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Interpretation of 200 Load Tests of Swiss Bridges

Interprétation de 200 essais de charge de ponts en Suisse

Auswertung von 200 Belastungsversuchen an Schweizer Brücken

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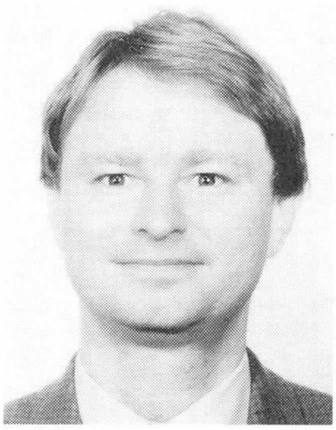
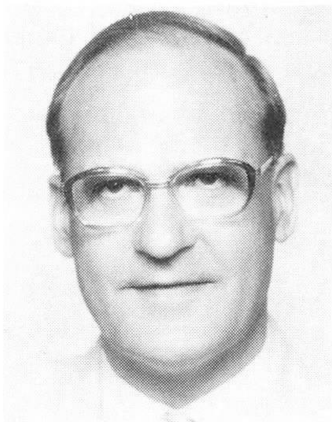




SUMMARY

The Institute of Reinforced and Prestressed Concrete (IBAP) of the Swiss Federal Institute of Technology has organized and interpreted over 200 load tests over the past 20 years. A full-scale load test is a real opportunity to observe and understand the behaviour of the bridge. A database containing the characteristics of the bridges along with their statistic and dynamic behaviour during the load test was established. The results of the statistical analysis of the database are presented. Some answers are proposed of the effective modulus of elasticity and the contribution to the rigidity of secondary elements, such as parapets or asphalt layer. The problem of estimating the structural capacity based on the results of load tests is discussed.

RÉSUMÉ

L'institut de béton armé et précontraint (IBAP) de l'Ecole Polytechnique de Lausanne a organisé et interprété plus de 200 essais de charge ces 20 dernières années. Un essai de charge en vraie grandeur est une réelle chance pour observer et comprendre le comportement d'un pont. Une base de données, contenant les caractéristiques des ponts avec leur comportement statique et dynamique observé lors de l'essai de charge, a été établie. Les résultats de l'analyse statistique de cette base de données sont présentés. Quelques réponses sont proposées pour le module d'élasticité effectif et pour la contribution à la rigidité des éléments secondaires, comme les parapets ou le revêtement. La problématique de l'estimation de la capacité structurale basée sur les résultats de l'essai de charge est abordée.

ZUSAMMENFASSUNG

Das Massivbauinstitut der Eidg. Technischen Hochschule Lausanne hat während der letzten 20 Jahre über 200 Belastungsproben durchgeführt. Ein Grossversuch im Masstab 1:1 ist eine Gelegenheit, um das Verhalten eines Bauwerkes zu beobachten und zu verstehen. Eine Datenbank wurde aufgestellt mit dem Gegebenheiten der Brücken und dem Verhalten während des statischen und dynamischen Belastungsversuches. Es werden Resultate einer statischen Analyse gezeigt. Es wird auf die Problematik des E-Moduls eingegangen sowie auf die Mitwirkung von Bordüre und Belag. Eine direkte Vorhersage der Tragsicherheit lässt sich allerdings aus einem Belastungsversuch nicht herleiten.

1. INTRODUCTION

For the past 20 years, the Institute of Reinforced and Prestressed Concrete (IBAP) has been involved with full-scale load testing of bridges (Fig. 1). This has resulted in over 200 bridges being tested. The Swiss Codes recommend a load test for any new bridge with spans exceeding 20 m [1-2].

The objective of a load test is to determine and quantify the global behaviour of a bridge. The majority of load tests are acceptance tests, aimed at examining the serviceability of a new bridge, and in consequence put it into service or not. The decision of acceptance is generally based on the concordance between the measured and calculated deflections, on residual deformations, on cracking and on the affinity between measured and calculated deflected shapes. Experience shows a strong correlation between an unsatisfactory behaviour during a load test and an abnormal long-term behaviour of the bridge, characterized by a non-stabilization of cracking and sagging. Therefore an abnormal behaviour of the bridge under a load test is an alarm signal, generally leading to more frequent inspections and early maintenance work.

