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Proof load testing of reinforced concrete bridges: Experience from a program of testing in the Netherlands

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Abstract: For existing bridges with large uncertainties, analytical methods have limitations. Therefore, to reduce these uncertainties, field testing of a bridge can be used. A type of such a field test is a proof load test, in which a load equivalent to the factored live load is applied. If the bridge can carry this load without signs of distress, the proof load test is successful, and it has been shown experimentally that the bridge fulfils the code requirements. It should be understood that this method for assessment is different from the diagnostic load tests that are carried out in Ecuador prior to opening a bridge. The loads used for proof load tests are significantly larger. Therefore, it is important to instrument the bridge for a proof load test, and to evaluate during the test that the load does not result in permanent damage to the bridge. To research this topic, and to develop recommendations for proof load tests, a series of proof load tests and a collapse test were carried out in the Netherlands. Additional laboratory testing was carried out as well. Based on this information, recommendations for proof load tests of reinforced concrete slab bridges have been developed for the failure modes of flexure and shear. In the German and North American guidelines for load testing, load testing for shear is not permitted. However, many existing bridges do not fulfil the requirements for shear upon assessment according to the current live load models. Even though more experimental research is needed to develop proof load testing for shear in a guideline or code for the Netherlands, the currently available research results already lead to interesting conclusions with regard to the behaviour of bridges proof load tested in shear, and the required safety margin to avoid damage to the bridge.

Abstract "Pruebas de carga en puentes de hormigón armado: experiencias de una programa de pruebas en Holanda': Para puentes existentes con largas incertitudes, métodos analíticos tienen limitaciones. Por esa razón, pruebas en el puente mismo pueden ser usados para reducir las incertitudes. Se puede utilizar pruebas de carga, en las cuales se aplica una carga equivalente a la carga viva con sus factores de carga correspondientes. Si el puente puede sostener esa carga sin aflicción, la prueba de carga es exitosa, y se ha demostrado de una manera experimental que el puente cumple con los requisitos de la norma en términos de capacidad. Se debe entender que ese método de pruebas de carga no es lo mismo que las pruebas diagnósticas que se usan en el Ecuador antes de abrir un puente al público. Las cargas involucradas en pruebas de carga son bastante largas. Por esa razón, es importante aplicar sensores en el puente, y evaluar si la prueba no aplica danos permanentes al puente. Para investigar ese tema, y para desarrollar recomendaciones para pruebas de carga, se hicieron una serie de pruebas de carga en Holanda, junto con una prueba de colapso, y pruebas en vigas en el laboratorio. Con esa información, se han desarrollado recomendaciones para pruebas de carga en puentes de hormigón armado tipo losa, para las modas de falla de flexión y cortante. En los códigos alemanes (DAfStB Richtlinie) y estadounidenses (ACI

437.2M-13 y el Manual for Bridge Evaluation) para cargas de prueba, no se permite probar estructuras que pueden fallar en cortante, pero muchos puentes existentes no cumplen con los requisitos para cortante cuando se los evalúa con las cargas vivas de hoy en día. Aunque todavía más datos experimentales son necesarios para permitir pruebas de carga para cortante en un código Holandés, la investigación presente ya resulta en observaciones importantes con respeto al comportamiento de elementos sometidos a cortante y el margen de seguridad que se necesita en una prueba de carga para evitar danos al puente.

1. Introduction

For the assessment of existing bridges with large uncertainties, analytical methods have limitations. Conservative assumptions need to be made, which typically results in (overly) conservative assessments. An example of such a case is the assessment of reinforced concrete slab bridges for shear [1, 2]. The transverse redistribution capacity of these bridges is typically not accounted for in the codes nor in the assessment practice, and these bridges typically do not have shear reinforcement, so that often they are found to be shear-critical upon assessment and insufficient according to the currently governing codes. Another source of uncertainty can be the effect of material degradation and deterioration on the capacity, which often leads to conservative estimations of the capacity.

