996	1.89
37F-110	T-Beam deck	1970	2.43
38D-103	Solid slab	1936	4.53
38F-108	Subway	1966	1.61
38G-112	Subway	1961	1.18
38G-103	T-Beam deck	1959	3.13
39G-114	Straight solid slab	1959	2.85
52G-105	Skew solid slab	1969	3.53

Fig. 2. T-beam bridge deck

Fig. 3. Solid slab bridge deck

In spite of the alarming UC-values, however, inspections did not show signs that confirmed the expectation of a serious lack of bearing capacity. Obviously there is a substantial residual bearing capacity, which means that the real bearing capacity is significantly larger than calculated. Therefore in Figure 1 a second declining line is shown, representing this higher bearing capacity. The vertical distance between the lines represents the hidden bearing capacity. It is clear that a more accurate determination of this reserve capacity is of large significance and should be regarded before eventually a decision for retrofitting of the bridge is taken.

3. Hidden bearing capacities

3.1. Considerations with regard to the concrete compressive and tensile strength

The first investigations of the bearing capacity of the bridges were carried out using the original design values for concrete and steel. The bridges were built with concrete of strength class C20/25. However, after 28 days the strength of the concrete still increases significantly, especially if a period of decades is concerned. Tests on drilled cores, taken from the bridges, showed even that the mean concrete strength is in the range 60-85 N/mm^2. Those high values can be explained by the fact that the cement particles used in those early days were relatively coarse, so that the hydration process will continue for a long time, causing a substantial gain of strength. The compressive strength is an important factor, but not the most important. Especially with regard to the shear capacity the tensile strength plays an important role, especially in solid slabs which normally do not contain shear reinforcement. In most design codes, the shear capacity is a direct, or an indirect, function of the concrete tensile strength. With regard to the concrete tensile strength, however, a remarkable observation was made. Tests on the drilled cylinders showed that the splitting tensile strength was in the range 4-5 N/mm^2, whereas the axial tensile strength was only in the range 1-2 N/mm^2 (Fig. 4).

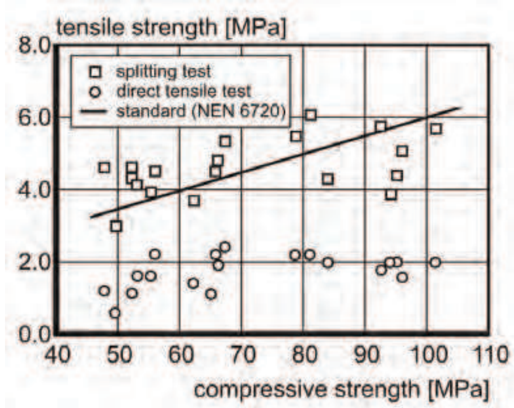


Fig. 4. Direct tensile strength and splitting tensile strength as a function of the concrete compressive strength, as determined on drilled cylinders taken from concrete bridges in the Netherlands

According to EC-2 the ratio axial tensile strength to splitting tensile strength should be 0.9, whereas the new Model Code 2010 proposes even a value 1.0. An important observation in Figure 4 is that the scatter in the values of the splitting tensile strength and the axial tensile strength is about the same. A possible explanation for the difference between splitting tensile strength and axial tensile strength is given in Figure 5. During casting and vibrating of the concrete, under the coarse aggregate water layers are built (bleeding), see Figure 5 left. Especially the concrete of those days was sensitive to this type of phenomenon, since in that period no superplasticizers were used yet, so that excess water was necessary for obtaining the required workability.