The main results of these two hundred tests have been collected in a computerized database. General conclusions on the real behaviour of a bridge under loading have been collected and are presented in this article.

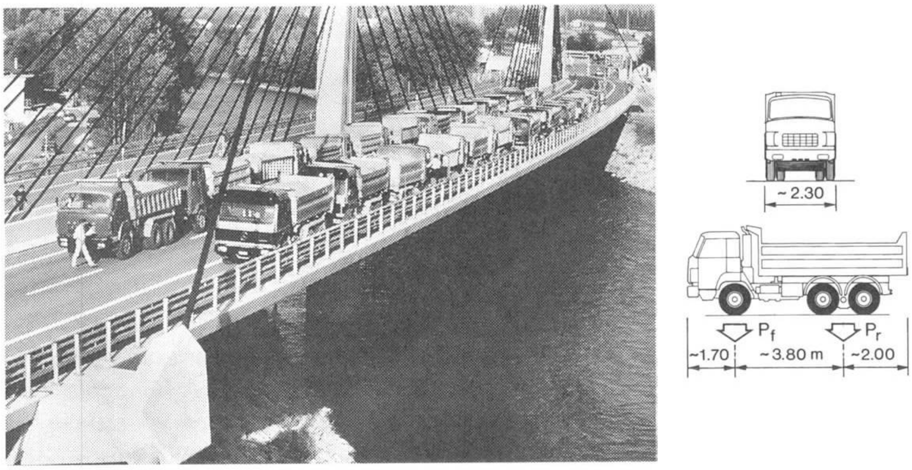


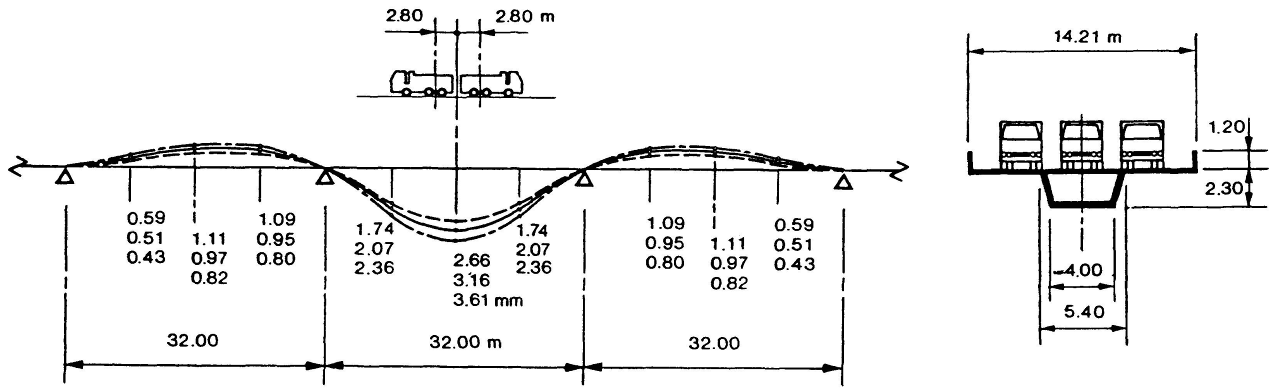
Fig. 1: Static load test of the Chandoline Bridge. The nominal dimensions of the lorries used for the load testing of bridges are also shown: $P_f = 60$ kN, $P_r = 190$ kN, $P_{total} = 250$ kN

2. INTERPRETATION OF LOAD TESTS

The main criterion to evaluate the behaviour of a bridge subjected to a load test is the concordance between measured and calculated deflections. On the measuring side, qualified operators, high precision instruments, and the repetition of each load case at least three times lead to highly accurate measurements. Temperature effects are eliminated by frequent "zero readings". On the computing side, more uncertainties are present, because of several parameters which are only imperfectly known.

2.1 Modulus of elasticity of concrete

The most important unknown parameter for the calculation of deflections is the effective modulus of elasticity of the concrete. Code formulas for estimating the modulus of elasticity of concrete based on concrete strength only are notoriously inaccurate. The modulus of elasticity is strongly influenced by local parameters such as the aggregates, the composition of the cement paste and the cure of the concrete. This complexity is increased by the fact that the actual modulus of elasticity is time- and strain-dependent. One possibility to determine directly this parameter is by testing cores taken from the bridge. Unfortunately, a limited number of cores is not necessarily representative of the entire structure; micro-cracking of the core may have occurred during its extraction and influence the results. Another possibility for determining the modulus of elasticity is to use non-destructive methods such as ultrasonic measurements. It is in all cases desirable to have results from samples taken during construction. The influence on the calculated deflections of the method used for determining the modulus of elasticity is shown in Fig. 2, taking the example of the viaduct of Coudray.