To reduce these uncertainties, field testing of a bridge can be used. Commonly, two types of field tests, each with different procedures and goals, are identified: diagnostic load tests and proof load tests. Diagnostic load tests [3-6] are used to update an analytical assessment. A low load level is used, and the structural response is measured. This measurement result is then used to compare the analytically predicted response, which is in practice often found from a finite element model. The differences between the field measurements and the analytical model are then minimized by updating the analytical model. Elements that can be updated are [7]: the effect of composite action, continuity at the supports, stiffness of the structures, and the participation of non-structural elements to the overall behaviour. In a proof load test [8-11], a load equivalent to the factored live load is applied. If the bridge can carry this load without signs of distress, the proof load test is successful, and it has been shown experimentally that the code requirements are fulfilled. A further assessment after the proof load test is then not necessary anymore. Since the loads that are applied during a proof load test are large, it is important to instrument the bridge. These measurements should be evaluated in real-time during a proof load test. Thresholds for the onset of nonlinear behaviour, the so-called “stop criteria” need to be determined prior to a proof load test. If such a threshold is exceeded, further loading is not permitted, and the proof load test needs to be terminated.

Assessment by proof load testing is a direct evaluation method of a structure. It should be understood that this method is different from the diagnostic load tests that are carried out in Ecuador prior to opening a bridge. The loads used for proof load tests are significantly larger, since they need to represent the factored live loads and/or the load combination that includes the factored live load.

2. Overview of research on proof load testing in the Netherlands

To research the topic of proof load testing of concrete bridges, and to develop recommendations for proof load tests, a series of proof load tests and a collapse test were carried out in the Netherlands over the past decade. An overview of the bridges that have been tested is given in FIGURE 1, and an overview of the main characteristics of each of these tests is given in Table 1.

FIGURE 1: Overview of tested bridges: (a) Halvemaans Bridge; (b) Viaduct Zijlweg; (c) Viaduct Vlijmen Oost; (d) Viaduct de Beek; (e) Ruytenschildt Bridge (collapse test).

In Table 1, the information is organized in the following columns: “case”, which gives the name of the tested bridge or viaduct, “reason” the uncertainty or reason for proof load testing, “mechanism” the critical mechanism that is tested during the proof load test, “load” the method of load application, “max load” the maximum applied load, “conclusion” the conclusion of the proof load test, and “lesson learned” the main lessons learned from the experiment, which served as a learning process to develop recommendations for proof load testing. The following abbreviations are used in Table 1: ASR for bridges where the uncertainity on the capacity was caused by the presence of damage caused by alkali-silica reaction, EC for Eurocode, SLS for serviceability limit state, ULS for ultimate limit state, Belfa for the German load testing vehicle [12], AE for acoustic emission measurements, and RBK for the Dutch guidelines for the assessment of existing bridges [13]. The method of load application was either by using a system with a steel bridge, jacks, and counterweights, indicated as “load spreader” or by using a special load testing from Germany, the Belfa. The conclusion which resulted from the load test depends on the considered load combination. This load combination is either based on the load factors from the Eurocode NEN-EN 1990:2002 [14], which is the governing code for design, or based on the Dutch guidelines for the assessment of existing bridges [13], which describes different load factors for different safety levels, calibrated to different values of the reliability index.

Table 1. Overview of proof load tests carried out in the Netherlands.

Case	Reason	Mechanism	Load	Max load (kN)	Conclusion	Lesson learned
Vlijmen Oost [15]	ASR	Flexure	Belfa	900	Proof load test: less than EC SLS level UC: RBK Design, EC ULS	No disturbance allowed for AE Load was actually not high enough to provide conclusions with regard to the achieved safety level.
		Shear		800	Proof load test: less than EC SLS level UC: RBK Renovation	
Halvemaans Bridge [16]	Insufficient flexural capacity	Flexure	Load spreader	900	RBK Renovation demonstrated by proof load test	Positive experience with load spreader Positive experience with timber measurement frame, but custom length not practical
Ruytenschildt Bridge [17]	Collapse test	Shear position, flexural distress	Load spreader	3049	No failure Load about 3 times more than necessary for RBK Design	Positive experience with aluminum frame Need for more robust measurement PC Extended Strip Model [18] predicts maximum load well
		Shear position, flexural failure + excessive settlement		3991	Failure (not full collapse) Load about 4 times more than necessary for RBK Design	
Zijlweg [19]	ASR	Flexure	Load spreader	1368	RBK Design + 8.7%	Determination of required proof load before test for the first time Three cycles of loading protocol for acoustic emissions
		Shear		1377	RBK Design + 12%	
De Beek [20]	Traffic restriction + large cracking	Flexure	Load spreader	1751	RBK Design + 6%	Structural response very dependent on loading protocol Span 1 is OK with proof load test, span 2 is critical and needs deeper assessment
		Shear		1560	RBK Design + 2%	

Additional laboratory testing was carried out as well. These experiments included testing three beams sawn from the Ruytenschildt Bridge in five experiments [21], as well as testing two beams cast in the laboratory in four experiments [22]. Based on these experiments, recommendations for the loading protocol have been formulated. For the stop criteria, a proposal has been formulated, but for the failure mode of shear insufficient experimental results are available.