Fig. 5. Drilled cylinder with visual flaw under one of the large particles (weakened interface)

The weakened interfaces below coarse aggregate particles explain the low axial tensile strength of the concrete. On the splitting tensile strength the weak areas have no large influence, since they are not in the planes where cracks are expected to develop. The same holds true for the cylinder compressive strength. In beams and slabs loaded in shear at first bending cracks occur, in a direction perpendicular to the axis of gravity. Such cracks are not influenced by the weak interfaces. Only after the transition from bending cracks to inclined shear cracks there might be an influence, but this is only at the stage that the shear crack is tending to progress at a low angel with the member axis, which is already near to shear failure. Tests haven been carried out between strips, sawn from old bridges, and newly made strips with the same geometry, reinforcement and concrete compressive strength. They show that the behaviour is similar, which confirms that the weak interfaces under the coarse aggregates do not play a significant role with regard to the shear carrying behaviour. The shear capacity can therefore be calculated with the usual formula's, introducing the measured cylinder compression strength.

The results of this investigation are more or less comparable with the results of tests carried out some years ago at TU Delft. Figure 6 shows a shear test carried out on a strip, sawn out of an older bridge.

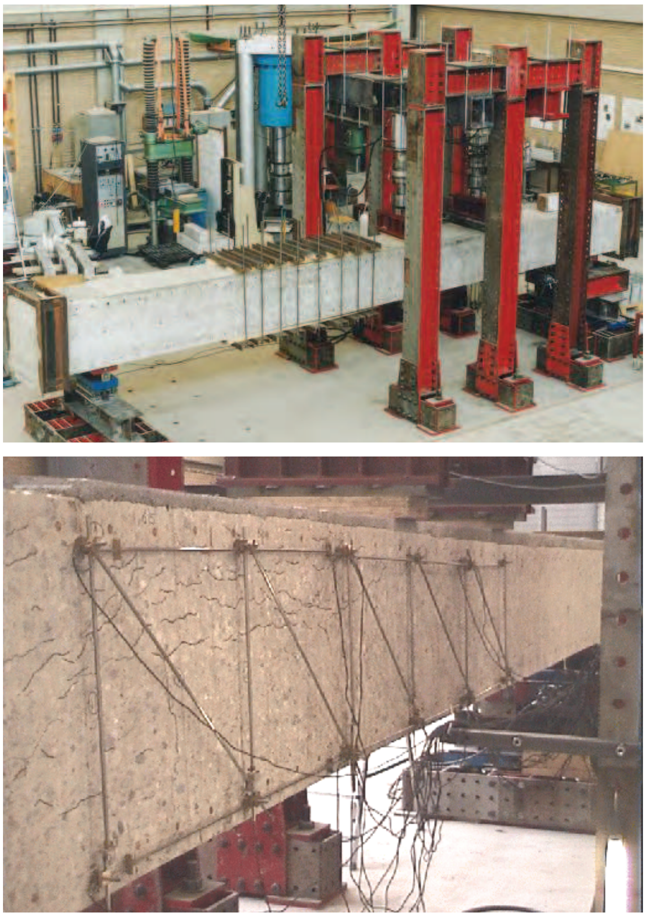


Fig. 6. Shear tests on beams damaged by many horizontal cracks due to Alkali Silica Reaction (TU Delft)

This solid slab bridge showed a large number of short horizontal cracks, due to the effect of Alkali Silica Reaction. The cracks can be explained on the basis of the swelling of the concrete under the influence of the ASR. In the horizontal direction a lot of reinforcement was available, both at top and bottom, which restrained the horizontal extension, and generated a type of axial prestressing. Therefore no vertical cracks occurred. In the vertical direction, however, the extension could occur freely so that the cracks were not suppressed. A considerable reduction of the shear capacity was feared, because cylinders drilled from the bottom, often showed tensile strength equal to 0, caused by the horizontal cracks. The tests on the severely damaged slab strips, showed however a reduction of the shear capacity of not more than 25%.

3.2. Consideration with regards to the choice of the method for the determination of the bearing capacity

Design of structures is mostly carried out using simplified formulations. For instance in the case of slabs, often the lower bound theory of the theory of plasticity is used (strip method, or equilibrium method). The slab is simplified to a system of independent strips, to which parts of the loads can be attributed. The sum of the bearing capacity of the strips is assumed to be equal to the capacity of the overall system. This method of design is simple, but results in larger amounts of reinforcement than e.g. a design on basis of the theory of elasticity. However, when in case of an investigation of the bearing capacity of an existing structure the question is raised which is the most probable real bearing resistance, lower bound models are not the appropriate tool, since they give too conservative results. An alternative is here the use of the theory of plasticity, investigating and comparing the bearing capacity of a number of kinematic models in order to find the minimum capacity.