------ Ec=38 GPa from elastic modulus-compressive strength relationship (SIA),
——— Ec=32 GPa from cores, —-—-— Ec=28 GPa from ultrasonic pulse velocity

Fig. 2: Calculated deflections for viaduct of Coudray based on three methods for determining the modulus of elasticity

2.2 Effective moment of inertia

At first sight, it would seem that the moment of inertia of the cross section is easily determined as it depends only on geometry. However, the effective inertia depends on several parameters such as reinforcement, parapets, asphalt deck surface, cracks and micro-cracks due to construction or other causes.

In the past, these parameters have been roughly taken into account in the evaluation of the results of load tests by adjusting the modulus of elasticity of the concrete. To cover the participation of such secondary elements, the value of the modulus of elasticity was taken as 40 GPa in most cases. A better solution is to base the calculated deflections on the real modulus of elasticity of the concrete and on a better estimate of the effective inertia of the cross section.

3. DATABASE

The differences between calculated and measured deflections during load testing led IBAP to establish a computerized database. The database contains the main characteristics of each bridge along with the results of the static and dynamic load tests. The objective of this database is a statistical study of bridge behaviour as observed during load tests. The influence on the behaviour of the type of structure, cross-section, parapet and other factors can be discovered and quantified by sorting and filtering the results.

Table 1 shows the structural system and type of cross-section of all bridges contained in the database. One hundred and sixty five of the tested bridges are post-tensioned concrete structures.

Structural system		Cross-section	
Type	Number	Type	Number
beam	168	box-girder of constant depth	55
rigid portal frame	21	box-girder of variable depth	25
arch	5	slab beam	28
cable stayed	3	open (beams connected by concrete deck)	89

Table 1: Structural system and type of cross-section of all bridges contained in the database

3.1 Selection of bridge type and statistical parameters

In order to obtain a homogeneous set of results, the analysis focused on intermediate spans of post-tensioned bridges with the structural system being a continuous beam. Because it was anticipated that the influence of massive R.C. parapets and of an asphalt layer would be important, bridges for which no information was available on the presence of these items at the time of testing were also rejected. Finally, bridges for which the ratio of measured to calculated deflections were inferior to 0.65 and superior to 1.30 were rejected because of doubts on the reliability of the engineer's calculations.

Sixty six bridges satisfied these criteria. In this article, "R_m" is used for the average ratio of measured to calculated deflections. At mid-span of the loaded span, $R_m = 0.94$ and $\sigma = 0.16$ (standard deviation) for the sample of 66 bridges; taking $E_c = 40$ GPa for the calculated deflections. The effect of the R.C. parapets and the asphalt layer is neglected for the calculated deflections. While the difference of the average ratio to one can be explained by the participation to the inertia of secondary elements, and by the value of the modulus of elasticity, the dispersion is large. In order to understand and reduce this dispersion, the following three sub-samples were examined:

- bridges with RC parapets (22 bridges), $R_m = 0.82$, $\sigma = 0.095$;
- bridges with a box-girder of variable depth (10 bridges), $R_m = 1.03$, $\sigma = 0.11$;
- bridges with an asphalt layer (33 bridges), $R_m = 0.93$, $\sigma = 0.15$.

The smaller dispersions of these three sub-samples shows the influence of certain characteristics of the bridge on its behaviour, as it clearly appears in Fig. 3.