3. Current recommendations

Based on the experience gained from the pilot proof load tests and laboratory testing, an extensive literature review, and additional desk research, recommendations for proof load tests of reinforced concrete slab bridges have been developed for the failure modes of flexure and shear. These recommendations are subdivided into the stages of preparation of a proof load test, execution of the test, and post-processing and analysis of the test and test results.

For the preparation of a proof load test, a technical inspection of the site is the first important step, and an important requirement for the practical preparation of the test. Additionally, calculations are necessary to assess the structure, as well as to have an estimate of the actual capacity by assuming all resistance factors as equal to 1 and using average values of the material properties. Then, the most unfavourable position for applying the proof load should be determined. For this purpose, the use of a linear finite element model is recommended. For a proof load test for bending moment, the position of the design tandem is varied until the largest sectional moment is found. For a proof load test for shear, the critical position is at $2.5d$ from the support, with d the effective depth of the cross-section. The proof load should then result in the same sectional moment or shear as the load combination for which the bridge needs to be assessed. A final step of the preparation is the development of the sensor plan. The minimum requirements for the instrumentation are measurements of the applied load, strains, crack width, and deflection profiles in the longitudinal and transverse directions. A reference strain measurement to correct for the effect of temperature and humidity is also necessary, as well as a measurement of the deflections at the support, to find the net deflection profiles.

For the execution of a proof load test, a loading protocol that uses at least four load levels and three cycles per load level is recommended. This protocol is shown in FIGURE 2. The first load level is used to verify if all instrumentation is working properly. Then, a load level that corresponds to the serviceability limit state is tested for three cycles. The final load level is the target level, which is the safety level that needs to be proven by the proof load test. In between the second and final level, an intermediate level is recommended. For the load levels past the serviceability limit state, it is recommended to apply the load in small steps, as shown in FIGURE 2, to check all measurements and evaluate if further loading is permitted. A second important aspect of the execution of a proof load test are the stop criteria. The currently proposed stop criteria for reinforced concrete bridges are given in Table 2. The stop criterion for concrete strain is:

$$\varepsilon_c < \varepsilon_{c,lim} - \varepsilon_{c0} \tag{1}$$

with ε_c the measured strain in the concrete, $\varepsilon_{c,lim} = 800\ \mu\varepsilon$ if the concrete compressive strength is larger than 25 MPa, and ε_{c0} is the strain caused by the permanent loads. The maximum measured crack width during the application of the load is w_{max}. Crack widths of smaller than 0.05 mm can be neglected. The stiffness is measured as the tangent to the load-deflection diagram.

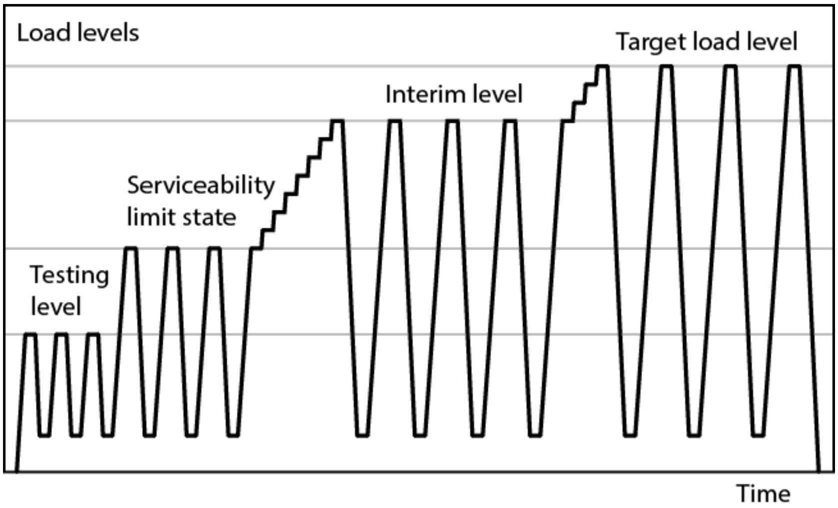

FIGURE 2: Recommended loading protocol

The limiting crack width for shear w_{ai} is determined based on aggregate interlock theory [23, 24] and needs further experimental validation:

$$w_{ai} = \frac{0.03 f_c^{0.56}\left(1+\rho_s n_e - \sqrt{2\rho_s n_e + \left(\rho_s n_e\right)^2}\right)\left(978\Delta_{cr}^2 + 85\Delta_{cr} - 0.27\right)R_{ai}}{v_{RBK}} + 0.01mm \qquad (2)$$

with f_c the concrete compressive strength, ρ_s the reinforcement ratio, n_e the ratio of the modulus of elasticity of steel to the modulus of elasticity of concrete, Δ_{cr} the critical shear displacement, R_{ai} a correction factor for high strength concrete, and v_{RBK} the limiting inclined cracking shear:

$$R_{ai} = 0.85\sqrt{\left(\frac{7.2}{f_c - 40MPa} + 1\right)^2 - 1} + 0.34 \text{ for } f_c > 65MPa \qquad (3)$$

$$v_{RBK} = \max(1.13 k_{slab} k \sqrt{\frac{f_c}{f_{ym}}}; 0.15 k_{slab} k \left(100\rho_s f_c\right)^{1/3}) \qquad (4)$$

with $k_{slab} = 1.2$ for slab bridges on lie supports and $k_{slab} = 1.0$ for other cases. The size effect factor k equals:

$$k = 1 + \sqrt{\frac{200mm}{d}} \leq 2 \qquad (5)$$

with d the effective depth of the cross-section. The critical shear displacement equals:

$$\Delta_{cr} = \frac{25d}{30610\phi} + 0.0022mm \leq 0.025mm \qquad (6)$$

with ϕ the bar diameter.

Table 2. Currently proposed stop criteria

	Cracked in bending or not?	
Failure mode	*Not cracked in bending*	*Cracked in bending*
Bending moment	Concrete strain, Equation (1) $w_{max} \leq 0.5$ mm $w < 0.05$ mm => $w \approx 0$ mm 25% reduction of stiffness Deformation profiles Load-deflection diagram	Concrete strain Equation (1) $w_{max} \leq 0.3$ mm $w < 0.05$ mm => $w \approx 0$ mm 25% reduction of stiffness Deformation profiles Load-deflection diagram
Shear	Concrete strain Equation (1) $w_{max} \leq 0.4w_{ai}$ 25% reduction of stiffness Deformation profiles Load-deflection diagram	Concrete strain Equation (1) $w_{max} \leq 0.75w_{ai}$ 25% reduction of stiffness Deformation profiles Load-deflection diagram

During the proof load test, the communication between the load operators and the engineers following the measurements is important and should be constant.

Since a proof load test gives an immediate answer to the question if a bridge fulfils the requirements for the prescribed live loads, the post-processing of the results is simply a matter of documenting the test and its results. The strain measurements should be corrected for the effect of temperature and humidity, and the measured displacements should be corrected for the displacements at the supports to find the net displacement profiles. The engineers carrying out a proof load test can formulate a recommendation for the bridge, but the final decision lies with the bridge owner.

4. Discussion

In the German [25] and North American guidelines [26, 27] for load testing, load testing for shear is not permitted. However, many existing bridges do not fulfil the requirements for shear upon assessment according to the current live load models. Therefore, the presented research aimed at including the failure mode of shear into proof load testing,

Even though more experimental research is needed to develop proof load testing for shear in a guideline or code for the Netherlands, the currently available research results already lead to interesting conclusions with regard to the behaviour of bridges proof load tested in shear, and the required safety margin to avoid damage to the bridge. It has been found that proof load testing for shear is feasible, as shown by the successful shear proof load tests presented in Table 1. However, further experimental validation of the proposed stop criteria for shear is recommended.

5. Summary and conclusions

Over the past years, the technique of proof load testing has been studied in the Netherlands for reinforced concrete bridges. The goal of a proof load test is to show with an experiment that a certain bridge fulfils the code requirements with regard to the prescribed live loads. In particular, the option of proof load testing for the failure mode of shear, which is not permitted by existing codes and guidelines, has been evaluated. In addition to a number of pilot proof load tests, and a collapse test in the field, controlled laboratory testing has been carried out, as well as theoretical desk research.

The result of this research is a set of recommendations for proof load testing of reinforced concrete bridges. These are divided into recommendations for the planning, execution, and post-processing of a proof load test. A method to determine the position and magnitude of the proof load was developed, as well as a loading protocol, a set of stop criteria, and recommendations for the minimum instrumentation. Whereas further research is needed with regard to the stop criteria for shear, the presented research has shown that proof load testing can be used for the assessment of existing concrete bridges for shear and bending moment.

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