Although meanwhile thousands of shear tests on beam type of elements have been carried out, there are hardly test results available for the shear capacity with concentrated loads near to line supports. Analyses of the bridge bearing capacity in recent times showed that appropriate modes for this loading case would be very welcome. Rodrigues, Muttoni and Olivier [1] carried out interesting tests in this respect. They investigated the shear capacity of the cantilevering part of bridge decks in box girder bridges. Figure 7 shows the cracking patterns in the upper and the lower parts of the slab. The researchers demonstrated that the behaviour can principally be described with the yield line theory. A complication is however the possible failure in shear before the kinematic model could fully develop. In the cases considered, the theoretical bearing capacity according to the yield line theory was nearly reached.

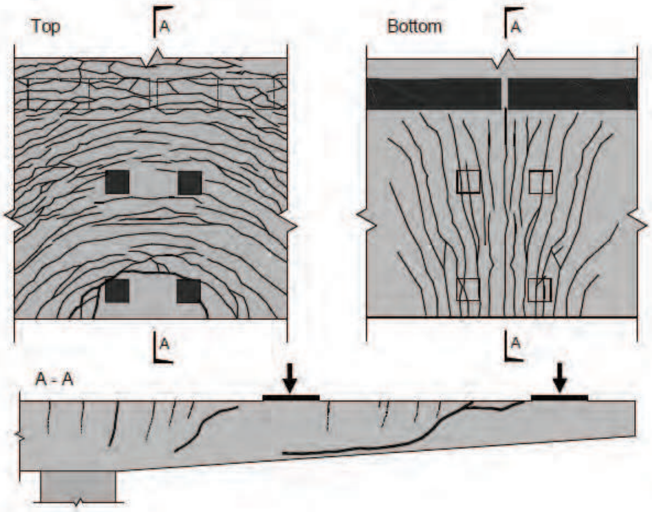
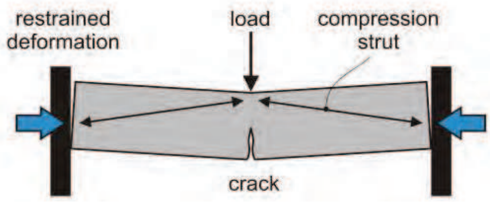


Fig. 7. Experiment investigating the behaviour of the cantilevered part of a box girder under a combination of concentrated loads (Rodriguez, Muttoni and Olivier [1])

3.3. Compressive membrane action in slabs

The design of solid slabs is carried out already for many years under the assumption that in case of a load perpendicular to the slab only bending and torsional moments occur. There is, however, another effect which is mostly ignored in design, but can significantly contribute to the bearing capacity. Already in 1955 Ockleston [2] carried out a test on one of the inner slabs in a slab field in the Old Dental Hospital in Johannesburg (that was available for research since it was bound to be demolished). The inner decks failed at a load which was about twice the theoretical load according to the yield line theory. The increase of the bearing capacity was explained on the basis of compressive membrane action. This mechanism occurs under the influence of a restraint of lateral deformations due to the surrounding part of the slab. The mechanism is explained in Figure 8.

a)



b)