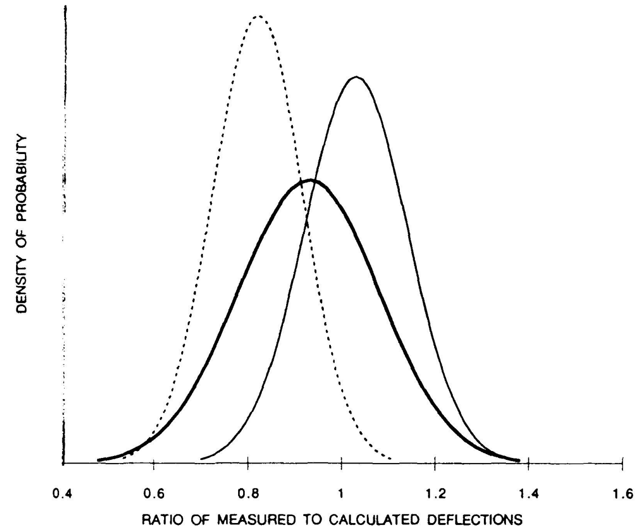


Fig. 3: Normal probability distribution curve for the ratio of measured and calculated deflections for: bridges tested with an asphalt layer; the box-girder bridges of variable depth; all the bridges with massive R.C. parapets (E_c = 40 GPa)

3.2 Analysis of data

The results of the load tests in the sample of 66 bridges were successively corrected using the reciprocal of the R_m determined for each factor contributing to the moment of inertia. The increase in stiffness due to the presence of normal and prestressed reinforcement was estimated to 6%.

After these corrections, the results of the calculations led to an average ratio of measured to calculated deflections of 1.19, with a modulus of elasticity of concrete equal to 40 GPa. In order to obtain $R_m = 1.0$ for this sample, the modulus of elasticity of the concrete should be taken to 33.5 GPa, which is much closer to actually measured values. Fig. 4 shows the histogram of the ratio of measured to calculated deflections and the Gauss distribution after correction of the influence of the parapets, of the asphalt layer, of the reinforcement and of the cross-section. Table 2 summarizes the participation to inertia of asphalt layer, R.C. parapets and reinforcement.

The asphalt surface increases the effective inertia of the superstructure. This participation depends strongly on the surrounding temperature and on the cross-section of the bridge. Fig. 5 shows the normal probability distribution for the ratio of measured to calculated deflections for bridges tested with and without asphalt.

Element	Asphalt layer	R.C. parapets	Reinforcement
Participation to inertia	6%	24%	6% (estimated)

Table 2: Participation to inertia of asphalt layer, R.C. parapets and reinforcement

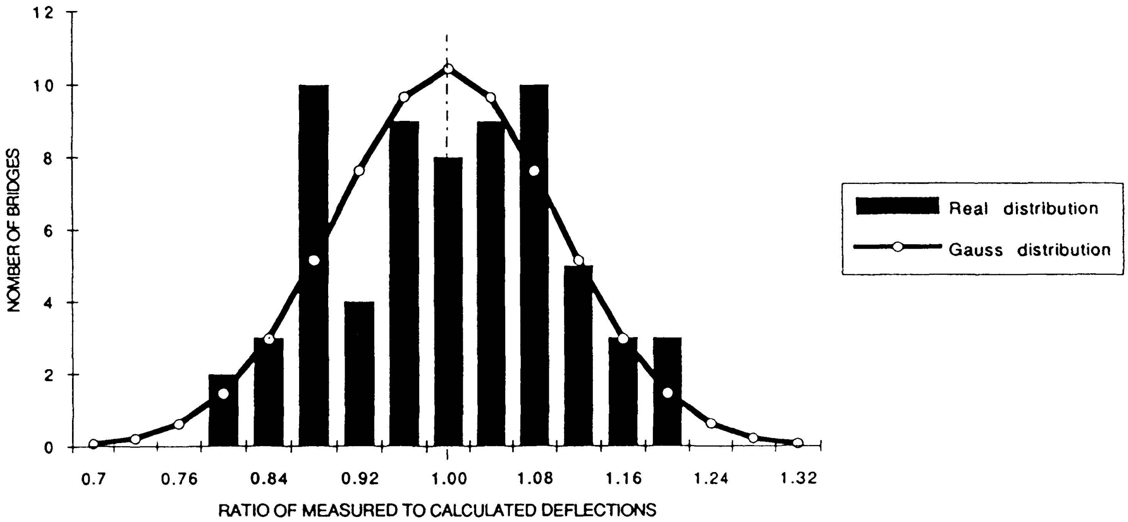


Fig. 4: Histogram of distribution of ratio of measured to calculated deflections for 66 bridges after correction (E_c = 33.5 GPa)

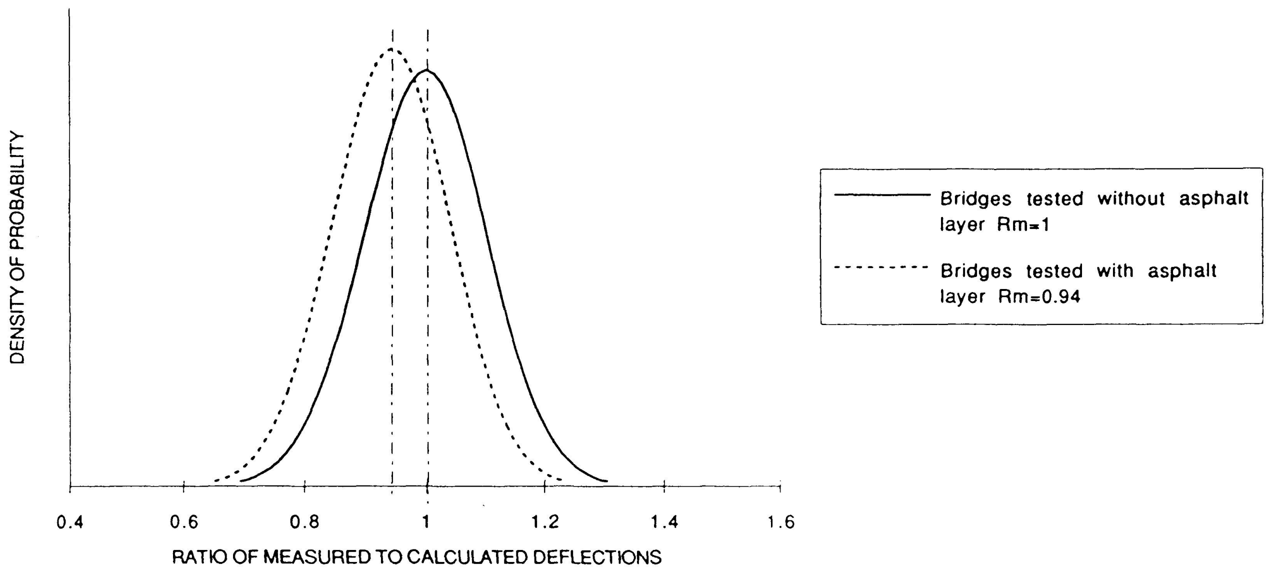


Fig. 5: Normal probability distribution curve for the ratio of measured to calculated deflections for bridges tested with and without asphalt (E_c = 33.5 GPa)

The parapets increase the effective inertia of the superstructure. The amount of this participation depends on the type of parapets, on the connection between the parapets and the superstructure and on the cross-section of the bridge. Fig. 6 shows the normal probability distribution for the ratio of measured to calculated deflections for bridges tested with and without reinforced concrete parapets. It should be noted that the effect of parapets is neglected for the calculated deflections.

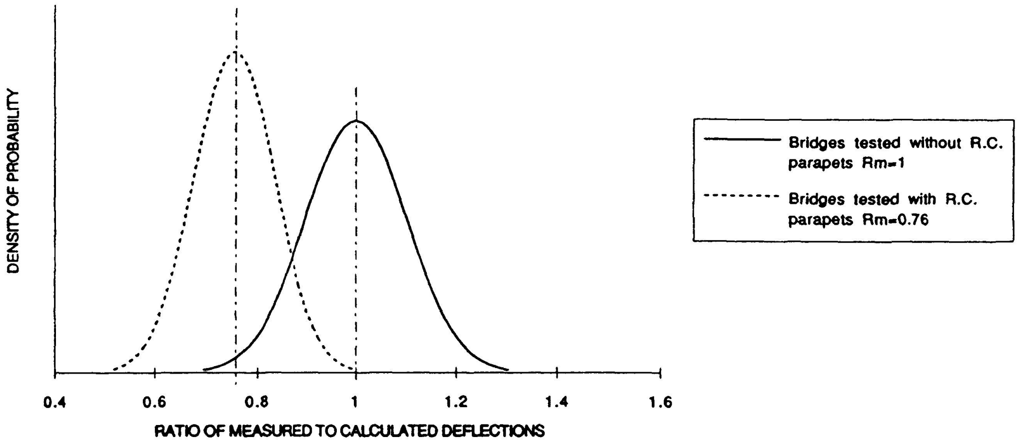


Fig. 6: Normal probability distribution curve for the ratio of measured to calculated deflections for bridges tested with and without R.C. parapets (E_c = 33.5 GPa)

Box-girder bridges systematically exhibit an effective modulus of elasticity lower than average, especially box-girders of variable depth. On the other hand, slab bridges and bridges of an open cross-section systematically show an effective modulus of elasticity greater than the average modulus. Table 3 shows the effective modulus of elasticity for the bridges with various cross-sections.