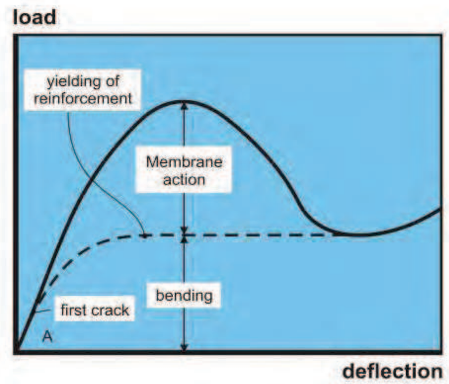
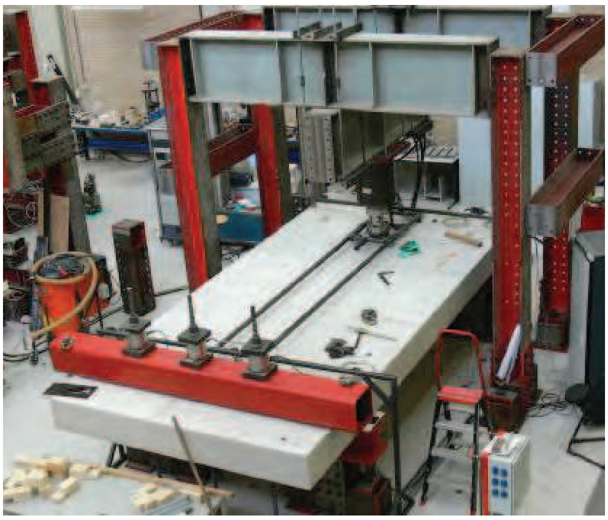


Fig. 8. Compressive membrane action in a bridge deck (a) and interaction between membrane action and bending (b)

As a result of the development of cracks at midfield and at the edges, a mechanism occurs, in which the slab tries to expand in lateral direction. Since this lateral extension is restrained a compressive arch forms, which is able to sustain appreciable forces. The increase of the bearing capacity depends on the degree of restraint. Already in the sixties it was demonstrated by tests (Tong, Bachelor [3]) that the punching shear capacity is considerably increased by compressive membrane action. The Canadian and New Zealand Building Recommendations allow the consideration of this effect in design. Although in these recommendations conservative values are given for the effect of compressive membrane action, considerable savings of reinforcement are obtained. Considering compressive membrane action, only a reinforcement ratio of about 0.5% is necessary, whereas without compressive membrane action about 1.7% is necessary.

The fact that up to now for the design of bridges in Europe compressive membrane action was not regarded means that there is still a considerable residual capacity with regard to bending and shear. Figure 9 shows a test by Taylor [4], carried out recently on a bridge in Nord Ireland. The reinforcement in the deck was applied in the middle of the deck plate. The loads reached values of 3-5 times the theoretical values, calculated without compressive membrane action. In none of the 12 tests failure occurred. The tests had to be stopped because the limit of the test facility was reached.

a) 

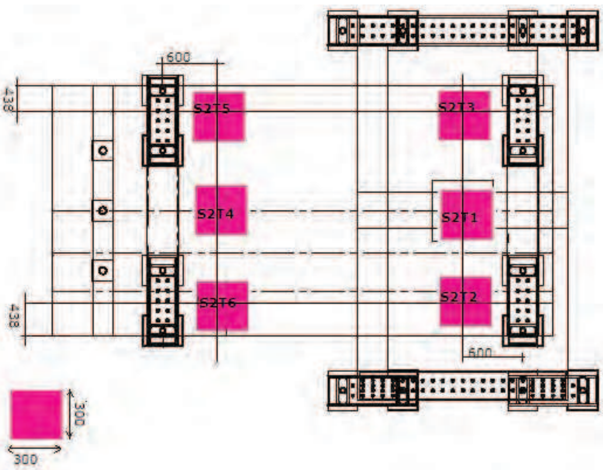
b) 

Fig. 9. Tests at TU Delft on solid slabs subjected to concentrated loads near the supports

3.4. Loads near to supports

From the control of the bearing capacity of solid slab bridges in the Netherlands it turned out that often loads near to supports, single or in combination, are governing for the shear bearing capacity, at least according to the design models. Therefore it was investigated whether the design practice in combination with the code requirements, isn't too conservative. According to those design methods the load is spread under angles of 45° to the support and then compared with the limit values for shear. Figure 9 shows the test equipment for a solid end slab in a continuous statically indeterminate bridge. A concentrated load, simulating a large wheel load, is applied near to the end support. The effect of loads was considered for linear end – and intermediate supports.