Type of cross-section	Effective modulus of elasticity [GPa]
Box-girder of constant depth	32
Box-girder of variable depth	31
Slab beam	37
Open (beams connected by concrete deck)	35

Table 3: Effective modulus of elasticity for the bridges of different types of cross section

A possible explanation for these variations lies in the fact that the method of construction is strongly dependent on the type of cross-section. Fig.7 shows the normal probability distribution for the ratio of measured to calculated deflections for box-girder bridges with a constant depth constructed on fixed scaffolding, for box-girder bridges with a variable depth constructed by the balanced cantilever method and for box-girder bridges with a constant depth constructed by incremental launching. In the same manner slab beams and open cross-section bridges are shown in the same figure.

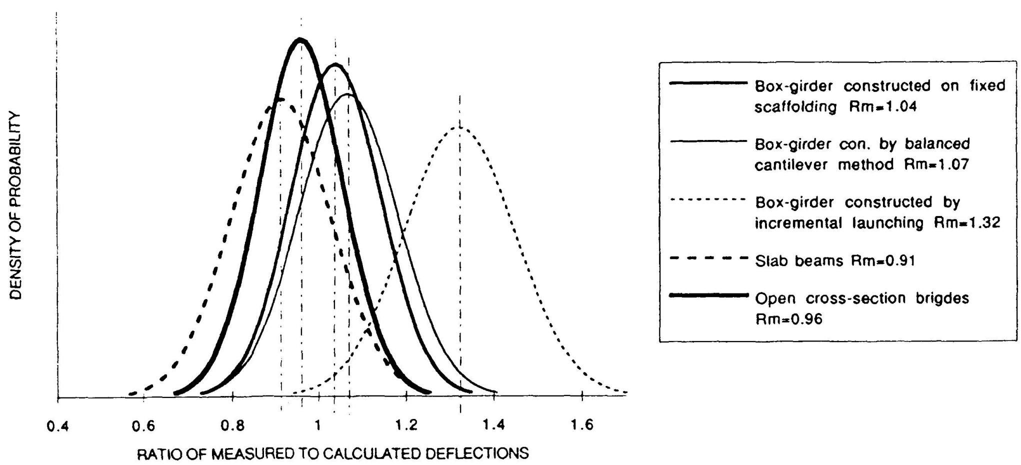


Fig. 7: Normal probability distribution curve for the ratio of measured to calculated deflections for bridges of different type of cross-sections and different construction methods (E_c = 33.5 GPa)

3.3 Affinity between the measured and calculated deflections

The ratio between the measured and calculated deflections in the loaded spans is systematically larger than those in the adjacent spans. If we make the calculated deflections correspond to those measured in the loaded spans at mid-span ($R_m = 1$), R_m becomes 0.84 in the adjacent spans (see Fig. 8). This systematic difference in stiffness between adjacent spans could be explained by cracking of the loaded span and/or a lack of continuity on supports. Another factor can be a reduction of the modulus of elasticity in the loaded span due to the level of stress in the concrete.

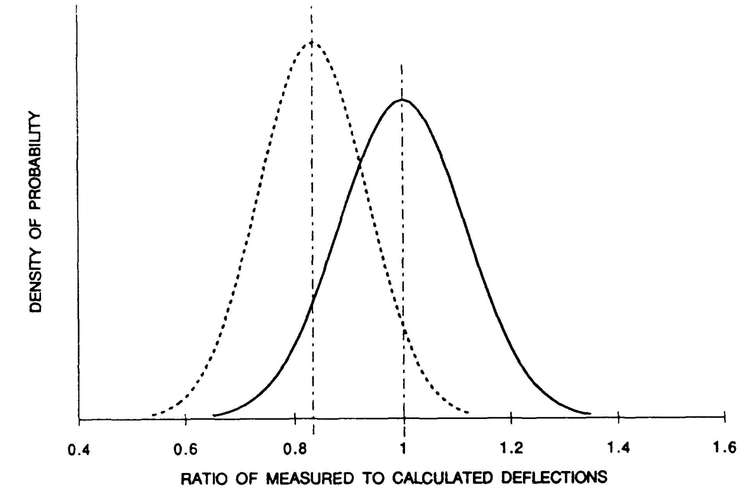


Fig. 8: Normal probability distribution curve for the ratio of measured to calculated deflections for the loaded central span and for the adjacent span

4. ULTIMATE LOAD FROM LOAD TEST RESULTS

The load-deflection curve for a prestressed concrete bridge can be approached by a tri-linear relationship as shown in figure 9, in which we have assumed that 80% of the permanent load is balanced by the effect of prestressing, a permanent load of 20 kN/m^2 and a live load of 5 kN/m^2. Considering these different values and assuming a global safety factor of 1.7, the ultimate design load is 1.7 (20+5) = 42.5 kN/m^2. Because the load test is an acceptance test the upper limit of loading is generally about 5 kN/m^2, which normally should not lead to cracking of the bridge. It seems that the extrapolation of the ultimate load based on the results of a single load test is senseless. However, a good correlation between measured and calculated deflections indicates a satisfactory structural behaviour, provided the deflections are reversibles and the requirements of ductility are fulfilled.

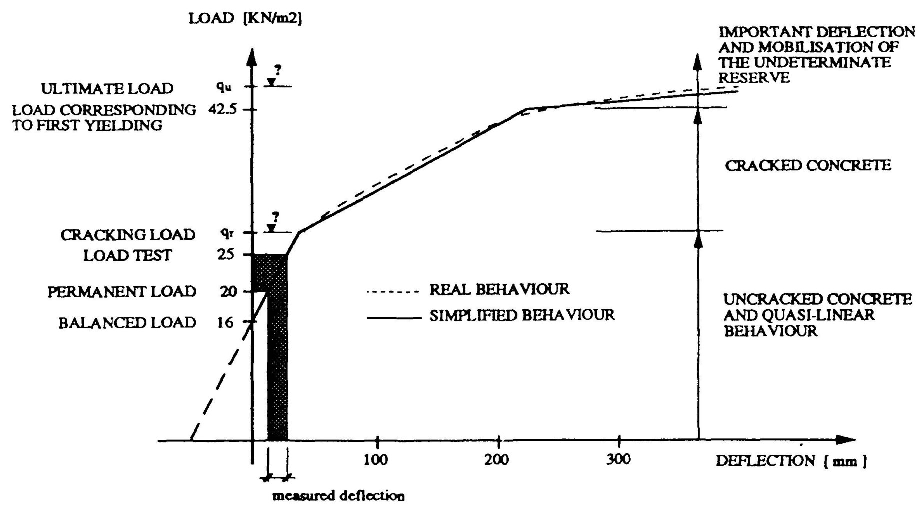


Fig. 9: Load-deflection curve of a prestressed concrete bridge (order of magnitude)

5. CONCLUSIONS

The load test is a real chance and a challenge to observe and interpret the actual behaviour of a structure under load on a 1:1 scale. A frequent correlation between an unsatisfactory behaviour during a load test and the long-term behaviour of a bridge regarding a non-stabilization of cracking and of sagging has been observed.

The contribution to the rigidity of the parapets, the asphalt layer and the reinforcement has to be taken into account for calculated deflections. The modulus of elasticity has to be experimentally determined and not only estimated according to the compressive strength of the concrete.

Although our research concerning 200 load tests is not completely finished, some important preliminary conclusions can be drawn:

Box-girder bridges exhibit an effective modulus of elasticity lower than the average. On the other hand slab bridges and bridges of open cross-section show an effective modulus of elasticity greater than the average modulus.

The method of construction influences the stiffness of the bridge; box-girder bridges with a constant depth constructed by incremental launching are greatly less rigid than those constructed on fixed scaffolding. This can be explained by micro-cracking during the execution.

Even if the calculated deflections are corrected to correspond to those measured at mid-span of the loaded span, the affinity between the measured and calculated deflected shapes is not perfect. A systematic difference in stiffness between loaded spans and adjacent spans is observed. This can be explained by cracking of the loaded span and/or a lack of continuity over the supports.

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