Figure 9b shows a top view on the slab with the different position of the loads. The tests ST1, ST2 and ST3 were carried out near to the linear end support (hinged support). The tests ST4-ST6 were carried out near to the intermediate support (with bending moments from adjacent slab fields. Table 2 shows that the bearing capacities found in the tests were considerably higher than obtained from the equations according to the Dutch Building Code VBC.

Table 2. Tests on slabs with concentrated loads near to supports: comparison between test results and results obtained with Dutch Building Recommendations

Test No.	P_u (test) (kN)	P_u (Dutch Code) (kN)
S1T1	954	539
S1T2	1023	533
S1T3	758	491
S1T4	731	470
S1T5	851	501
S1T6	659	501

4. Improvement of the reliability of nonlinear finite element analyses

In order to find out whether a bridge has a sufficient bearing capacity very often nonlinear finite element calculations are used. From experiences with NLFEM calculations it is known that this method is particularly useful for the interpretation of test results. As Reinhardt [5] mentioned in his retirement lecture at TU Delft "Measuring and calculating belong together". However, it is much more difficult to predict the behaviour and a reliable value for the bearing capacity of existing bridges, without prior available test data which could be used for calibration. Furthermore, using nonlinear FEM calculations, there is a large choice with regard to element types, element sizes, calculation procedures and material parameters. A possibility to enhance the reliability of NLFEM calculations is to carry out calibrations on test results obtained on similar types of elements. Figure 10 shows an example. In order to develop a basis for a reliable prediction of the behaviour of prestressed T- and I-beams, trial calculations and calibrations are carried out with the numerical programs DIANA and ATENA on the behaviour of long prestressed beams known from literature. This calibration on similar types of beams, the behaviour of which is well documented, is expected to increase the reliability of NLFEM prediction.

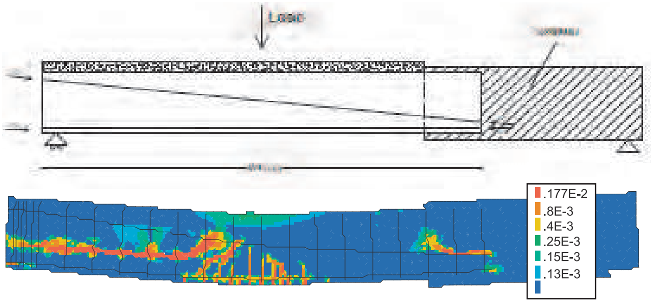


Fig. 10. NLFEM analysis of a beam under shear loading as a part of a research program to develop tailor-made analysis programs for particular types of beams

Meanwhile a practitioner's guide for NLFEM analysis has been adopted in the Model Code for Concrete Structures 2010 [6].

Fig. 11. Proof loading of an existing bridge with especially instrumented German Loading Truck (BELFA) in The Netherlands

Another way of optimizing the use of nonlinear numerical programs for the reliable calculation of the bearing capacity of existing bridges is to combine them with proof loading and Acoustic Emission. Figure 11 shows the proof loading of a small bridge with the specially developed German vehicle BELFA (BELastung FAhrzeug = Loading Truck). I order to guide the testing, acoustic emissions are registered. In future the combination of proof loading, acoustic emission and numerical analysis is seen as an important method for the estimation of the behaviour of existing bridges. A new research program, aiming at further optimizing this method is at the onset of starting at TU Delft.

5. Conclusions

1. When old bridges are analyzed for the higher traffic loads of today, and the old design data are used for this analysis, often the analysis will suggest that the bearing capacity is insufficient.
2. The bridges dispose of considerable residual capacity with regard to higher concrete strength after decades of hydration, compressive membrane action, better redistribution that assumed in design.
3. Verification of the results of concrete strength on the basis of drilled cylinders should be done with utmost care.
4. Nonlinear FEM methods can be developed tailored to the prediction of the behaviour of particular types of bridge beams.
5. The combination of proof loading, numerical analysis and acoustic emission deserves further development, since it may become an important tool for future assessment of existing bridges.

References

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